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A Centralized Architecture for Cooperative Air-Sea Vehicles Using UAV-USV

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***Abstract*—This paper deals with the problem of monitoring and cleaning dirty zones of oceans using unmanned vehicles. We present a centralized cooperative architecture for unmanned aerial vehicles (UAVs) to monitor ocean regions and clean dirty zones with the help of unmanned surface vehicles (USVs). Due to the rapid deployment of these unmanned vehicles, it is convenient to use them in oceanic regions where the water pollution zones are generally unknown. In order to optimize this process, our solution aims to detect and reduce the pollution level of the ocean zones while taking into account the problem of fault tolerance related to these vehicles.

***Keywords*—Centralized architecture, fault tolerance, UAV, USV.

I. Introduction

MARINE pollution is the result of the presence of oil in the ocean and excessive quantities of toxic products rejected in the environment by human activities. This pollution concentration occurs in the marine environment via runoff and watercourses, or is brought by winds and rains, or comes from products and objects discharged into the sea. This causes damage at the level of the marine flora and fauna. Thus, industrial sectors have been encouraged to improve existing techniques and the development of new processes, satisfying the restrictive international standards to protect such environments. For that purpose, there was a growing interest on several sectors to use unmanned vehicles to help weather forecasts; monitor and preserve the flora and fauna; evaluation of natural disasters like the floods; cleaning oceanic regions where soil and water pollution is dispersed.

Region monitoring is an important task to collect information about different phenomena. Unmanned vehicles, by their characteristics and capacities, they became a candidate solution in the deployment of such field. We are interested in the use of unmanned vehicles to monitor and clean dirty ocean zones. In this regard, some researchers have embedded decisional autonomy in their system as the system of Belbachir et al. [5]. This decision includes an agent that automatically plans the robots tasks, monitors the performance of their tasks, and monitors the state of the systems.

The interest of this work is to present a centralized approach which allows easier management between different unmanned vehicles. This management requires a central node which has deterministic decision-making capability and easy coordination to implement. This coordinator has a global view of the unmanned vehicle activities of his appropriate system. These unmanned vehicles cooperate with each other to execute a mission of surveillance of the oceanic regions and the cleaning of their dirty zones, and follow the requests (tasks) of its coordinator.

The major disadvantage of a centralized system is the failure of the central node. Our goal is not to study the failure of central node (general coordinator) of our system but to develop a solution to manage the breakdown of the unmanned vehicle. Given that the latter is a mechanical, electronic and computer system which will can a given moment fails in hardware / software level in the performance of its tasks. These failures can be a failure of the actuators with their power supply, motor failure, loss of the piloting radio signal, loss of the GPS signal, Sensitive to the meteorological conditions (strong winds, rain), etc. For this our solution allows to select and replace the failed USVs by the competent USVs during the realization of the cleaning mission.

In this paper, we propose a centralized architecture which is embedded in an UAV and an USV in order to detect and clean ocean areas. We suppose that a camera embedded in the UAV gets geo-referenced images which determines the positions of the dirty zones. The UAV discretize its environment map and update this map by the collected information related to dirty zones. The UAV sends its environment map to the general coordinator (represented by a human operator). After an analysis of these collected data, the general coordinator allocates way-points to the USV to clean dirty zones. The latter navigates to the assigned dirty zone and clean it. The novelty in this work is that our proposed method is extended by a fault-tolerance service.

The paper is organized as follows: in Section II, we present some related works (on cooperation and coordination between different Unmanned vehicles); we describe, in Section III, the proposed approach for the different unmanned vehicles; we propose, in Section IV, a formalization of our proposal; and we illustrate, in Section V, an example to simulate the operation of our approach. We finally conclude our work in Section VI and show some future directions.

II. Related Work

The field of heterogeneous unmanned vehicles represented by UAVs, UGVs (Unmanned Ground Vehicles) has received some attention where several reactive approaches and deliberative search methods have been proposed. This article discusses a centralized approach to the problem of monitoring and cleaning of the oceanic spaces in a cooperative mission.

Based on this problem, we have selected some work to define tasks such as the exploration of the regions, the planning

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of movement, the elimination / the localization, the transport of the objects, etc. These tasks are provided by unmanned vehicles in an objective of surveillance and cleaning. While inspiring from these studies, we will propose and improve an approach based on the notions of collaboration / cooperation between the various unmanned vehicle systems in these applications.

The types of these applications are diverse, they can be used for autonomous aerial surveillance of urban areas in a geometrically complex environment using a group of UAVs as mentioned in the work of Jakob et al. [1]. This work consists of finding the shortest path for the UAV which guarantees the coverage of all points of interest by taking into account occlusions.

UAVs can also collaborate with UGVs to accomplish a common mission such as inspection of the area, transport of objects, etc. The UAV provides an overview of the explored area to assist a human operator to supervise and guide a group of UGV [2]. The latter us also used to locate and eliminate simulated mines (called: UneXploded Ordnance (UXO)) in an unknown environment where an UAV generates a map of the explored region to define the waypoints and the UXOs positions to send them to the base station. The UGV uses its sensors to visit the waypoints in order to eliminate UXOs [3].

In this last work [3], the defined communication between vehicles and the base station are carried out using messages from JAUS (Joint Architecture for Unmanned Systems). This architecture manages the problem of interoperability between different cooperative unmanned systems called "Autonomous System cooperative (CAS)" [4]. CAS is a real time system designed to coordinate UAVs and UGVs missions in unknown area. On the other hand, it is a complex system that do not take into account fault tolerance of the system. In the work of Belbachir et al. [5], forest monitoring approach is proposed. The authors developed a distributed approach to localize forest fires in real time via a cooperative exploration strategy. The authors have integrated an autonomous decisional system adapted to UAVs using a task planning, combined with a drone controller to execute and control the generated path.

However, there are other works of monitoring maritime area, which try to reduce the water pollution in seas and ocean. Valada et al. [6] uses a team of watercraft equipped by specialized sensors which autonomously samples the physical quantity being measured and provides an on-line situation of the water quality.

The main causes of the pollution of these maritime spaces are the oil slicks caused by shipwrecks of oil tankers as well as the waste rejected by factories at the bottom of the ocean, etc. Thus, these ecological consequences have been catastrophic. For that purpose, we are trying to contribute to this problem by proposing a solution to monitor the ocean regions and clean dirty zones using a heterogeneous group of unmanned vehicles. We are proposing a centralized approach based on a cooperation between vehicles air-sea, and define an exploration strategy to generate the paths for UAVs and USVs. Each study above has characteristics / parameters that differentiate it from others. For this, we have introduced in our approach a fault-tolerance service for USV vehicles. Table I shows a comparison study of the previous cited work and our proposed approach.

III. Proposed Approach

The objective of this work is to propose an approach based on the cooperation between unmanned vehicles. This cooperation minimizes work overload to accomplish a given mission. This mission is composed of tasks which must be distributed on the various vehicles. This allocation requires air-sea coordination to facilitate the execution of tasks. This coordination solution allows to reduce the competition and the conflict between tasks of the various vehicles. Since the approach is centralized then there is a central unit that allows to order the circulation of these tasks. In this part, we will describe the proposed approach, as well as its functioning.

A. Hierarchical Role of Each Vehicle

The role of each used vehicle is presented in Fig. 1. It shows the general coordinator (GC) with the highest decisional level. The GC allocates all the tasks to the needed unmanned vehicles (UAV_{MR}, USV_{CZ}, $Vehicle_{Rec}$) located in the base of life with the adequate region.

The surveillance drone is described as an UAV, it monitors each region and supervises the cleaning vehicles. The latter has the role of carrying out the cleaning action of the zone which was intended to emit a light by its LEDs according to the level of its energy. The used vehicle is an USV.

The recovery vehicle, is chosen and launched by the general coordinator, aims to recover the failing vehicles. The recovery vehicle is a special unmanned vehicle.

B. Environment Modeling

This section describes the model of our environment.

1) Description of the Environment:

- *Set of tasks.* We define the five high level tasks that are used by UAV and USV:
  1) *Monitoring task:* t_{mr} represents a task of monitoring the region r.
  2) *Cleaning task:* t_{cz} represents the task of cleaning a dirty zone z.
  3) *Supervising cleaning task:* t_{sz} *represents the task of supervising the cleaning of a dirty zone* z.
  4) *Allocating task* t_a represents the task of allocating Unmanned vehicle to different regions and dirty zones.
  5) *Launching task* t_l represents the launching spot of the different previous tasks (Monitoring, cleaning, Supervising Cleaning and Allocating tasks).
- *Set of vehicles.* We represent different used vehicles with their related roles.
  1) *Monitoring Drone* UAV_{MR} *(Supervisor* Sup_{MR}*):* are homogeneous and identical UAVs. They are responsible of:
     a) monitoring their regions, their dirty zones, their cleaning vehicles.
     b) supervising their cleaning vehicles (USV_{CZ}).

TABLE I
COMPARISON BETWEEN THE RELATED WORKS

Work/Criteria	[1]	[2]	[3]	[4]	[5]	Proposed Approach
Type of Approach	Agent-based Coordination / Planning	Hierarchical Architecture / Air-Ground Coordination	UAV / UGV collaboration system	Unmanned Embedded System	Localization mission: Forest fires	Air-sea cooperation
Proposed system	Centralized	/	Centralized	/	Distributed	Centralized
Targeted type of problem	Aerial surveillance with occlusion	Collaboration between mobile robots	Localization / Elimination of mines	Interoperability between multiple vehicles	Fire Detection / Prediction	Aerial Monitoring /Detection and Cleaning
Problem Solution	Surveillance of multiple regions with the allocation of drones	Consideration of heterogeneous mobile robots	Expand UGV by integrating UAVs perception capabilities	CAS: cooperative autonomous system in real time	Autonomous system for UAV / decision	UAV-Monitoring and USV-Cleaning
Used type of gear	UAV: fixed-wing	Quadcopter drone, UGV of type WMR.	Aircraft helicopter, UGV (automated Suzuki)	UAV (Aircraft), UGV (MGSP)	UAV (rotorcraft)	UAV, USV
Environment	Geometricall-y Complex	Industrial Zone	Unknown	Unknown Military zone	Generally unknown	Maritime / Atmosphere space
Used algorithms	Alternating, Spiral, Zigzag – Trajectory	/	A* waypoint –Localization	/	NextCell Exploration	Calculate the number (USV)
Metrics to measure	Average information age with the number of UAVs	Waypoints model avoiding obstacles	UGV positioning capability and UAV detection capability	Target position error	2D trajectory by identifying forest fires	TEC - selected USV and average CEC-zone
Interoperability	/	/	Yes (by JAUS)	Yes	/	
Decision Level	Coord	Coord/Coop/ Collaboration	Collaboration	Coop/ Coord	Coop	Coop/ Coord
Quality of Service	Produced trajectories	/	/	/	Measured time	QoS Cleaning of USV

c) launching and return the data and the results to the general coordinator ($General_{Crd}$).

2) *Cleaning vehicle (USV_{CZ}):* are homogeneous and identical USVs. They are answerable of:

a) Cleaning theirs dirty zones.

b) Launching and returning the data and the results to their Sup_{MR} (UAV_{MR}).

c) Coming-back to the base of life which represents a storage area of UAV_MR, USV_{CZ} and $Vehicle_{Rec}$.

3) *Recovery vehicle ($Vehicle_Rec$):* it is a special vehicle named recovery vehicle ($Vehicle_Rec$). It allows bringing back the faulty vehicles (out of order) towards the base of life.

- *Descriptive table of the different agents.* Table. II shows different types of agents with their names and roles.
- *Set of regions.* The monitored area is divided into regions. The region is composed of two levels; a higher level (atmospheric space) where we find the UAV_{MR} and a lower level (maritime space) where we find the USV_{CZ}, base of life and dirty zones.
- *Dirty zones.* They represent dirty part where we find the water pollution, for example oil slicks, plastic waste, etc. In this work, we propose that the water color is the metric that shows the dirt of a region. We define the degree of dirt, where we assume four colors corresponding to the following intervals [0..25],]25..50],]50..75],]75..100]. Each interval is represented respectively by the following color: the white (the water is clear where there is no or a little of dirt); the light brown (the dirt is low/weak); the dark brown (the dirt is average) and the black (the dirt is strong).
  Each zone is characterized by a list «$List_{zone}$» which delimits its borders by « $Coordinate_{zone}$». The latter is composed by degree of dirt «$Degree_{cell}$»; the position of the cell «$Position_{cell}$» and it is attached to a zone by «$Position_{zone}$».
- *Base of life (storage zone).* It is a zone (can be a boat, ship and an island, ...) to store a fixed number of UAV, USV and $Vehicle_{Rec}$.

2) The Used Parameters for Our Proposal: The used parameters in this approach are represented on Table III.

C. Main Phases of the Proposed Approach

Our approach is made up of a set of phases which are: assignment, preparation, recovery, monitoring, decision and cleaning phases.

1) Assignment Phase: This phase consists to prepare the monitoring drones according to the number of existing regions.

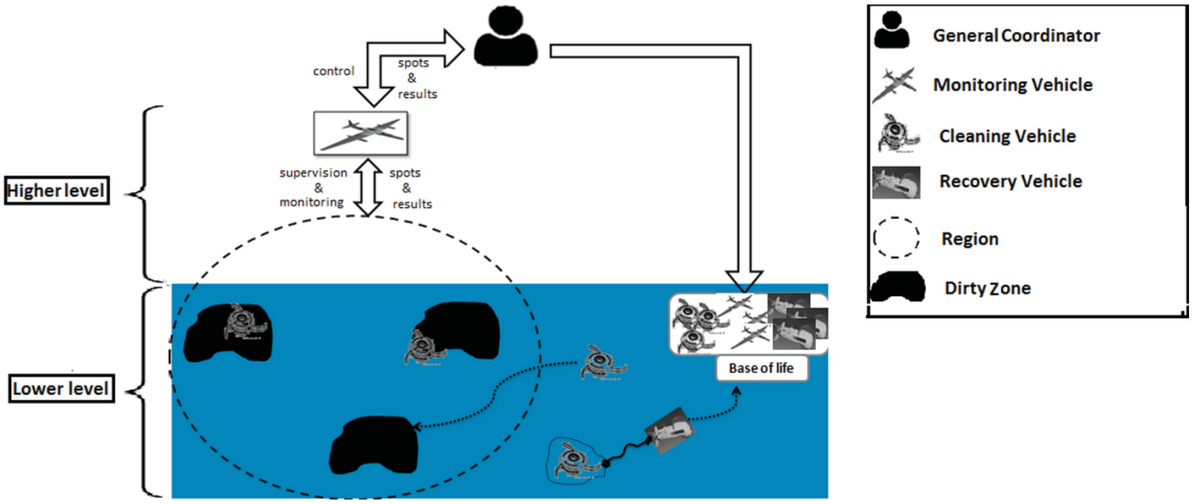

Fig. 1 Deployment of our centralized system based on a Coordinator, UAVs, USVs and Recovery vehicles

TABLE II
DESCRIPTIVE TABLE OF THE DEFINED AGENTS

Type of agent	Agent name	Description/Agent roles
$General_{Crd}$	General Coordinator	The agent is responsible of: The base of life; allocating tasks to vehicles; Launch of vehicles; The data of regions and dirty zones.
USV_{CZ} (free)	Cleaning vehicle in free state	It is a cleaning vehicle that has completed its task.
USV_{CZ} (discharge)	Cleaning vehicle in discharge state	It is a cleaning vehicle, that has not yet completed its task and energy capacity are low during cleaning.
USV_{CZ} (prepared)	Cleaning vehicle in prepared state	It is a cleaning vehicle prepared in the base of life by the $General_{Crd}$ which will replace the USVCZ (discharge).

It is triggered by the general coordinator «$General_{Crd}$» which allocates to each region a UAV_{MR}.

2) Preparation Phase: It consists in preparing the methods of navigation [7], planning [8] and checking the existence of vehicles in the base of life. This phase starts by putting sufficient vehicles in the base of life. We illustrate a case where the supervisor Sup_{MR} assigns an USV_{CZ} to clean a dirty zone. It sends a request to the General Coordinator ($General_{Crd}$). If the $General_{Crd}$ finds an available vehicle then it will activate the chosen USV_{CZ} to reach the assigned zone and associates a positive response to the query made by the Sup_{MR}. Otherwise, it will request to wait for an available USV_{CZ} by registering this request in a waiting list.

3) Recovery Phase: When a vehicle realizes its task, plans its movement towards its dirty area / region or towards the base of life thus a given moment it may break down. Algorithm 1 shows a faulty vehicle recovery service which is installed on a special vehicle called: repair vehicle ($Vehicle_{Rec}$). This vehicle is responsible of bringing the failed vehicle towards the base of life.

4) Monitoring Phase: The monitoring phase consists mainly of two stages:

1) *The launching phase of monitoring drones.* In this step, the $General_{Crd}$ triggers the monitoring operation according to the following actions:
   a) Before launching UAVs, the $General_{Crd}$ assigns for each UAV_{MR} a startup parameter "$Parameters_{start-up(M)}$".
   b) UAV_{MR} is launched from the base of life, and it follows the path to reach its region.
   c) Once UAV_{MR} (Sup_{MR}) arrives at its region, it follows the same steps:
      i) Sup_{MR} collects data from its environment and updates its grid.
      ii) Sup_{MR} divides its region into two levels: higher (atmospheric space) and lower (maritime space).
      iii) Sup_{MR} executes its trajectory to reach its monitoring region.

Algorithm 1 : Recovery phase

if USV_{CZ} = State out of order **then**
  $General_{Crd} \leftarrow$ Send the request by Sup_{MR}
  $Vehicle_{Rec} \leftarrow$ Send the request by $General_{Crd}$
  if $Vehicle_{Rec}$ receives the request **then**
    $Vehicle_{Rec}$ returns the USV_{CZ}
  end if
end if

2) *Collection and Analysis of dirty Zones.*
   a) Sup_{MR} periodically processes the collected data to identify dirty zones.
   b) Sup_{MR} sorts the $List_{zone}$ in $List_{Threshold}$ using the thresholds classification, then sends them to the $General_{Crd}$.

We propose a diagram of activity shown in Fig. 2 to describe the used approach for Sup_{MR}.

TABLE III
USED PARAMETERS FOR OUR PROPOSAL

Parameters	Description
$Threshold$	It is a fixed threshold that allows classifying the zone coordinates according to the $Degree_{cell}$.
$List_{zone}$ ($Degree_{cell}$, $Position_{cell}$, $Position_{zone}$)	This list contains all the zone $Coordinate_{zone}$.
$List_{zoneS}$	It is the $List_{zone}$ sorted in relation to the degree of dirt.
$List_{threshold}$	This list contains the coordinates of the zone that are compared with the dirt threshold.
Nbr_{CZ}	A function that gives the number of selected USV_{CZ} by $General_{Crd}$.
$Parameters_{start-up(M)}(Id_{region}$, $Position_{region}$, $Path_{region})$	A triplet of start parameters for each UAV_{MR} which represents the identifier, position, and path of a region.
$Parameters_{start-up(C)}(Id_{region}$, Id_{zone}, $Position_{zone}$, $Path_{zone}$, $Id_{UAVMR})$	A triplet of start parameters for each USV_{CZ} which represents the identifier of a USV_{CZ}, identifier of a region, identifier of an zone thus its position and path.
$List_{characteristics}$ (Id_{zone}, Id_{USVCZ}, Dur_{EC}, $Cons_{EC}$, Dur_{ED}, $Cons_{ED}$)	This list contains the USVCZ characteristics: Id_{zone}: identifier of an zone, Id_{USVCZ}: identifier of a Id_{USVCZ}, Dur_{EC}, $Cons_{EC}$: the duration and the energy consumption of cleaning, Dur_{ED}, $Cons_{ED}$: the duration and the energy consumption of displacement.

5) Decision-Making Phase on the Number of Cleaning Vehicles: Algorithm 2 represents the selecting phase of a number of cleaning vehicles. The coordinator calculates from $List_{Threshold}$ the average of the dirt and determines the minimum value of these averages. It calculates then, the distance from the average and the minimum ($x \leftarrow$average($Lists_{Threshold}$) / min($Lists_{Threshold}$)). Finally, it computes the needed number of USV_{CZ} to explore the determined dirty zones.

Algorithm 2 : Calculate the needed number of USV_{CZ}

```
m: represents the number of USV_CZ in base of life;
y: the solution variable to find the number of USV;
sum = 0;
for all average (Lists_Threshold) calculated do
    x ←average(Lists_Threshold)/min(Lists_Threshold)
    save x in List_x
    sum ← sum + xy
end for
m = sum
y = m/x
for all x found in List_x do
    Nbr_CZ ← y × x {Calculate the number(Nbr_CZ) of (USV_CZ)}
end for
```

6) Trigger Phase of the Cleaning Process: After the execution of Algorithm 2, a decision is made to trigger the cleaning operation. The selected USV_{CZ} is assigned to the appropriate zone by the $General_{Crd}$ according to a known a priori path. In our approach, we assume that only one cleaning vehicle is assigned to one dirty zone. Each USV_{CZ} has LEDs that shows the energy level to know the vehicle state (Led_{green}: Strong energy; Led_{yellow}: Average energy; Led_{red}: Low energy).

The cleaning process. This process consists of the following steps:

1) $General_{Crd}$ sends the identifier of the selected USV_{CZ} to its supervisor (Sup_{MR}).
2) After reception, $SupMR$ sends its latest received exploration map (discretized environment) to the $General_{Crd}$.
3) USV_{CZ} will get the $Parameters_{start-up(C)}(Id_{region}$, Id_{zone}, $Position_{zone}$, $Path_{zone}$, $Id_{UAVMR})$ + the explored map by a message from the $General_{Crd}$.
4) USV_{CZ} is launched on the water. It begins to swim by following the predefined path to reach its dirty zone with its activated: Led_{green} in the beginning.

7) Cleaning Phase: This phase consists of:

- *Initialization.* The monitoring drone periodically check its own USV_{CZ} and saves their characteristics (Id_{zone}, Id_{USVCZ}, Dur_{EC}, $Cons_{EC}$, Dur_{ED}, $Cons_{ED}$) in $List_{characteristics}$.
- *Start cleaning.* USV_{CZ} plans its way from the centralized explored map and generates its trajectory to clean its zone while taking into account its energy level.
- *Finish cleaning.* This operation consists of identifying the end of cleaning and collecting the current characteristics of each USV_{CZ}. The details of this part are defined in article [11].This part consists of three following cases:
  Case 1. The cleaning task is completed:
  - When the USV_{CZ} finishes its cleaning task, it informs Sup_{MR} by its mission completeness by sending a message.
  - Upon reception of the message, $SupMR$ informs the USV_{CZ} to return to the base of life.
  - When the USV_{CZ} arrives at the base of life, it informs Sup_{MR} by sending a message. When Sup_{MR} receives this message, it stops saving the characteristics of the USV_{CZ}.
  - Sup_{MR} sends the updated $List_{characteristics}$ to the $General_{Crd}$.

  Case 2. The cleaning task is not completed and the yellow Led_{yellow} is activated: The preparation of an USV_{CZ} to replace the discharged USV_{CZ}. UAV_{MR} searches for a free USV_{CZ} to send in the same region for cleaning.
  Case 3. The cleaning task is not completed and the Led_{red} is activated: This case involves replacing

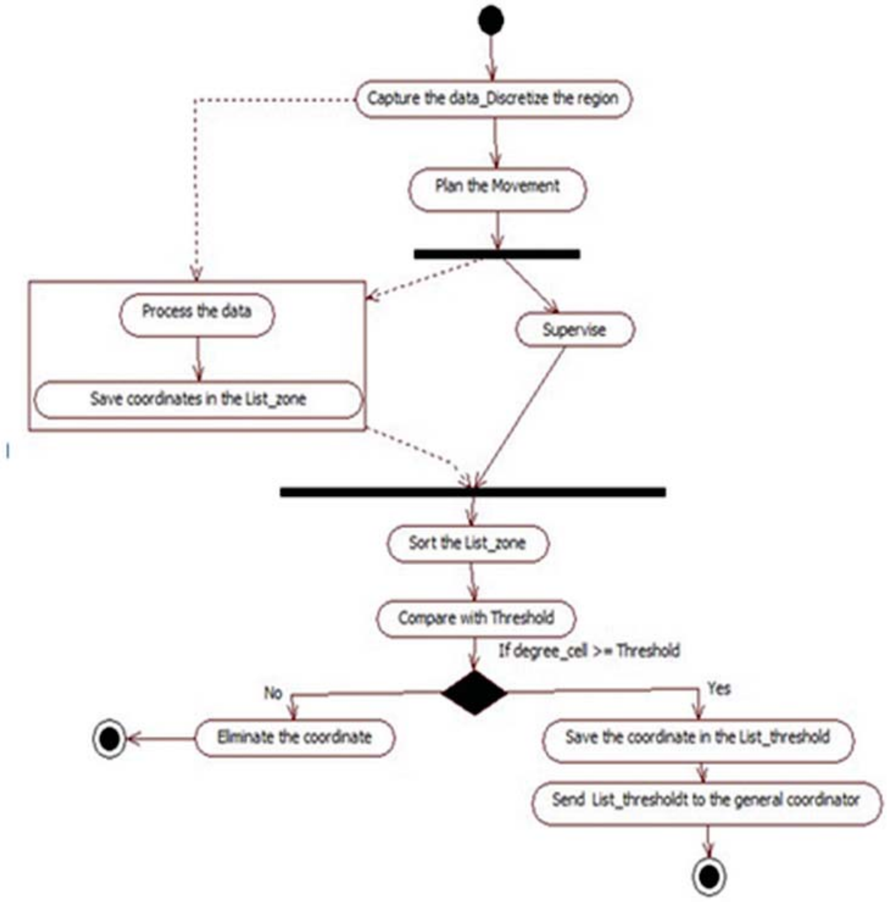

Fig. 2 Diagram of activity to collect and analyze the coordinates zone.

the USV_{CZ}(discharge) by the USV_{CZ}(prepared) or USV_{CZ}(free).

IV. Logical Formalization of the Proposal

A. Conceptual Model for Planning

A conceptual model is a simple theoretical device for describing the main elements of a problem [9]. Most of the planning approaches described in [9] rely on a general model, which is common to other areas of computer science, the model of state-transition systems (also called discrete-event systems) [10]-[9].

Example 1. This example shows two states transition systems that are defined for two domains: UAV-Monitoring (Fig. 3) and USV-Cleaning (Fig. 4). We represents a region involving a base of life (such as a boat), object of the crane type for picking up, putting down and releasing unnamed vehicles. We define two locations, one dirty zone and one UAV_{MR} for the UAV-Monitoring domain. For the USV-Cleaning domain, it has three locations, two zones and one USV_{CZ}.

For the first domain (UAV-Monitoring), the set of states and actions is *{s0,s1, s2, s3}*, *{stayinbase, flaputbase, move1∧start-monitor, move2∧fin-monitor, discover, undiscover}* respectively and there are no events. The arc *(s2, s3)* is labeled with the action *«discover»*, the arc *(s1, s0)* with the action *«stayinbase»*. For the second domain (USV-Cleaning), the set of states is *{s0, s1,s2,s3, s4,s6}*, *{take, put, start-clean, fin-clean, move1, move2}* respectively and there are no events. The arc *(s0, s1)* is labeled with the action *«put»*, the arc *(s4, s5)* with the action *«start-clean»* (see Fig. 4).

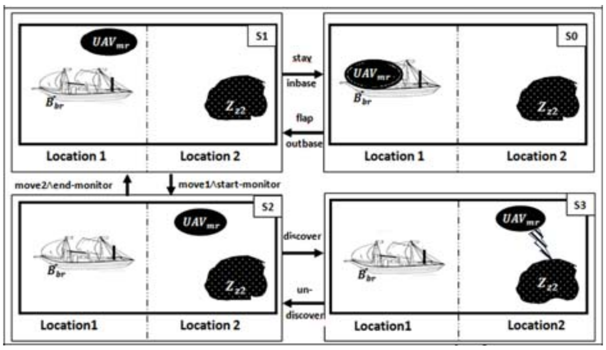

Fig. 3 A state-transition system for UAV-Monitoring domain

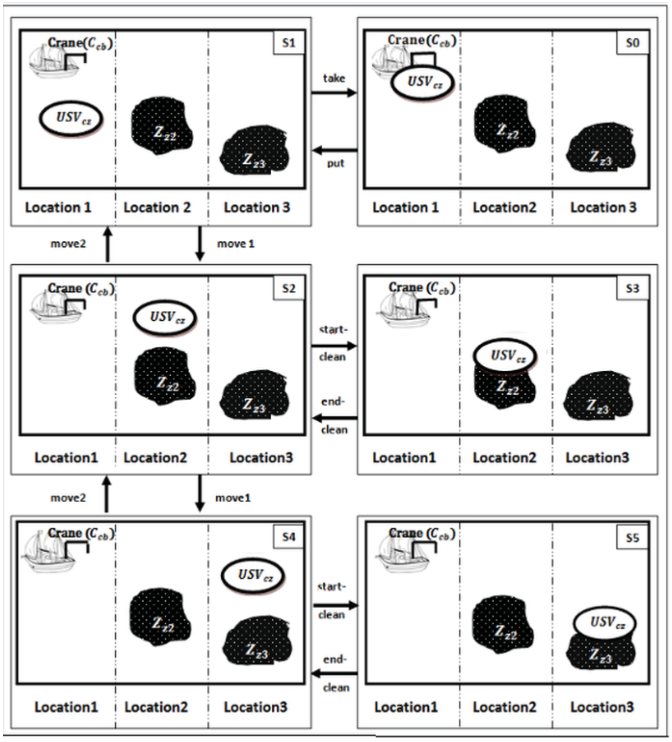

Fig. 4 A state-transition system for USV-Cleaning domain

B. A Running Example "USV-Cleaning" and "UAV-Monitoring"

The planning procedures and techniques are illustrated on two scenario one called the scenario USV-Cleaning (USV-C) and another called scenario UAV-Monitoring (UAV-M).
A version of the used domains are defined using seven finite sets of constant symbols:

- A set of regions (R_r) where a region r (r=1,...,n n>0) is a space of two levels (atmospheric and maritime) which contains a base of life, one or several dirty zones, several vehicles.
- A set of locations for each region (L_{lr}) where a location l (l=1,...L, L>0) is part of a region r.
- A set of base of life (B_{br}) where a base of life b (b=1,...B, B≥0) can be found in each region r.
- A set of dirty zones (Z_{zl}) where a dirty zone z (z=1,...Z, Z>0) is located in one or more locations l.
- A set of monitoring vehicle (UAV_{mr}) where each monitoring vehicle m (m=1,...M, M>0) may be in a certain location of a region r. It may move to another adjacent location of the same region r.
- A set of cleaning vehicle (Usv_{cz}) where each monitoring vehicle c (c=1,...,C. C>0) may be in a certain zone z or location l, it can move to another adjacent zone or adjacent location either in the same region or in another adjacent region.
- A set of cranes (C_{nb}) where a crane-type object n (n=1,...N, N≥0) is found in every base of life b.

The topology of the UAV-M and USV-C domain is noted using the instances of Predicates:

- adjacent(E, E'): The localization E= {L_{lr}, R_r} is adjacent to the localization E= {L'_{lr}, R'_r}.
- belong (C, L): The crane C={C_{nb}} belongs to location L.
- belong (B, R): The base of life B={B_{br}} belongs to region R={R_r}.

The current configuration of the two domains is denoted using instances of the following predicates, which represents the relationships that changes over time:

- at(NAME, E): vehicle NAME={UAV_{mr}, USV_{cz}} is currently at location E.
- start-clean (NAME, Z): vehicle $NAME.USV_{cz}$is ready for cleaning in the dirty zone Z={Z_{zl}}.
- end-clean(NAME, Z): vehicle $NAME.USV_{cz}$ is finished the cleaning of the dirty zone Z.
- start-monitor(NAME, R): vehicle $NAME.UAV_{mr}$ is currently ready to start monitoring in the region R.
- end-monitor(NAME, R): vehicle $NAME.UAV_{mr}$ has now completed monitoring of his region R.
- discover (NAME, Z): dirty zone Z is discovered by the drone $NAME.UAV_{mr}$.
- undiscover(NAME, Z): region does not contain a dirty zone Z or the dirty zone Z is not discovered by the drone $NAME.UAV_{mr}$.
- holding(C, NAME): crane C is currently holding vehicle $NAME.USV_{cz}$.
- stayinbase(NAME, B): vehicle $NAME.UAV_{mr}$ is currently in the base of life B.
- flapoutbase(NAME, B): vehicle $NAME.UAV_{mr}$ is outside its base B. It flies in the air.

We can enumerate the possible actions in the two domains UAV-M and USV-C:

- Move(NAME, E1, E2): a vehicle NAME moves from a location E1={L_{lr}, R_r} to some adjacent and unoccupied location E2={L'_{lr}, R'_r}.
- Take(NAME, C, R): an empty crane C takes a $NAME.USV_{cz}$ vehicle in the same region R={R_r}.
- Start-Clean(NAME, Z): a vehicle $NAME.USV_{cz}$ begins cleaning a dirty zone Z.
- End-Clean(NAME, Z): a vehicle $NAME.USV_{cz}$ has finishes cleaning a dirty zone Z.
- Start-Monitor(NAME, R): a vehicle $NAME.UAV_{mr}$ begins the monitoring of a region R.
- End-Monitor(NAME, R): a vehicle $NAME.UAV_{mr}$ finishes the monitoring of a region R.
- Discover(NAME, R, Z): a dirty zone Z is discovered by the vehicle $NAME.UAV_{mr}$ in its R.
- Undiscover(NAME, R, Z): a dirty zone Z is not discovered by the vehicle $NAME.UAV_{mr}$ in its region R.
- StayinBase(NAME, B): a vehicle $NAME.UAV_{mr}$ remains in the base of life B.
- FlapoutBase(NAME, B): a vehicle $NAME.UAV_{mr}$ flies outside base B.

NB: The action "move" is executed in parallel with the action "start-monitor" and "end-monitor".

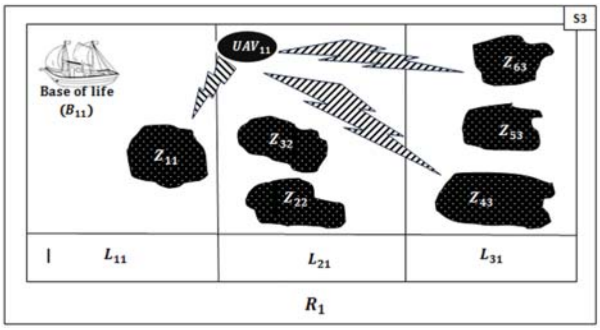

Fig. 5 UAV-M planning domain

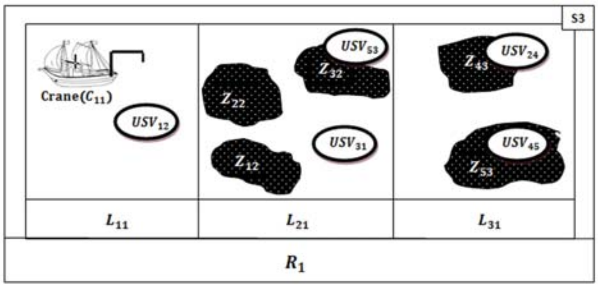

Fig. 6 USV-C planning domain

C. *Representations for Classical Planning*

There are three different ways to represent classical planning problems [9], namely: i) Set-theoretic Representation, ii) Classical Representation, iii) State-Variable Representation. In this work, we focus on the second representation (classical) to apply its planning on our proposition.

Example 2. This Example illustrates a classical representation of the two scenario domains (USV-C and UAV-M) which are described in Example 1. We suppose that:

1) For the UAV-M Domain: We want to formulate a UAV-M planning domain in which there is a drone (UAV_{11}), a region (R_1), a base of life (B_{11}), three locations (L_{11}, L_{21}, L_{31}) and six dirty zones (Z_{11}, Z_{43}, Z_{63}, Z_{22}, Z_{32}, Z_{53}). The set of constant symbols is UAV_{11}, R_1, L_{11}, L_{21}, L_{31}. One of the states is the state 3 illustrated in Fig. 5.

S3 =belong(B_{11}, R_1), flapoutbase(UAV_{11}, B_{11}), start-monitor(UAV_{11}, R_1), discover(UAV_{11}, Z_{11}), discover(UAV_{11}, Z_{43}), discover(UAV_{11}, Z_{63}), undiscover(UAV_{11}, Z_{22}), undiscover(UAV_{11}, Z_{32}), undiscover(UAV_{11}, Z_{53}), adjacent(L_{11}, L_{21}), adjacent(L_{21}, L_{11}), adjacent(L_{21}, L_{31}), adjacent(L_{31}, L_{21}), occupied(L_{11}), occupied (L_{21}), occupied(L_{31}).

2) For the USV-C Domain: We want to illustrate a USV-C planning domain in which there is a region(R_1), three locations (L_{11}, L_{21}, L_{31}), five cleaning vehicles (USV_{12}, USV_{31}, USV_{53}, USV_{45}, USV_{24}), a crane(C_{11}) and five dirty zones (Z_{12}, Z_{43}, Z_{22}, Z_{32}, Z_{53}). The set of constant symbols is R_1, L_{11}, L_{21}, L_{31}, USV_{12}, USV_{31}, USV_{53}, USV_{45}, USV_{24}. One of the states is the state3 illustrated in Fig. 6.

S3 = belong(C_{11}, L_{11}), holding(C_{11}, USV_{12}), start-clean(USV_{53}, Z_{32}), start-clean (USV_{24}, Z_{43}), start-clean(USV_{45}, Z_{53}), at(USV_{31}, L_{21}), at(USV_{12}, L_{11}), adjacent (L_{11}, L_{21}), adjacent(L_{21}, L_{11}), adjacent(L_{21}, L_{31}), adjacent(L_{31}, L_{21}), occupied(L_{11}), occupied(L_{21}), occupied(L_{31}).

V. Simulation Example

This section presents an example illustrating the simulation the functioning of our proposal. The evaluation of this simulation may include several metrics such as cleaning quality, energy consumption, cleaning time, reliability of the cleaning vehicle, etc. To highlight the contributions of our approach, we focus on the following metrics: The total energy consumption of the selected USV_{CZ}, average of energy consumption of cleaning by zones.

We have developed two approaches "Direct Displacement to Another Zone (DDZ)" and "Indirect Displacement to Another Zone (IDZ)". DDZ is when a free USV_{CZ} moves directly from its dirty zone to another dirty zone. On the other hand, the IDZ approach is when the free USV_{CZ} moves to the base of life first and then to another dirty zone.

In order to study the behavior of our approach "DDZ" and to analyze its obtained results on simulation, we compare them to the approach "IDZ" (Passage through the base of life). A series of simulations were realized according to different parameters. Before starting the experiments, we describe our virtual environment and its discretization.

A. *Virtual Environment*

We took an example of a region "Region1" that includes two locations "Location1 and Location2". There is a dirty zone "Zone1" in "Location1", a second dirty zone "Zone2" and a base of life in "Location2". Fig. 7 shows this virtual environment.

B. *Discretization of the Environment*

After defining randomly the degrees of dirt in the example shown in Fig. 7, and launching the discretization step on this environment (Region1), we obtain the following matrix (see Fig. 8). The green and violet cells represent respectively Zone 1 and Zone 2.

For our environment, we make some assumptions:

- The operation of classifying the list of coordinates of the dirty zone is done by comparing the value of the predefined threshold (equal to 24 % of degree of dirt) with the $Degree_{cell}$ of each cell.
- The number regions is 12 identical which have the same surface.
- The number of USV_{CZ} for each zone is equal to 6 according to the proposed Algorithm 2. Since our proposition is based on an USV_{CZ}, then one USV_{CZ} is assigned to each dirty zone.
- Solid (hard) obstacles are unavailable that can prevent vehicles from navigating and plan its trajectory in this environment.
- The energy of displacement between the cells is negligible.

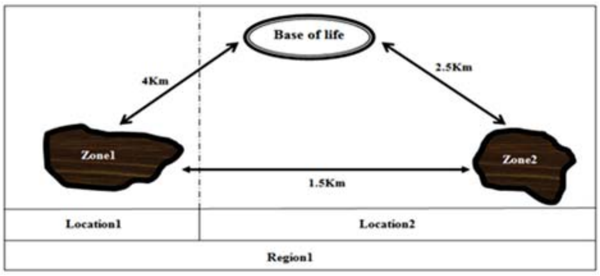

Fig. 7 Example of a simplistic virtual environment

C ij	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	12	10	18	13	19	14	9	11	3	12	16	12	2	9
2	16	11	22	20	17	9	8	5	2	4	18	16	8	1
3	19	34	13	85	80	5	25	22	4	87	70	22	68	11
4	12	18	89	69	26	25	9	19	23	22	64	86	68	13
5	9	30	12	74	98	40	25	23	16	10	90	62	40	14
6	8	80	46	8	70	24	63	89	12	12	27	50	74	15
7	10	50	20	22	40	7	82	100	11	65	1	24	43	17
8	16	26	45	37	53	4	18	23	15	73	11	75	7	22
9	20	14	18	14	9	5	11	22	19	20	12	18	21	9

Fig. 8 Matrix of discretization of the environment

- Total Energy Consumption (TEC) = Cleaning Energy Consumption (CEC) + Displacement Energy Consumption (DEC) to the zone or base of life.
- It is assumed that the needed energy to clean a black cell (too dirty) is 5%, for an average of dirt is 3% and for a small dirt cell is 1%.

C. Result of Total Energy Consumption of Selected USV

Fig. 9 shows the percentage of energy consumption (TEC) for both approaches. The selected USV_{CZ} is the vehicle that has consumed less energy than the other USV_{CZ} in zone 1; so, it is chosen to complete the cleaning of zone 2 (the case of a free USV_{CZ}). We notice that our approach (the black curve) lies below the curve of the DIZ approach (gray curve). So our proposal is better than the IDZ approach and it allows a significant reduction in the TEC of the selected USV_{CZ} with an average gain of +10.75%.

D. Result of the Average Energy Consumption of Cleaning by Zone

Fig. 10 presents the simulation to evaluate the behavior of USV_{CZ} with respect to the average of energy consumption for

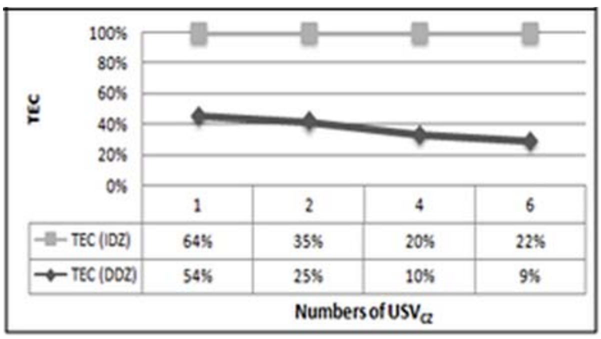

Fig. 9 Total energy consumption of selected USV_{CZ}

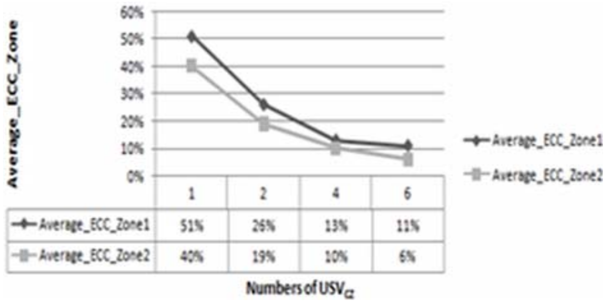

Fig. 10 Average of energy consumption of cleaning by zone

cleaning (CEC) zones1 and zone2. We note the curve of the average CEC of zone 1 is above the curve of the average CEC of zone 2. Also, the mean CEC of the two zones decreases when the number of USV_{CZ} increases. We conclude that the USV_{CZ} needs more energy to clean the zone1 compared to the zone2. Therefore our proposal could reduce the energy consumption of cleaning by zones which is estimated by an average of gain +6.5%.

VI. Conclusion

In this article, we presented a hierarchical decision-making system for the cooperative air-sea. This centralized approach serves to cooperate a set of of heterogeneous unmanned vehicles (UAV, USV) and coordinate it by a general coordinator. Moreover, it allows to manage the problem of fault tolerance of the USVs while performing their tasks. This proposed approach uses an UAV for each region and an USV to clean dirty zones. In the monitoring section, we choose the color as the degree of dirt so that the UAV can detect the dirty zones and initiate the cleaning. We suggested using the LEDs for each USV to measure the amount of energy, as well as participating in the resolution of USV failures. The supervisor (sup_{MR}) detects the average energy amount of USV by its LED. It makes these decision operations to find a competent USV that replaces the unloaded USV. As soon as the amount of energy is low then the supervisor launches the competent USV to complete the task of the unloaded USV.

We formalize our proposal by means of a classical representation. The measured metrics are the total energy consumption of the selected USV and average of energy consumption of cleaning by zone. The realized approach shows that the proposed method provides encouraging results.

In this work, we have not dealt with the problem of failure of the central unit. For this, as a future work, we plan to develop our approach to a distributed approach. In this distributed approach, we would like to build a decentralized architecture with a task planner and compare both approaches. We will propose to assign a UAV cluster for each region in a complex environment through obstacles. We will consider using other criteria to determine if a zone is dirty such as chemical criteria and other water pollution indicators (Temperature and dissolved oxygen, suspended sediment, potential hydrogen, etc) [12].

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