PERSISTENCE THROUGH COLLABORATION AT SEA FOR OFF-SHORE AND COASTAL OPERATIONS

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Abstract

Collaboration (Bruzzone et al., 2013) is often mentioned as an opportunity to develop new capabilities for autonomous systems; indeed this paper proposes a practical application where use this approach to enhance the autonomy of the systems during operations in coastal areas or around offshore platforms. The proposed case deals with developing a collaborative approach (Bruzzone et al., 2013) among an USV (Unmanned Surface Vehicle) with several AUV (Autonomous Underwater Vehicles) to guarantee persistent surveillance over a marine area (Shkurti, 2012). Obviously, the proposed solution could be adopted also for defense and homeland security (Bruzzone et al., 2011; Bruzzone et al., 2010) as well as for archeological site protection in consistence with related cost analysis. The authors propose a technological solution as well as a simulation framework to validate and demonstrate the capabilities of this new approach as well as to quantify expected improvements.

Key Words: *Simulation, AUV, USV, Autonomous Systems, Collaboration*

Introduction

The increase of marine traffic and growth of marine activities creates many issues related to protect and reduce vulnerabilities by using new technologies, such as those based on autonomous system (Bhatta et al., 2005). Therefore, this field is challenging (Bruzzone, 2013) and often it is necessary to develop computer simulation (Bruzzone, 2011) to investigate different alternatives related to: their use; the technological and engineering solutions to be adopted; their operational effectiveness and efficiency (Bruzzone, 2016). In addition, nowadays, it is possible to develop these new solutions for supporting regular operations, carrying out inspections and assistance activities in order to maximize their use as well as to improve the overall performance. This is very interesting for cases such as those related to off-shore platforms (Bruzzone et al., 2013) or critical infrastructures and industrial plants located within ports (Bruzzone et al., 2012). It requires to consider the necessity to transform marine autonomous systems in reliable solutions integrated with other assets and systems operating within this framework (Kalra et al., 2007) as well as to guarantee continuous services to the operations (Martins et al., 2011). The authors in this paper propose a solution devoted to enhance persistence on surveillance and operation within the marine domain by adopting a new engineering solution that support collaboration among different robotic systems (Feddema et al., 2002). The case is described in terms of solution and it is proposed a combined use of simulation to test the engineering solution and detailed configuration as well as to evaluate the operational performance respect a scenario. This research further develops previous activities carried out on the combined use of USV (Unmanned Surface Vehicle) and AUV (Autonomous Underwater Vehicle) out in C++ and Vega Prime and specifies them respect new simulation framework based on C# and Unity 3D as well as respect a new scenario of interoperability (Massei and Tremori, 2010) with other assets such as ROV and human divers (Tanner and Christodoulakis, 2007).

Marine Domain and Protection of Critical Infrastructures

Protecting Critical Infrastructures in coastal areas (Bruzzone et al., 2013) as well as facing open sea such as offshore platform, is a critical issue for Industrial Development and should address a wide spectrum of potential threats. Therefore, also important outline could result critical to improve performances. For instance, the use of AUV for Off-Shore Platform is growing and it is providing great support to inspections in deep sea as well as supervision to divers on middle range operations (50-300m) with the big advantage respect ROV (Remote Operated Vehicles) that operating without cables guarantees much more agility, mobility and accessibility over the different underwater areas. These considerations make potentially convenient to adopt solutions that use intensively these systems despite their limitations in terms of autonomy that usually correspond to few hours or maximum one day for propelled systems. Similar considerations could be adopted for operations related to screening or patrolling an area as well an archeological site, to conduct intensive mine hunting or other kinds of missions (Bruzzone et al., 2004)

A classical approach to speed up these process is add additional autonomous systems operating in parallel by subdividing areas and possibly, by collaborative approach, calling support from others into a specific zone when something critical emerge (e.g. suspect image coming from side scanner sonar to be checked by another point of view). However, the limited speed of most AUV (usually less equal to 4 knots) is a hard limit in redeploying the assets around based on emerging needs.

In addition, the single AUV autonomy is still limited despite the availability of multiple assets (Medeiros et al., 2010). Finally, the use of AUV at sea refers to R&D, with limited capability to deploy and recover the vehicle at sea in real operations. Usually these activities are carried out by RHIB (Rigid Hull Inflatable Boat) with humans operating manually and resulting into hard limitations respect usual sea conditions in oceans and open sea (Shafer, 2008; Sujit, 2009)

Due to this sum of reasons, the authors propose an automated release and recovery system that rely on a flexible solution involving a “catcher” and a “revolver”. The catcher is a special AUV connected with a “base” by a cable designed to finalize the final search of an AUV and the docking operations, so the catcher could collect AUV at sea, download data, recharge them and/or simply pull them back to the base (Stilwell, 2004). The base include the revolver, which is an automated mechanism able to hold different AUV (e.g. 3 middle size AUV) ready to be re-deployed and/or restored. Indeed a special winch with a basic robotic arm allows to pull back the catcher with its *prey* and to put the captured AUV in the revolver that block it by special adaptable jaws (Ferrandez et al., 2013; Vail and Veloso, 2003).

In the proposed case, the revolver is mounted over a special USV, based on a SWATH (Small-waterplane-area twin hull) that is a special boat characterized by extreme capabilities in terms of sea keeping as well as a good configuration to hold the revolver into a central bay; in addition SWATH speed guarantees the capability to react promptly to requests and to deploy and recover quickly the AUV even in challenging weather conditions. The authors developed an engineering solution for this system and simulated it to check the convenience over operations.

The simulation consider the necessity to maintain a persistent surveillance over underwater operation around an Off-Shor Platform and measure the responsiveness, persistence, costs (Magrassi, 2013) and redundancies respect a traditional approach. It results evident the improvement based on this collaborative approach among the AUVs, the catcher and the SWATH, as well as the importance to properly design the logic of these cooperation and the autonomous capabilities of each system by an effective AI solution.

It is evident that the proposed solution is dealing with quite sophisticated systems and complex case to justify costs; therefore, the authors are even considering operating on smaller AUV and SWATH to create flexible solutions to be used in coastal areas in flexible way that could be intensively used over multiple applications thanks to their readiness.

Collaborative Operations based on the *Revolver*

This innovative system was conceived in order to automate and speed up the recovery and release of AUV systems into the sea.

The author has taken into account different general scenarios. The two main different scenarios are the military one and the civil one (Bruzzone and Massei, 2017). AUV and ROV system are used in various military operations, such as: inspection and identification of ports and infrastructures (Bruzzone A.G. et al., 2013) mine sweeping (cut mines from the minefield), mine hunting (through a sonar identifies and inspects the mine, and then sends the divers to neutralize it), mine breaking (using a ship difficult to sink sent into a minefield in order to explode all the mines), coastal patrol, long-distance missions (Bui et al., 2017). These systems AUV and ROV are also widely used in the civil with different purposes: background mapping, underwater archeology, wreck search.

AUV and ROV system are widely used because of their multiple vantages. AUV is equipped with a battery compartment so it does not have to be attached to the electricity, wireless technology in order to use the Data transfer unit and the Data receiving unit.

Usually are made in Torpedo shape and, finally yet importantly, AUV can make decisions with AI using data of the GPS. ROV are equipped with fiber optic cable for data transfer to control and command Unit that is on the ship that released the ROV, it has not a battery compartment so it needs a Power Supply cable (Richards, 2002)

In order to ensure that the operator that controls ROV can monitor it is equipped with cameras (Tuan Bui et al., 2018) and in some circumstances even with mechanical arms.

To support collaborative models we designed the release system taking into account the customer's precise requests (Bruzzone et al., 2013)

The loading system with AUVs must be transportable both on board a SWATH catamaran and on board an SH-60 helicopter. In order to respect these specifics we minimize the weight of the system. Originally, the structure was a cylinder with 4 housing for the AUV. Its weight without the AUVs was over 5000 kg that was not good because the maximum load transportable by the SH-60 is 3400kg. Then, it was decided that 3 housing were enough; indeed the structure was still too much heavy. In a second moment, we also proceeded to lighten the structure passing from a full form to an empty one by over-dimensioning the most stressed areas that were spotted through a FEM analysis. In facts, we inserted an axial-symmetric cylinder to uniform the distribution of pressure. Total weight of the structure without the AUV is now only 633 kg, a good optimization.

Lightening the structure has also made it necessary to design a system of pliers and housings where to hinge them.

There are 3 pliers for each AUV in order to make it stable. We can see below the structure data extrapolated from the modeling program PTC CREO PARAMETRIC.

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VOLUME = 8.0147249e + 07 MM ^ 3
AREA SURFACE = 9.9802928e + 06 MM ^ 2
DENSITY = 7.9000000e-09 TONNE / MM ^ 3
MASS = 6.3316327e-01 TONNE

BARICENTRO compared to coordinate system _TAMB:
X Y Z 1.6707669e-01 2.5000000e + 03 -6.8959770e + 01 MM

INERTIA TENSOR:
Ixx Ixy Ixz 5.2086376e + 06 -2.6446706e + 02 -1.1614802e + 00
Iyx Iyy Iyz -2.6446706e + 02 7.9650937e + 03 1.0915698e + 05
Izx Izy Izz -1.1614802e + 00 1.0915698e + 05 5.2056357e + 06

BARBELD INERTIA with respect to the _TAMB coordinate system (TONNE * MM ^ 2)

INERTIA TENSOR:
Ixx Ixy Ixz 1.2483562e + 06 0.0000000e + 00 -8.4565151e + 00
Iyx Iyy Iyz 0.0000000e + 00 4.9540998e + 03 0.0000000e + 00
Izx Izy Izz -8.4565151e + 00 0.0000000e + 00 1.2483652e + 06

KEY MOMENTS OF INERTIA: (TONNE * MM ^ 2)
I1 I2 I3 4.9540998e + 03 1.2483512e + 06 1.2483703e + 06

ROTATION MATRIX from orientation _TAMB to MAIN AXES:
0.00000 0.00000 1.00000
1.00000 0.00000 0.00000
0.00000 1.00000 0.00000

ROTATION CORNERS from orientation _TAMB to MAIN AXES (degrees):
angles around x y z 0.000 90.000 90.000
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ROTATION RAYS compared to MAIN AXES:
R1 R2 R3 8.8455435e + 01 1.4041404e + 03 1.4041512e + 03 MM

The material chosen for the construction of the structure is martensitic steel and the production process is stamped in the sand, at least for the prototype. The movement of the structure is entrusted to an electric motor in C.C.ad with high braking torque chosen from the AEG catalog with efficiency class IE1 IE2 with protection degree IP54, IP55, IP56 and power of 35KW. The sensor chosen is very practical and economical, a phonic wheel with proximity sensor.
The cylinders were chosen from the Enerpac catalog. We opted for double-acting cylinders of the RR series and we chose a RR-20024 for the front, that is, those with longer strokes and one RR-20018 for the one with the shortest run.
We also proceeded to realize a simulation on Unity where it was necessary to create a various script in C #.
The first was the buoyancy model (Oddone et al., 2017) to be able to position the catamaran SWATH with other boats and ships to demonstrate the potential of a second script, which, in fact, is an AI that makes the catamaran able to conduct itself and avoid the obstacles that are interposed. The AI was also applied to the SH-60 because the specifications required a completely autonomous application with a good degree of interoperability (Bruzzone et al., 2015; Weiss, 2011)
The concept of interoperability comes to the fore when the interaction between the helicopter or catamaran controller and the engine that drives the release structure is necessary. In fact, under certain conditions of proximity to a Waypoint, the script starts to activate the engine of the structure providing for the release of the AUVs
There were many other scripts used for controlling the ship and the helicopter remotely and even one in the case that we want to simulate the AUV. We fixed 3 independent variables and we provided an RSM analysis.

Figure 1: Automated Revolver able to Deploy 3 AUV (Autonomous Underwater Vehicle)

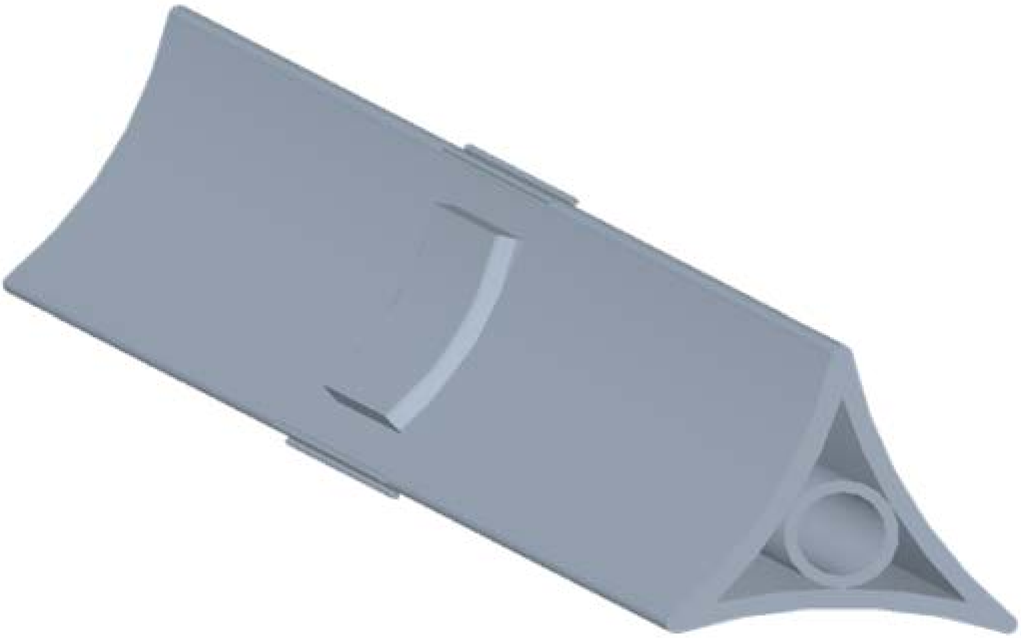

Figure 2: Body of the Revolver designed to hold the 3 AUV within the SWATH (Small-waterplane-area twin hull) bay

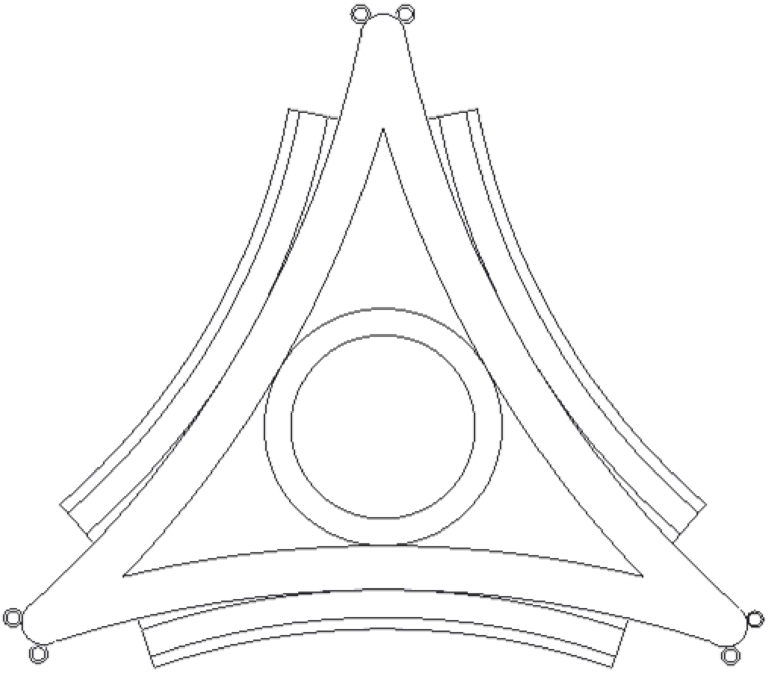

Figure 3:Section of the Revolver able to hold the 3 AUV within the SWATH (Small-waterplane-area twin hull) bay

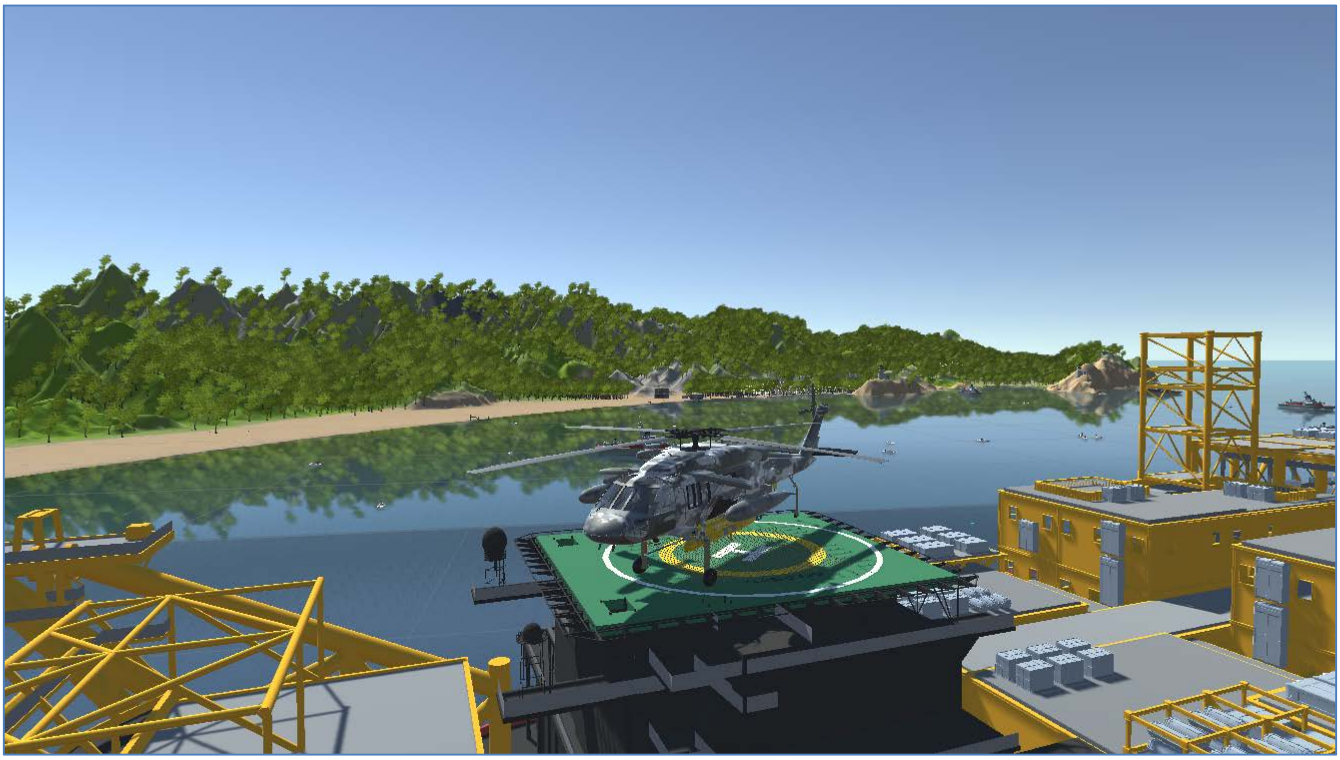

Figure 4: Example of Helicopter holding device for deploy and recovery AUV

Mission Models & Scenario Description

In order to evaluate the effectiveness and efficiency of proposed solutions and to improve collaboration capabilities among USV and AUV (Stary, 2018), it was decided to define specific missions respect the scenario related to operations around an offshore Platform. In this case, it is supposed to operate respect a permanent offshore tension-leg oil platform (TLP) operating in open sea by considering possibility to use Divers up to 300 m for operations as well as ROV and AUV in supporting roles. The main activities are summarized as following:

- 1:	Intensive Operation	up to 300 m underwater
- 2:	Underwater Operation	between 300 and 2000 m underwater
- 3:	Main Inspection/Support	up to 2000 m underwater
- 4:	Minor Inspection/Support	up to 2000 m underwater

The activity 1 requires use of Humans or ROV, while activity 2 could operate just by ROV. Other mission could be addressed by any of the different available resources based on the most convenient and effective result also respect dynamic availabilities, location, autonomy level, capability and efficiency.

In particular, the scenario is based on:

-Human Divers with hyperbaric chambers and all related infrastructures (Bruzzone et al., 2017)
-ROV operating from support boats
-AUV using Revolver Solution from the platform
-AUV using Revolver Solution operating from SWATH

The simulator developed to reproduce the detail of the operations is integrated with a scenario generator based on Stochastic Discrete Event Simulation that generate the mission over a time frame that in our case was based over 12 months of operations even considering the different sea conditions and impact on operations

The generation activities is summarized in following figure that present the mapping of operations, while in the table is proposed an extract from the inspections and operations created by the simulator to be addressed by different system.

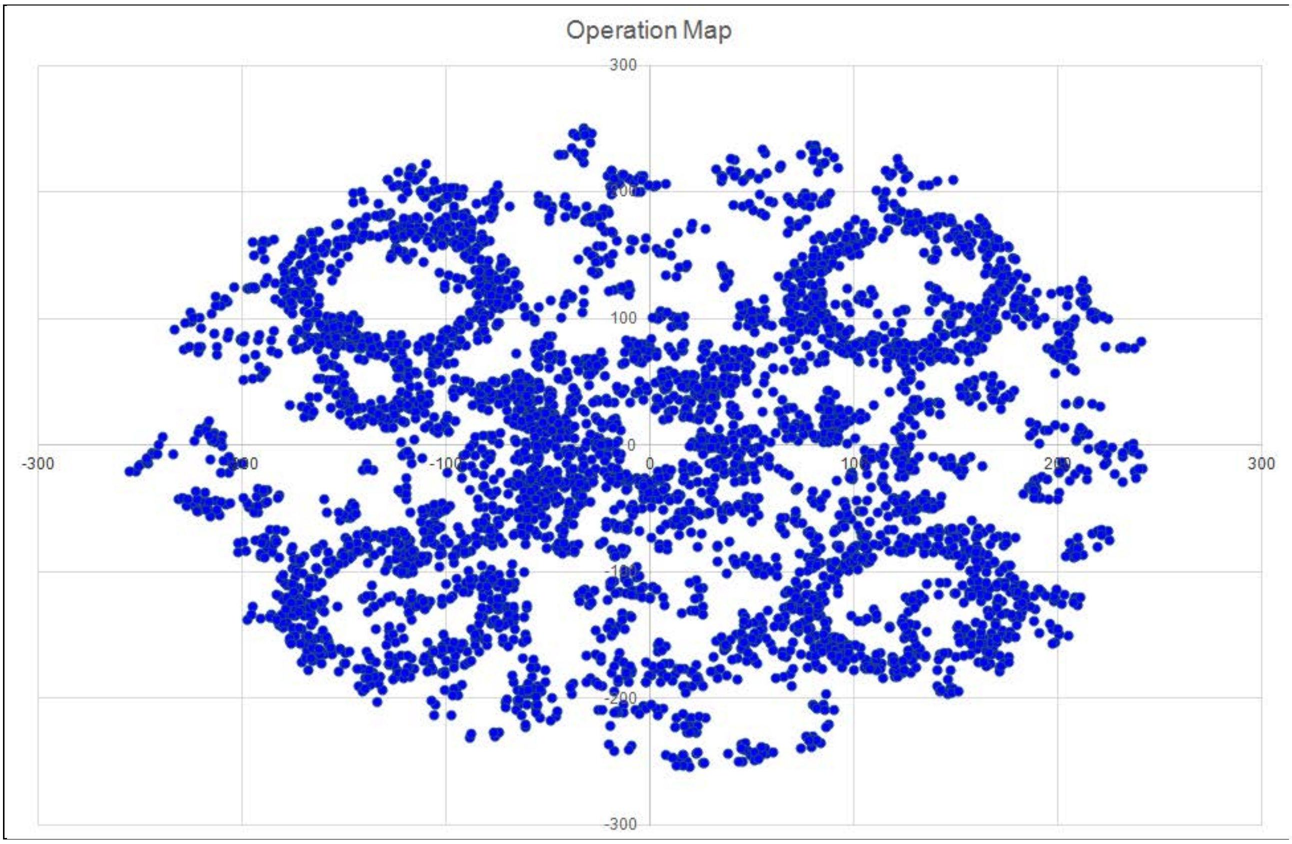

Figure 5: Operation mapping around oil platform

Time	ID	Mission Code	Workload [h]	X [m]	Y [m]	Depth [m]	Solution	Asset Tag	Time to Finish[h]	Responsiveness [min]
203.12	1690	4	13.91	-26.3	5.9	1'761	Swath & AUV	1	13.97	14
203.45	1691	4	14.21	-21.3	3.3	1'749	Swath & AUV	1	14.26	14
203.79	1692	4	14.58	-32.4	-1.8	1'749	Swath & AUV	1	14.62	15
204.13	1693	4	14.16	-20.8	1.6	1'743	Swath & AUV	1	14.25	14
204.59	27	1	223.06	65.4	-128.4	96	Human Team	3	258.58	48
205.23	1694	4	14.31	-41.3	-13.8	1'227	Swath & AUV	2	14.36	15
205.57	1695	4	14.86	-33.4	-9.6	1'224	Swath & AUV	2	14.95	15
205.92	1696	4	13.92	-42.1	-3.9	1'227	Swath & AUV	2	13.97	14
206.25	1697	4	14.82	-35.6	-4.8	1'225	Swath & AUV	2	14.90	15
206.30	1131	2	13.91	76.6	116.0	1'636	ROV	1	13.94	61

During the dynamic simulation, at each request for a mission, the simulator identify the most suitable asset based on its capability to address the request, the time required for it to respond, its efficiency on this task, its cost and its residual autonomy. The simulation does not provide directly the optimal configuration, therefore the authors introduced some simplified meta-model that estimate impacts on cost of different high level characteristics of AUV, Swath, ROV adopted on the proposed configuration, in order to estimate also economic relevance of each solutions. These meta-models have been developed based on available data on different assets, correlating costs of operations, acquisition and speed, autonomy, etc. In this way, it was possible to define a Central Composite Design able to investigate the different configurations and to identify most promising combined solutions (Montgomery, 2000)
The independent variables considered for this case are summarized in the following table

Table: Ind.	ROV	Human Teams	Swath	Swath	Swath Autonomy	AUV	AUV	AUV	Catcher	Catcher
Variables Ranges	Number	Number	Number	Speed [knots]	Autonomy [h]	Number	Speed [knots]	Autonomy [h]	Cable [m]	Speed [knots]
Min	0	1	0	10	12	0	3	8	25	2
Central	2	2	1	18	24	3	4	16	50	3
Maximum	4	3	2	26	36	6	5	24	100	4

The Human Teams are composed by 8 people operating all around the clock, able to support redundancies related to preparations and just deal with the missions generated by the simulator and does not consider all other activities. Swath number considers having a Vehicle with a Catcher and a Revolver with 3 AUV, while number of AUVs represents the number of AUV supported directly by the platform. Mean Square pure Error analysis was used to validate and verify the model while (Kleijnen, 2007) Experimental Results obtained by applying Central Composite Design allowed to create a meta-model to support configuration optimization achieving the improvement proposed by following figure in terms of responsiveness and costs. Some data have been altered due to confidentiality reasons.

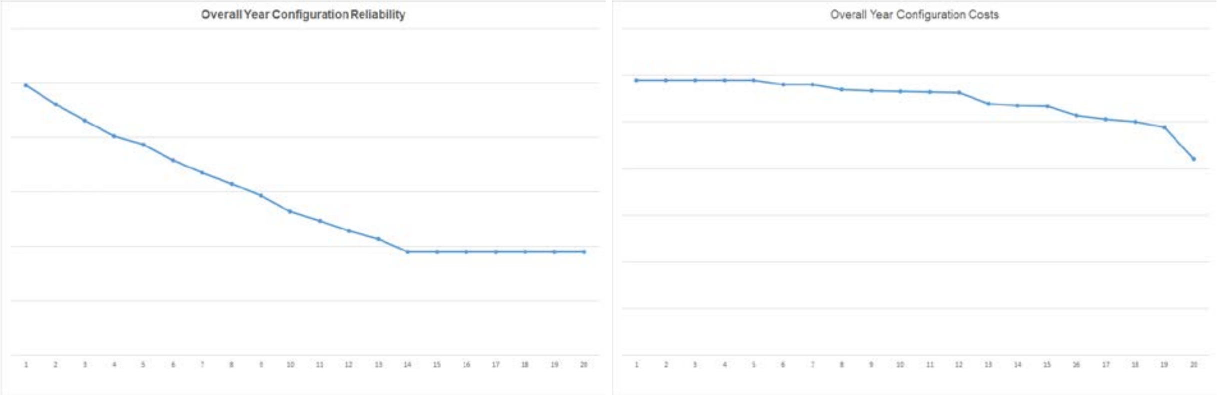

Figure 6: Fitness Function respect Cost and Reliability Target Functions

Conclusions

The proposed research represent an integrated approach to support design, engineering and operations within collaborative use of autonomous systems; the models resulted interesting to support decisions about the configuration as well as how to integrate the new systems with pre-existing assets and how to coordinate their operations (Balci, 1998; Telford, 2012).

This is just a preliminary and synthetic result of the research, therefore the author are currently working on further detailing the models and the simulation experimentation to support decisions in this specific scenario as well as in developing other mission environments (Tether, 2009)

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