SIMULATION OF AUTONOMOUS SYSTEMS COLLABORATING IN INDUSTIAL PLANTS FOR MULTIPLE TASKS

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ABSTRACT

The autonomous systems are continuously extending their application fields and current advances in sensors and controls are enabling the possibility to operate also inside buildings and industrial plants. These new capabilities introduce challenges to be addressed in order to carry out new tasks and missions. This paper proposes advances in Modeling, interoperable Simulation and Serious Games devoted to support researches supporting autonomous system operations within Industrial Facilities.

Keywords: Autonomous Systems, Safety, Industrial Plants, Security, Modeling and Simulation

1 INTRODUCTION

Industrial Plants represent a complex mission environments considering the characteristics of their processes as well as the high density in such facilities of equipment, machines and components. Classical examples are represented by Power & Chemical Plants, On-Shore & Off-Shore Platforms, Water Treatment Facilities and large industrial Area. These examples are characterized by several heavy constraints related to safety and security, indeed they often are critical infrastructures and, in case of accident, could generate dangers for human life over wide areas (Merabiti et al. 2011). In this context, most cases are related to the release of toxic compounds into the atmosphere and to the onset of critical concentration of gaseous flammable mixtures (Fabiano et al. 2015; Reverberi et al. 2016). Obviously the urbanization currently is further stressing these aspects by encompassing within large towns the industrial complexes. In case of accidents, many of these facilities result immediately pretty dangerous for humans and requires to address specific tasks respect industrial processes (e.g. shut down machines and apply safety procedures) to verify the possibility of accident escalation, addressing a proper emergency planning and actions for injured personnel such as triage (Palazzi et al., 2017). Due to these reasons the use of autonomous systems to act as “first responders” assessing the situation and to support relief operations are very promising especially if integrated with legacy systems already available on the field (Bruzzone et al. 2016b); up to now these activities have been developed and tested mostly in outdoor environment for large disasters such as earthquakes and forest fires (Apvrille et al. 2015). It is very interesting to develop similar capabilities to operate within Industrial Plants, even if the structures, obstacles as well as the very intensive dynamics of the accident could make very challenging for the robots to operate within this environment; for instance in the case of Fukushima accident the robots sent inside the plant had severe damages making them unable to return back and finalize most of their missions (McCurry 2017). It is evident the necessity to develop virtual experimental frameworks to investigate and test new solutions in these scenarios by using dynamic Modeling and Simulation (McLeod 1968; Massei et al. 2016). Indeed, this paper proposes a simulation framework able to support this analysis and a case study related to a plant accident where different robotic systems, operating over multiple domains, collaborate by carrying out multiple tasks autonomously (Veil & Veloso 2003; Ferrandez et al.2013). The example is very useful for validating the potential of the modeling approach adopted and the issues about Composability of mixed solutions. In this context, it is important to include innovative techniques of Artificial Intelligence such as Intelligent Agents and Swarm Intelligence (Wooldridge 1995; Bruzzone et al. 2011; Stodola 2014). Currently the authors are further developing this researches by focusing on the development of a new flexible UGV able to operate inside big industrial plants with multiple missions and to interoperate with other systems.

2 AUTONOMOUS SYSTEMS AND MODELS FOR INDUSTRIAL PLANTS

In facts, in order to benefits from the new capabilities of the autonomous systems and to support the development of innovative solutions able to address these new missions, in a feasible and sustainable way, it is required to carried out extensive R&D activities. In facts these researches could drastically benefit from accessing synthetic environments devoted to virtually test the new engineering solutions as well as to measure their performance, capabilities and reliability levels. It is evident that these scenarios have an high degree of complexity related to the industrial plant nature itself, but also to the high number of stochastic factors (e.g. malfunctions, plant process and accident dynamics, boundary conditions, human presence, etc.). Based on these elements and due to the necessity to carry out extensive experimentation, the use of M&S (Modeling and Simulation) emerges as most promising investigation methodology (Bruzzone et al. 2016a).

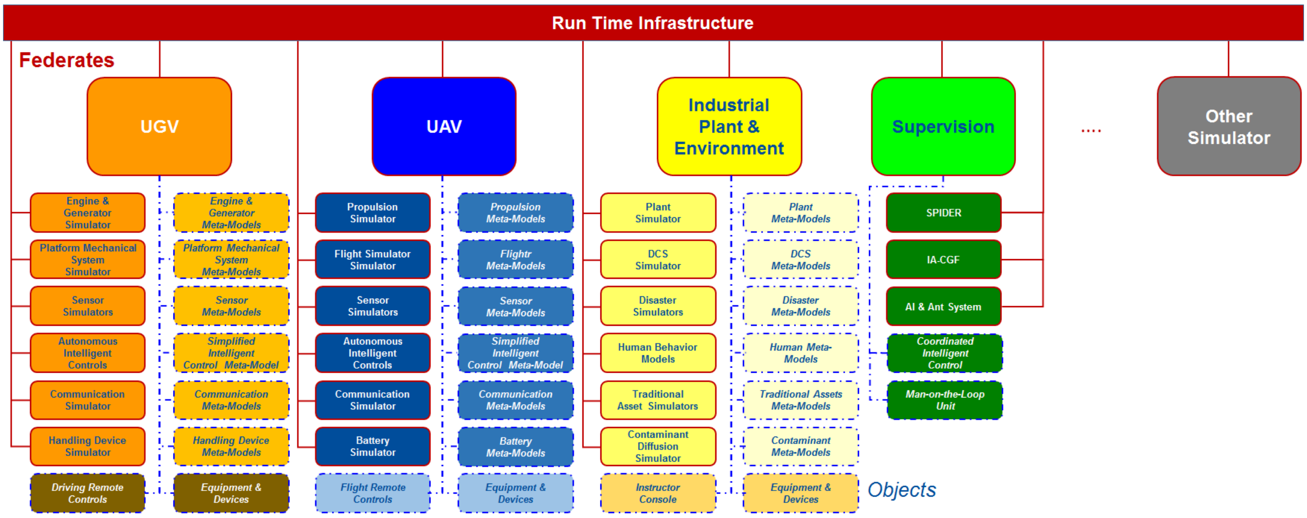

Fig.1- Example of Federation including Simulators and Objects

In industrial plant the use of UAV (Unmanned Aerial Vehicles) have been studied in several case with special attention to Nuclear Plants in critical conditions (Sugisaka 2011; Moranduzzo et al. 2014). Recently indoor operations as well as missions within GPS-denied areas have been investigated to carry out inspections, for instance within Boilers of Power Plants (Nikolic et al. 2013). In addition UAS (Unmanned Aerial Systems) have been applied also to address performance measures such as in the case of Photovoltaic Plants (Grimaccia et al. 2015). In reference to UGV (Unmanned Ground Vehicles) there are expectations to further developments in industry based on technology advances (Tilbury et al. 2011). From this point of view the experiences in Oil & Gas both in on-shore and off-shore is pretty promising respect use of UxV (Unmanned multi domain Vehicles) in terms of inspections, controls, etc (Shukla & Karki 2016). In facts Simulation Team developed examples of these applications combining UAV, USV and AUV for Off-Shore Platforms and On-Shore Industrial Complexes (Bruzzone et al. 2016b).

3 MULTIPLE MISSIONS FOR AUTONOMOUS SYSTEMS IN INDUSTRIAL PLANTS

In facts, the large investments required for developing new solutions based on innovative autonomous system for safety and emergency management in industrial plants need to be carried out in a sustainable way; so it is strongly recommended to develop and tailor these UxV for being able to carry out multiple missions devoted to cover regular industrial operations as well as to complete critical tasks during crisis (Bruzzone et al.2016a). In facts, often it is not possible to adopt and install industrially the solutions based on current state of art advances, such as last DARPA competitions, also to the pretty high costs related with these developments (Tether 2006; Guizzo et al.2015; Lim et al. 2015). In facts, it is evident that the impressive capabilities proposed by the very advanced KAIST robot, are still not able to satisfy industrial requirements not only in terms of costs, but also of speed and responsiveness for most accidents that are characterized by very fast dynamics (Ackerman et al. 2015). Therefore in real industrial plants, usually, the generalization needed for addressing emergency management could be quite severely restricted due to specific context, making it possible to develop with today affordable technologies much more lean solutions (e.g. simple positioning, pre-defined access methods, redesign of some element of the plant for autonomous system use, etc.); this consideration is confirmed by recent researches in this sector (Ross et al.2006; Bruzzone et al. 2016b)

In facts, several industrial plants are plenty of tasks and activities currently carried out by humans in dangerous frameworks (e.g. controls on confined spaces and on tall chimneys) where autonomous systems could be very useful for improving safety; these autonomous systems obviously have to address similar challenges to that ones to be used for emergency management or during accidents (e.g. moving around, conducting measurements or inspections, obstacle avoidance, etc.); so it is evident the importance to develop solutions able to address multiple tasks to increase utilization and return of investments for these new systems. In facts today, it is possible to develop autonomous systems able to carry out multiple missions in this context: for instance monitoring the plant processes, inspecting symptoms of malfunctions, controlling environmental and operational parameters, relieving the presence of humans in dangerous areas and supporting security.

In this way these devices could increase efficiency, effectiveness and safety even during regular operations, so in case of accident they could be already operative on site for being used in emergency management and disaster relief. In addition to the aspects related to the Industrial use of these autonomous systems, it could be even considered the possibility to tune them to address security and defensive tasks in reference to critical infrastructure protection respect different kinds of threats (Bachmann et al.2014). In facts the increase of security issues along last years (e.g. terrorism, social instability, etc.) suggests that this aspect could provide a

significant improvement with marginal costs, while it could represent even an opportunity to obtain public support for dual use: vulnerability reduction of a critical infrastructure and improvements on safety for working condition within the plant (Pugh 2005; Brown et al.2006; Bruzzone et al.2016b).
However it is important to outline that UxVs need to be protected and operating within secure networks in order to avoid vulnerability from cyber attacks that could turn them into resources for threat networks (Rani et al. 2016).
In facts, this is a very good example of general use that sustain the diffusion of innovative solutions able to interact with legacy system and to reduce vulnerability and improve safety.

4 CHALLENGES OF INDUSTRIAL PLANTS FOR AUTONOMOUS SYSTEM

As anticipated industrial plants represent a very challenging environment to operate autonomous systems for several reasons; first of all many electromagnetic interferences and obstacles are present in plants; for instance inside there is often a very high density of suspended pipelines, cable trays, cables, wires; the industrial production usually requires high power installation generating intense electromagnetic field; in addition the dense metallic structures represent physical and electromagnetic challenges for autonomous systems. In addition to these element the mechanical, thermal and chemical processes related to the industrial production could represent additional challenges altering the perception of the sensor and their reliability (e.g. high irradiating sources, dust, etc.).
All these conditions affects drastically not only movement and regular visibility, but also IR spectrum and electromagnetic compatibility and communications as well as positioning system.
In facts, an UxV (Unmanned x-th domain Vehicle) usually requires to be able to use different sensors and data functions features to properly complete their missions (Stodola & Mazal 2010b) as well as to have an high degree of autonomy to continue to operate and collaborate with other autonomous entities in case of communication failure with centralized supervision system (Feddema et al. 2002; Tanner et al.2007b). In addition to these elements the presence of pipelines, tanks with flammable gases and liquids, as well high tension cables make this environment subject to dangers while moving autonomous systems or remotely piloted vehicles that could crash or hit sensitive parts; these considerations are especially true for process plants, therefore it is also important to keep in mind that the co-presence of humans in the areas provide other sources of risks in this joint operations.
In addition, operating within industrial plants to carry out monitoring activities during crucial moments (e.g. as response to an alarm) or for emergency management in case of accidents, introduce additional challenges to the UxV operations and it is very critical to identify the best configurations and solution to be put in place.

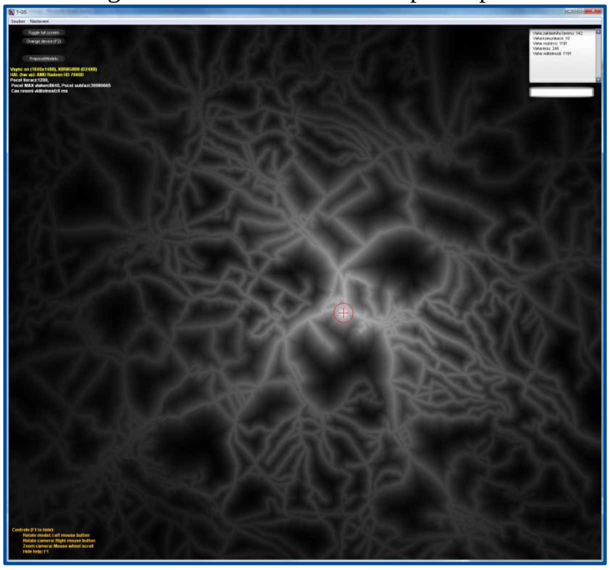

Fig.2- Path Optimality Map implementing multi criteria constraints: Initial Path Point within the Red Circle

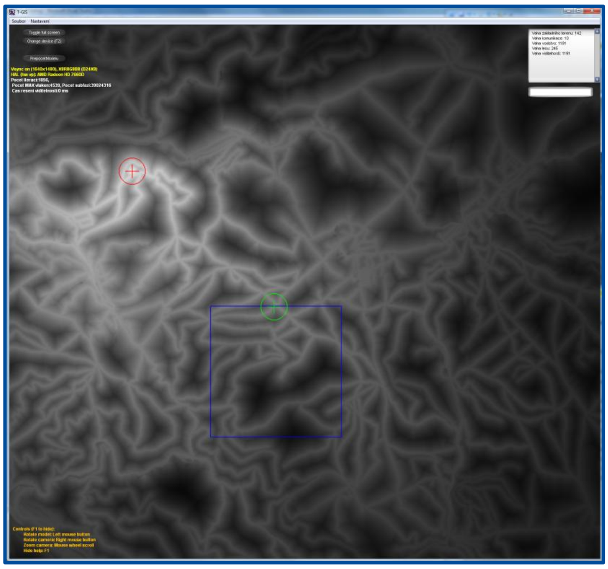

Fig.3- Path Optimality Map: Initial Path Point in Red Circle & Optimal Destination Point in Green Circle within selected Destination Area (Blue Square)

Therefore, despite all these elements that represent challenges, it is evident that in these context the introduction of autonomous unmanned systems to substitute people provide a great opportunity to reduce risk to human life.

5 MODELING USE & AI ALGORITHMS

The proposed application field requires the models and simulators to be used for different purposes; for sure crucial objective is to support requirement and configuration definition during early design in order to identify the most promising platform type (e.g. UGV or UAV, wheeled or tracked, single domain vs. multi domain) and operational mode (e.g. single platform, multi platform, collaborative, etc.).

Fig.4- UAV moving inside the Industrial Plant

Fig.5- UAV supervising UGV relief mission

In this phase the simulation should act on relaxed fidelity constraints, therefore the evaluation of confidence band should be carried out and controlled to verify and validate the model, check the result consistency and support comparative analysis among different configurations (Richards. et al.2002; Massei et al.2003). In addition it should be outlined that M&S plays decisive role within AI (Artificial Intelligence) algorithms and decision support approaches at all levels; for instance, the *deployment destination optimization,* including *obstacle avoidance* and *multi-criteria compromise,* could be calculated, for every possible path option and destination within operations area, in real time (approx. 50ms, 2x2 Km, area attribute resolution 1x1m) thanks to the multi-path algorithm improvements, as presented on figure 3 (Mazal 2012). Based on the initial path point and criteria, *Path Optimality Map* could significantly differ and "opens the door" for additional analyses, like trivial destination optimization demonstrated on figure 2 & 3. Path optimality map calculation is based on minimization of purpose function:

$$POM_{x,y} = \min \rightarrow \sum_{i=1}^{M} K_{I_i,J_i} \qquad (1)$$

where:

$K_{x,y}$ 2D weighted "safety" matrix of operational area, derived from the criteria's and analyses

I_i, J_i Mathematical progressions set coding the individual components/axes of the path.

$POM_{x,y}$ Path optimality matrix

Also must be fulfilled the condition:

$$\forall\, i \in (1..M) => (|I_{i+1} - I_i| + |J_{i+1} - J_i|) <= 2 \quad (2)$$

In facts, the M&S should be reach quite high fidelity levels in order to address engineering and finalize the check up of the whole new solution as virtual prototype. In this case, the technical and operational tests could be executed within a virtual, but realistic, environment, to verify the performance and to measure the reliability, effectiveness and efficiency of new solution based on autonomous systems; in case of configurations dealing with multi-platform collaborative UxVs, the use of simulation turn to be even more crucial as well as when it is required collaboration with traditional assets and other plant systems.

A not secondary aspect is the training of personnel in charge of managing the autonomous systems. This aspect deals with both traditional man-in-the-loop training (e.g. the pilot of a small UAV) as well as with the man-on-the-loop education and training dealing with people in charge of supervising the use of multiple autonomous systems assigning high level tasks (Magrassi 2013). This secondary kind of skills will become more and more important in the future and simulation will be fundamental to prepare these new supervisors. Last, but not least, M&S could be used to support preventive definition standing operational procedures and operational planning to be ready to act in case of necessity to carry out critical operations in challenging cases. For instance for optimizing and evaluating all risks of a mission for inspecting a confined space very hard to access, or to deal with plant area affected by an accident such as a fire. Considering these different objectives for simulation in this context, it could be necessary to consider the use of different models, so hereafter it is proposed a paradigm and an architecture that could simplify development, enhance maintainability and reusability with limited costs and efforts.

6 MODELING PARADIGM & ARCHITECTURE

As anticipated the use of Autonomous Systems in industrial plant is a challenge from many different aspects, pretty innovative in terms of implementations, and requires to be flexible for different uses; due to these reasons, it is proposed to develop a flexible approach that could maximize usability with limited efforts; the authors propose hereafter the MS2G (Modeling, interoperable Simulation and Serious Games) paradigm that combines interoperability, high fidelity simulation and serious games (Bruzzone et al.2016c); indeed this approach allows to develop intuitive virtual and augmented representations running on multiplatform, from CAVE (Cave Automatic Virtual Environment) down to smartphones; in this way it becomes possible to develop models that benefits from interoperability standard HLA (High Level Architecture) from technological point of view and that have usability and interactivity of games.

Fig.6- UGV carries an injured out of contaminated area

The international standard (IEEE1516) allows to federate different simulators and also real equipment into an open architecture; so by this approach it becomes possible to complete tests on the federation of simulators integrated also with external systems and sensors (Bruzzone et al.2016c).
In order to guarantee different uses and different fidelity models, the proposed approach adopts the architecture presented in figure 1, where meta-models could be used as substitute of federates during early development phases or in case of criticalities in data & knowledge availability as it happen in Lean Simulation (Massei et al. 2003). Among the elements of this federation of models and simulators it is obviously very important to include the IA and AI systems (Intelligent Agents and Artificial Intelligence) able to guarantee the autonomous capabilities of the UxV (Stodola et. al. 2014; Massei; Bruzzone et al.2016a). In facts this approach guarantee the possibility to overpass several of the challenges of conceptual interoperability and to get benefits of simulation technology advances (Bruzzone et al.2016c).

7 CASE STUDY: CRISIS & MULTIPLE COORDINATED TASKS

In order to validate the concept, it is hereafter proposed the case of an innovative system for addressing crisis and operations industrial plants developed by the authors; the scenario used deals with an accident including explosions, fires and hazardous material spills affecting an industrial complex; the air contamination and fire provide a challenge to use unmanned vehicles to define the dangerous area outside and conduct inspections outdoor and inside the building; the authors propose a combined use of UAV and UGV taking care of collecting measures and samples, detecting people inside and completing triage assessment (Grocholsky et al.2006; Tanner 2007a; Bruzzone 2016c).
UAVs are in charge of the majority of measurements to finalize the scenario picture and its dynamics while the UGVs provide a direct support for collecting the injured people and carry them out to the safe areas where first responders such as firefighters and ambulances are available as proposed in figures 2, 3 and 4 (Bruzzone et al.2016b). In facts the UGV could collect injured people and transport them out of contaminated areas (see figure 5 and 6); it is very interesting from this point of view to include into the federation also a simulator of the patient including dynamic reaction to events (e.g. his handling) and to environmental conditions (e.g. crossing areas affected by other contaminant agents) to create an even more comprehensive scenario (Bruzzone et al.2012). The operations require the UxV to be able to move within the whole industrial complex: inside as well as around, for instance in order to be able to identify the safe perimeter in terms of contamination and to continuously monitor the situation. In addition, it is necessary to conduct inspections in outdoor areas and inside the buildings considering the complex obstacles and electromagnetic interferences, the degraded sensor performance as well as the consumption of the UAV and UGV battery based on the subsystem and functions activated on board. These challenges suggest to develop a collaboration capability within an heterogeneous network of autonomous systems (Maravall et al.2013; Bruzzone et al. 2013b). It is fundamental to introduce Performance Indexes to evaluate the effectiveness and efficiency of different configuration as it has been done, for instance, in reference to bordering the contaminated area in the industrial plant:

$$Ace(t) = \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{\mathrm{FIA}_{i,j}(t)}{\mathrm{H}(\mathrm{L_{i,j}}(t)-\mathrm{Ll})} \tag{3}$$

$$Acrp(t) = t^{*}/Acr(t^{*}) \geq Acr(t_g)\forall t_g \in [t_0, t] \tag{4}$$

$$Acr(t) = t^{*}/Acr(t^{*}) \geq tl \text{ and } t^{*} \leq t \tag{5}$$

Ace(t) Detected Contaminated Area percentage
n number of strips used for classify horizontally the 2D map of the area around the contaminated plant
n number of strips used for classify vertically the 2D map of the area around the contaminated plant
t current simulated time
t_0 simulation starting time
H(x) Heavyside function of x
i i-th strip considered horizontally
j j-th strip considered vertically
$\mathrm{FIA}_{i,j}(t)$ Function [0,1] returning if the area is identified As contaminated by UxV systems at t time
$L_{i,j}(t)$ Real Contamination Level in the i-th and j-th area at t time
Ll Safety Concentration Limit for contaminant Agent
Acrp(t) Responsiveness at t time respect best achieved identification of contaminated areas
Acr(t) Responsiveness at t time respect best full correct identification of contaminated areas

Obviously in this case, the simulation is the best technique to conduct the tests and experiments; this consideration is valid for the virtual prototyping of a single platform (including sensors and controls) and even more important for a combined system based on multiplatform and multi-domain collaboration as that one proposed here. As anticipated, the paradigm adopted is MS2G (Modeling, interoperable Simulation and Serious Game) and the tests have been carried out

by using the SPIDER (Simulation Practical Immersive Dynamic Environment for Reengineering), a virtual immersive interactive interoperable CAVE developed by Simulation Team, providing virtual and augmented reality features to users (Bruzzone et al.2016c).
The SPIDER allows to carry out multiple experiments easily and to complete the VV&A by experimental design (Montgomery 2000).
In addition to dynamic quantitative techniques it is also possible to get face validation by Subject Matter Experts (SME) by supervising the multi domain autonomous system collaboration as well as to the dynamics of the disaster evolution affected by stochastic factors.
It is interesting to note that the quantitative results of the simulation (e.g. contamination levels, battery level, etc.) could be presented as augmented reality information during the evolution of the simulation.
In facts, this simulator is integrated with AI (Artificial Intelligence) provided by Simulation Team and by Czech University of Defence for addressing different issues (Mazal et al.2012; Massei et al.2014).
For instance, the IA-CGFs from Genoa University allow to take care of coordination among UxVs and other traditional assets (Bruzzone et al.2011). Vice versa the IA from Czech University are focusing on routing and obstacle avoidance as well as on planning issues (Stodola et al.2014a; Stodola & Mazal.2010a).
The proposed scenario is pretty challenging and the demonstration carried out in this context allows to define algorithms and configurations that result reliable for operating in this kind of environment.
For instance, as anticipated, the simulator estimates battery consumptions related to the different operational modes and sensor activations while the positions of fires and areas subjected to risk of explosions are evaluated for identify most convenient path during rescue missions with and without injured people on board for the UGV or, for the UAV, during different task accomplishments.
Some synthetic experimental results are summarized hereafter about the test conducted indoor and outdoor by collaborative use of the autonomous systems respect regular operations and emergencies.

8 CONCLUSIONS

In the proposed case, it is outlined the importance to apply conceptual interoperability in development of innovative autonomous system solutions; in facts by combining the M2SG approach with AI, such as the intelligent navigation developments, it becomes possible to multiple the effectiveness of the solutions based on the autonomous systems. The different modeling approaches devoted to support the development of these new solution, should be based on innovative interoperable architecture in order to finalize the match among different models covering specific issues. In this way the whole federation of simulators and models, combining all different aspects together, is able to reproduce the challenges of the whole mission environment.
The proposed example confirms the capability offered by modern simulation paradigms and AI algorithms in supporting the introduction of autonomous systems within new challenging scenarios.
Currently the authors are working towards the development of additional projects devoted to carry out specific tasks, actually assigned to humans, to improve safety and security in dangerous environments in industrial plants and defense scenarios.

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