INTELLIGENT AUTONOMOUS SYSTEM DEVOTED TO IMPROVE EFFICIENCY AND SAFETY IN INDUSTRIAL PLANT

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ABSTRACT
The industrial plants, in process industries, are often characterized critical environments and dangerous conditions respect the utilization of human workforce.
These aspects are quite common in chemical, oil & gas, iron & steel plants where this combination of factors causes serious accidents. The aim of this study is to develop a new generation of intelligent autonomous system capable to support operations in these environments reducing the presence of workers in most risky operations. In order to succeed in this task, these new systems must be suitable to operate in complex industrial environments and to face related threats and risks. Indeed, this paper proposes an analysis of a complex industrial environment related to hot metal production by identify the most dangerous areas and operations as well as potential critical elements for autonomous vehicle use. Consequently, simulation solutions are proposed to support engineering of these innovative robotic system as well as development of new operations and procedures.

Keywords: Autonomous Systems, Virtual Prototyping, Safety

1 INTRODUCTION

Nowadays, thanks to the new technologies, especially the ones related to autonomous and robotic systems, it is possible to safely carry out operations in industrial areas where human presence could be dangerous (Bruzzone et al. 2017). Indeed, thanks to the advances of the autonomous and intelligent systems, sensors and robotics it became possible to introduce new solutions to already well-known problems, tailoring systems for specific sectors, which in the past were poorly covered, especially in such sector as metal production. Indeed, combination of "old economy" and modern autonomous systems could lead to significant improvement of safety and efficiency in this field and create new services. Such considerations are supported by the statistics and other data provided by experts, which confirms that in the hot metal production there are many work areas that are dangerous for humans and that lethal accidents rate is significantly higher than that in many other industrial fields (Shikdar & Sawaqed 2003). This information suggests introduction of new automated solutions, especially the ones based on autonomous systems, able to deal with complex operational procedures (e.g. monitoring activities, inspections, measurements, etc.) in order to stave off personnel on site from most dangerous zones, or at least to reduce time of exposure to hazards, hence, to reduce risks.

2 SIMULATION AND REQUIREMENTS

Considering complexity of the industrial plants, processes and operations, it is evident that the development of the new systems should be supported by M&S (Modeling & Simulation) to analyze the scenario complexities. From this point of view, it is evident that simulation have to include not only the platform for an UGV (Unmanned Ground Vehicle) or UAV (Unmanned Aerial Vehicle), but also its payload and systems, plus the production line or even of an entire plants.
Obviously, this scenario results pretty complex and it requires to develop not only "physical" parts (e.g. platform, hardware), but also new control systems and new dedicated procedures for the robotic solutions. Furthermore, potential limitations, pitfalls and requirements, related to these new systems, could be discovered by employing Modeling and Simulation. It is important to state that is not necessary always to adopt high fidelity models for these analysis, while resolution and confidence band should be consistent with the purpose of the simulation.
In addition, the data available, or supposed to be available when the simulators and its results are required (e.g. new plant not yet completed when the new autonomous system has to be designed) represent another major constraint in definition of simulation requirements. For instance, in this paper this issue is addressed considering the necessity to evaluate capabilities to operate in high temperature and aggressive environments without having too much detailed data from the field.
In this context, it result necessary to develop a Dynamic Virtual Interoperable Simulation able to combine 3D and thermodynamic models for the industrial scenario. In this way, it become possible to simulate the heating of the autonomous system due to many factors such as irradiation in different initial and boundary conditions. Hence, this is pretty crucial to quantify the dynamic impact of the environmental conditions, also related to the plant operational mode that could change along the production phases, respect the vehicle and eventually vice versa impact of vehicle operations on the plant

components. Indeed, this paper proposes a methodological use of different models to face possible thermodynamic issues much time before to finalize engineering and construction of the physical vehicle. In this way the definition of new operational modes for this new component of the industrial plant could be defined concurrently during design getting benefits of simulation dynamic environment.

3 PLANT OPERATION, TASKS AND CRITICAL ISSUES

As mentioned, process industry is a challenging framework and, specifically, hot metal production is often characterized by dangerous work conditions that impact human personnel, equipment and automated systems (Pardo & Moya 2013). Based on conducted study and experimentations it is identified that the most critical characteristics of the work environment are intensive heating by irradiation, spills of molten metal and occasional presence of corrosive and/or poisonous gas; it is evident that new autonomous systems have to deal with these issues and provide a major advantage for safety. Precisely, the authors focus their attention on simulation of a new UGVs to support inspection and monitoring in hot areas.

Obviously, in this environment a major critical issue is related to the high temperatures due to the proximity of molten metals (e.g. over to 1400ºC). However, the overall conditions are changing dynamically depending on several external factors: e.g. external temperature considering that also indoor area is mostly “open” and current operational mode of the industrial plant; indeed, these facilities are located in very diverse parts of the world, sometime in places with very high or very low temperature (e.g. Siberia and India).

In any case, a very significant part of the heating is caused by irradiation, due to the presence of white hot metal; for instance in runners (channels which are used to transport molten metal) located on a blast furnace during casting operations this has a big impact, while when the tap hole is close the boundary conditions are pretty different (Brimacombe 1999; Geerdes et al. 2015). Near white hot metal infrastructures and even the floor could assume quite high temperature (e.g. over 100 ºC). Hence, in zone adjacent to the most hot parts, the strong irradiation affects also personnel and equipment, but it could turn also critical for the autonomous systems considering the temperature limitation of its electronic components.

Indeed the temperature result to be a constraint also for operation with autonomous vehicles or robotic systems. Furthermore, same zones are characterized by presence of dust, toxic gas, whiffles, sparks and spills of molten metal, which could easily damage the robots. Considering these aspects, it is important to include into the simulation models also these elements.

In order to achieve sufficient fidelity of the simulation, it is essential to employ different interoperable models, able to cover different aspects of the operations. Indeed, the authors adopted the MS2G (Modeling, interoperable Simulation & Serious Game) paradigm to combine heat exchange model with 3D model of the UGV and environment. In such case, data obtained from simulation of spatial state evolution of the vehicle is combined with thermodynamic model which takes into account position of the system of interest respect to the sources of heat and current hot metal production phase on the plant. Hence, the model analyzes, not only accessibility constraints, procedures and interactions with other machines and present equipment, but also the impact of the most important boundary conditions on the plant. The paradigm allowed to employ previously developed solutions based on autonomous systems for emergency management in industrial plants and to facilitate creation of digital twins of these new autonomous systems. In facts these simulations could be used in virtual prototyping, but also for real tests of control systems and operational procedures as well as to improve the operations on site (Bruzzone et al. 2017).

4 DIGITAL TWINS AND DIGITALIZATION AS SUPPORT FOR PLANNING

Digital twin is a high fidelity virtual replica of a physical asset which allows to perform tests and experimentations even on not yet existing systems; this approach gained special popularity in the last years thanks to the technological advances. By this approach, it turns possible to check proposed modifications of real system, to evaluate its efficiency in new boundary conditions, or to use it for training or even to develop new procedures.

Due to these reasons this concept is now largely adopted and supported by simulation, where the digital twins are often considered as the next step after the simulation-based system design (Boschert & Rosen 2016).

In facts, availability of precise and realistic model of a system permits conduction of tests with high precision respect the use modes. In the same time, cost of modification of virtual model is usually much lower in comparison to the physical asset, making possible to carry out fast evaluations of the efficiency respect different configurations, as well as to obtain exploitation characteristics in different conditions.

Obviously, in such cases the cost of initial development of the model could be relatively high and requires high qualified skills and experience. Such solutions could be used not only to test single assets, but to validate the entire systems or even systems of systems (SoS), making it useful tool for strategic decision making on new developments (Massei et al. 2014, Bruzzone 2018).

Indeed, in the presented paper, the authors employed this approach since the beginning of the project, supporting basic and detailed engineering, acquisition of components and production of the new system.

Development of a digital twin could be quite challenging; in the presented case the UGV includes numerous elements and sub-systems, staring from sensors and up to robotic arm, which must be integrated and optimized for different boundary conditions.

For example, the authors analyzed different platforms in combination with distinct propulsion systems, sets of sensors, robotic arms, manipulators, tools, instruments and cooling system. Thanks to the digital twin and virtual prototyping approach the authors identified optimal architecture for the autonomous system within the plant and related operations. As mentioned, another important aspect of digital twins and virtual prototyping is the possibility to test assets in different boundary conditions; the authors used such opportunity to test the proposed solution in distinct layout of real plants in order to optimize configuration and procedures performed by the autonomous system. For example, there were analyzed accessibility constraints, which are often strict due to the presence of bulky equipment; in the same time different tools and instruments were analyzed respect to the required operations. In the same time particular attention was focused on thermodynamic analysis of the new system in such dangerous environment.

Indeed, the authors combined a 3D virtual simulator of the plant operations and procedures with thermodynamic model for estimating temperature dynamics and is impact of UGV. In facts, it is possible to simulate not only the movements of the UGV and to analyze how it is subjected to the heating by irradiation, but potentially to integrate these models with other ones already available to create a more comprehensive scenario (Bruzzone et al. 2016). Indeed, interoperability could be provided by HLA and could guarantee a standard based tight coupling of different models which represent distinct assets and that address different types of interactions. In some cases, it could be convenient to employ also standards such as FMI (Functional Mock-up Interface) in order to support data exchange (Garro et al. 2015). In particular, in this case it was adopted the concept of creating a digital twin to support the development of a new system and related procedures. At the same time this approach allowed to analyze critical issues such as overheating, which is a crucial aspect for this kinds of industrial plants. For example, the approach could be used to design properly an effective and adequate HVAC system (Heating, Ventilation and Air Conditioning) for the UGV as well as to find a correct combination of heat shields and other passive elements which could help to prevent overheating.

5 PRODUCTION PHASES AND RISK ANALYSIS

The presented study aims to stave off personnel from the riskiest operations, or at least to reduce the time it is exposed to the hazards. In order to achieve these goals, it was decided to conduct a specific case study to evaluate efficiency of proposed solution in a real plant.

The proposed case is related to a plant with casting; as presented in the figure 1, a typical cycle of casting is characterized by different hazards related to phases of the process. For example, at the end of the casting phase it is possible to observe whiffles of molten metal coming from the tap hole. Indeed, during the operation, hot metal is melted inside the furnace, forming sometime puddles; in order to discharge the hot metal, it is required to open an hole near the bottom part, wait until the level of liquid metal drops to the minimum (casting), then close the hole and wait until the level in the grows up to sufficient value. In ideal case, the level of metal does not go below the tap hole, keeping this part of the furnace over the molten metal, however, in practice, this level could be too low, opening partially or completely the hole. Obviously, in such case the gases exit from the furnace altogether with the metal, reducing efficiency of the furnace, furthermore, such combination causes a mixture of gas and liquid metal, creating a foam which could be blasted away from the furnace. Such situation is one of most dangerous events in the cast house because the whiffles could fly away to up to tens of meters, potentially damaging equipment or even causing injures of personnel. In such circumstances the personnel is required to perform inspections, sampling and measurements, which is often not very safe. Furthermore, shortly after finish of the casting, when the tap hole is already closed, but the molten metal is still present, it is necessary to carry out cleaning procedures, which could be quite dangerous due to the temperature of surfaces and strong irradiation caused by presence of still hot metal. Indeed, in these cases the temperature could overpass 1400ºC.

Obviously, in such short, but dangerous interventions it is convenient to substitute human personnel with dedicated automatic and autonomous systems; in such case the list of activities to be done contains following operations: sampling, measurements, cleaning as well as periodic and emergency inspections (Sarcar et al. 1982; Mailliet & Metz 1993; Nelson 2014; Nelson & Hundermark 2016).

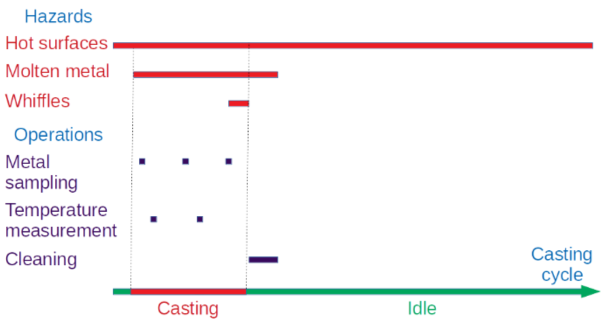

Figure 1. Hazards during casting cycle

It is important to note that the hazards for people and new autonomous systems are essentially similar: both human operators and robotic solutions could be damaged by molten metal, strong irradiation, gases and dust. Indeed, starting from the beginning of the design phase these risks should be assessed properly in order to identify the optimal configuration of the system as well as to choose proper components (e.g. motors capable to sustain heat). In particular, the authors focused their attention on the problem of overheating of the UGV. To address this issue the authors conducted series of experiments on hot metal production sites in order to identify critical environmental parameters of such plants.

In particular, the simulation determines intensity of thermal radiation received by the vehicle, taking into

account relative position of the system respect to molten materials and hot surfaces, current phase of casting process, environmental conditions, etc. Indeed, based on the 3D simulation of operations it is possible to obtain information regarding special state of the vehicle and trajectory of its movement $P(x_g,y_g,z_g,\alpha,\beta,\gamma,t)$ in the plant, combine it with actual state of the environment and use all this data to supply the thermal model.
The parameters x, y and z represent position of the UGV, while angles α, β and γ represent its rotational state at moment t. At the same time, exposure time is used to evaluate heating during different tasks, such as sampling, but performed in matter of seconds or cleaning activities which are done without exposure to molten metal , but requires more time (e.g. a couple of minutes).
In addition the geometry of vehicle is used to obtain overall heat absorbed by the UGV. Another important aspect is related to the internal heating due by the internal system, indeed, many components, especially motors of the propulsion subsystem and robotic arms could produce substantial amount of heat during the operation. Considering this, it is possible to list principal factors which contribute to the thermal balance:

- Heating of UGV by thermal irradiation from molten metal and hot surfaces
- Heating of UGV by internal heat generation
- Cooling (or heating) of UGV by convection due to environmental temperature
- Cooling by UGV by internal cooling unit

All this data allows to obtain complete set of information required to perform thermal analysis.
In particular, since there is no direct contact between the hot surfaces and materials and the UGV, the heat exchange is based mostly on convection (1) and thermal radiation (2). Of cause, there is still present heating by contact with ground, however, its impact is relatively small.

$$Q_c = h_c S(T - T_{env}) \tag{1}$$

With:
h_c: Conduction Coefficient [W/(K m^2)]
S: Surface [m^2]
T: Temperature of the surface [K]
T_{env}: Environment temperature [K]

$$Q_{1,2} = \varepsilon_1 * A_1 * \varepsilon_2 * A_2 * F_{1-2} * \theta * (T_1^4 - T_2^4) \tag{2}$$

With:
ε_x: Emissivity coefficient
A_x: Area of the Emitting Body [m^2]
$F_{(1-2)}$: Shape Factor
ϴ: Boltzmann constant 5.669 10^{-8} W/(m^{2}K^4)
T_x: Temperature of emitting body [K]

In this case, Modeling and Simulation are essential for correct design. Indeed, such calculation could be performed manually, however, they would neglect important details of positioning and require big time investments. Meanwhile, the model allows to evaluate different configurations of platform and combinations of environmental parameters in the real time.

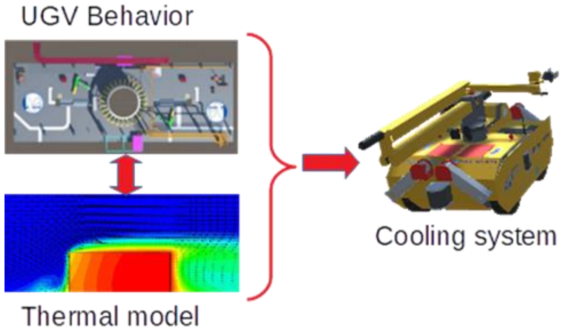

Figure 2: Coupling of 3D simulation and thermal model

In order to obtain precise data about environmental conditions, the authors conducted a series of onsite measurements and experimentations. These activities allowed to measure temperature of surfaces including ground in different points and during different phases of the casting process. This data was obtained from different sources (plant's sensors, pyrometers, thermometers) and summarized in the table below.

Table 1: Temperature measurements for determining boundary conditions.

Description	*Acquisition Mode*	*Temperature*
Hot metal temperature during casting	SCADA System plus Pyrometer	1500C°
External Air Temperature, depends on the location of the plant	Thermometer/ Historical Data Set	-20 C°$<T_{env}<$45 C°
Temperature of the slag residual. Time dependent due to natural cooling of the hot metal	SCADA System plus Laser Pyrometer	$T_{env} < T_{Slag}(t) < 1500\ C$
Tap hole zone temperature	SCADA System plus Laser Pyrometer	$T_{env} < T_{VHS}$ <400C°
Ground temperature	Laser Pyrometer	$T_{env} < T_{ground} < 120$C°

6 THERMAL DESIGN AND SIMULATION

As mentioned, simulation is essential for design of autonomous system for operation in harsh environments, such as high temperature in hot metal production; interestingly, similar requirements are applied even to satellites (Humphries and Griggs 1977; Tsai 2004, Faghri 1995; Maydanik 2005, Baturkin 2005).
Indeed, necessity to introduce thermal regulation is present in various fields, which often address such issues

in different ways, such as focusing attention on thermal shields, reflective materials and active cooling systems (Fortescue and Stark, 1995; Swanson and Birur 2003, Osiander et.al 2004). In general, a thermal control system can be distinguished into following main categories:
Passive Systems. This category does not require any source of external power supply to influence the internal temperature. Indeed, they utilize special materials and paints, in order to guarantee required emissivity and reflection to protect from external thermal irradiation. Such systems include

- Surface Coating and paints
- Insulation
- Thermal straps and radiators

Contrary to the passive systems, Active Systems require external power to operate, but often several important benefits, such as precise thermal regulation as well as possibility to handle much more intensive heat flows. Typical devices of this type are:

- Heat exchangers
- Heat pumps

In the case of interest, the inside temperature must be maintained in the range between -5…40C°, while the system could be subjected to 1-2 kW heat flow. In such case active cooling system is required. In the following is presented equation of heat balance of the system of interest.

$$\frac{\partial E_{in}}{\partial t} + \frac{\partial E_{out}}{\partial t} + \frac{\partial E_{gen}}{\partial t} = \frac{dE_{Stored}}{dt} \qquad (3)$$

With
E_{in}: Total incoming energy [W]
E_{out}: Total outgoing energy [W]
E_{gen}: Total generated energy [W]
E_{stored}: Total stored energy [W]

This equation is the heart of the thermal model. Indeed, combining equations (1-3) it is possible to take into account such factors as natural convection, heating due by irradiation as well as impact of different active and passive cooling systems.
The 3D virtual simulation has been developed mostly in C# (operational models, industrial processes and procedures) and Unity engine, while thermal model is implemented in Matlab; the models could be integrated by means of a HLA gateway. This approach could allowed to obtain a set of overall Key Performance Indicators in different configurations of the system within distinct boundary conditions. The resulting simulation confirmed a strong correlation between operation type (sampling, cleaning, etc) and heating. At the same time, proper passive heat protection (e.g. reflective material) allows to save power of on-board cooling unit significantly reducing consumptions. Finally, using the digital twin and the virtual experimentation, it was calculated that in order to operate at high temperature for a required periods of time an on-board cooling system with a heat capacity around 500W is necessary.

CONCLUSIONS

The paper addresses important safety issues in the field of industrial plants dealing with hot metal production. In this context, the autonomous systems are a very promising solution and could be develop in optimal way by using innovative simulation models. Indeed, different models have been wrapped into a digital twin able to support engineering of an ad hoc autonomous system for this kinds of plants. Indeed, it was validated the fact that this approach allows to assess the efficiency of alternative proposed configurations and operational models, hence, to perform optimization of the configuration.
Considering this, it is evident that virtual prototyping applied to autonomous vehicles is useful at all stages of development, during the production as well as in the future exploitation.
The severe working conditions in the sector of Iron & Steel are quite typical also for other industries. Indeed, the authors expect to extend the field of application of the proposed solution and methodologies to other field in order to improve safety and efficiency of operations.

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