A DIGITAL TWIN APPROACH TO DEVELOP A NEW AUTONOUS SYSTEM ABLE TO OPERATE IN HIGH TEMPERATURE ENVIRONMENTS WITHIN INDUSTRIAL PLANTS

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ABSTRACT

The study aims to develop an innovative system solution by creating a digital twin that combines virtual prototypes, mathematical models and simulation environments. The paper focuses on the case of a new UGV (Unmanned Ground Vehicle) devoted to operate within hot metal industries. The digital twin supports both the UGV engineering as well as the redesign of the industrial procedures and plant components. The authors address the development of the heating/cooling system able to guarantee UGV reliability within a wide spectrum of operative modes in the complex environment of industrial plant. The digital twin allows to evaluate how the vehicle configuration, boundary conditions and interactions with other plant components affect the UGV systems and subsystems performance. The complexity of interactions and factors requires extensive use of simulation.

Keywords: Autonomous Systems, Digital Twin, Virtual Prototyping

1 INTRODUCTION

Today, technologies related to autonomous and robotic systems are enabling the possibility to carry out operations in industrial areas where human presence is dangerous (Bruzzone et al.2017). Indeed, thanks to the recent advances of the autonomous systems including artificial intelligence, sensors and robotics this field of applications is fast evolving. Due to these reasons new researches are developing solutions tailored for specific industrial sectors, which were poorly covered by autonomous systems in the past. This paper addresses specifically the case of hot metal industry where there are many zones that are dangerous for humans, as confirmed by statistics which shows that lethal accidents rate is significantly higher than that in other industrial fields (Shikdar and Sawaqed 2003). This aspect suggests to introduce new automated solutions even based on autonomous systems able to deal with complex operational procedures (e.g. inspections, monitoring activities, sampling, etc.). Due to the complexity of industrial processes in this sector, it is evident that these new automated systems should be developed by using simulation and virtually testing the new solutions within the whole plant. This paper proposes the creation of a digital twin of the new robotic systems to be used during engineering of the solutions as well as the design of the new operational procedures.By this approach the boundary conditions, such as duration of the heat exposition and intensity, are calculated by means of a Dynamic Virtual Interoperable Simulation that enables to evaluate the irradiated surfaces and the distance from the heat sources according to the different mission tasks and production modes. In the specific case the virtual experimentation allows to match the vehicle systems and subsystems characteristics with the dynamic thermal data in order to guarantee valid working temperatures of the most critical UGV components along all phase of operations and production.

2 BOUNDARY CONDITIONS AND CRITICAL ISSUES

In facts, the hot metal industries are characterized by dangerous conditions that impose limitations on operations of human personnel, but affect also automated systems (Pardo and Moya 2013). In similar way, also new autonomous systems have to deal with these conditions so, it is important to consider the related requirements in terms of temperature operational ranges as well as reliability respect presence of dust or aggressive chemical agents. Among the different possible kinds of autonomous systems this paper focuses on a new UGV (Unmanned Ground Vehicle) used to support operations in hot metal production facilities. Obviously, in the hot metal industry one of critical challenges is related to the high temperatures due to the exposure to hot objects (e.g. over to 1200 degree C), so the new robotic systems should be reliable and even able to face this aspect, but also to operate in a wide spectrum of boundary conditions; indeed, the hot metal plants are located all around the world, often in quite inhospitable environments, while the large facility dimensions and spaces make the indoor conditions pretty similar to the external environment, which could move from hot Emirates to cold Siberia.

Furthermore, as anticipated, the presence of the hot metal generates hot spots that cause intensive heating by irradiation, affecting the people, when present, but also the robotic and autonomous systems that due to the presence of electric and electronic components result vulnerable to extreme temperatures. Moreover, it is important to outline that other environmental conditions influence the UGV performance and reliability (e.g. dust, corrosive agents) and even introduce risks (e.g. explosions). From this point of view, the authors propose a model to be coupled with a simulation of the new robotic systems to check the reliability as well as the feasibility and effectiveness of this solution to face different extreme conditions.

The authors adopt the MS2G (Modeling, interoperable Simulation & Serious Game) paradigm to create a simulation that include, specifically in this paper, heat exchange models to consider mutual interactions all over the different production conditions of the plant as well as operational task of the UGV; indeed several plant elements are affect UGV in terms of accessibility, hot spot exposure and operation compatibility; among these there are the runner layout configuration, plant production control, type and status of machines devoted to drilling and tapping as well as heating protections and bridge crane status. These specific models are used to extend capabilities of existing interoperable simulation solutions; indeed, the authors adapted MS2G environments originally developed to study accidents and emergency management in industrial plants. This extension allowed to create a digital twin of the new robotic systems to be used not only in virtual prototyping, but ready to be applied during incoming real tests and experimentations on the field (Bruzzone et al. 2017).

3 DIGITAL TWINS AND DIGITALIZATION AS SUPPORT FOR PLANNING

In the last years, digital twins became widely used support tool for engineering. Indeed, using virtual prototype of a system it is relatively easy to perform tests and evaluations of future, not yet produced, systems. In the same time, it is possible to analyze behavior of modified versions of already existing systems, adapting them to new requirements. Obviously, such possibility not remained unnoticed by the simulation experts which often consider digital twins as the next step in simulation after the simulation-based system design (Boschert and Rosen 2016). Indeed, availability of a complete and exhaustive model of the system of interest allows to perform experimentations with the near real-world precision, while the cost of modification of such model is irrelevant respect to a real-world prototype. Surely, after the first investment in development of a model, it is possible to place it nearly instantly in almost any imaginable boundary conditions, easily performing modifications and re-running the tests.

Such approach affects not only engineering of specific products, but could also be used to support development and management of very complex systems or even Systems of Systems (SoS), extending capabilities of planning and strategic decision making (Massei et al. 2014). In the case of interest, the authors developed a digital twin for the new UGV system in order to evaluate feasibility of different solutions as well as their capabilities to carry out required tasks. In facts, this corresponds in present case into support engineering, acquisition, construction, installation, commissioning and operations of a completely new autonomous vehicle devoted to operate in hot metal industry. This is a very good example where the digital twin could be used as part of a Strategic Engineering initiative devoted to introduce new technologies also in old economy industries; this allow to identify the potential of new approaches, to properly tune their design and to support continuously their introduction on the market as new competitive advantage for operators improving production efficiency as well as safety (Bruzzone 2018).

In the proposed case, the new UGV incorporates many different elements (e.g. sensors, actuators, motion system, HVAC, control system) that need to be coupled and optimized also respect external conditions and plant components and processes; to validate the new UGV configuration and to test respect all changes in engineering as well as in industrial process the use of digital twin provides great advantage as well as in supporting further future developments of the different plant elements. For instance, the authors performed analysis of different platforms in combination with distinct sets of sensors, robotic arms, manipulators, tools, cooling and propulsion systems. Indeed, taking benefit of availability of such data the authors identified optimal architecture of the autonomous system. Furthermore, using model of several plants of interest, it was possible to recreate also multiple test scenarios. For example, based on characteristics of the base platform, it was possible to identify and test accessibility constraints, which are very important in the industrial plant; indeed, they are often full of very bulky equipment and machines, leaving only relatively small passages which can be used by UGV. Another example is related to selection of proper tools required to carry out the procedures; in this case, it was possible to analyze different solutions based in their weight, size, power consumption and efficiency.

Considering this, it is evident that digital twins combined with the simulation allow to perform complete and exhaustive prototyping, support development of procedures and improve corresponding production planning at different levels. In facts, in this paper it is presented an innovative approach devoted to create a thermal model able to evaluate the heat exposition for a potential UGV working in hot zones. A virtual interoperable simulation, developed for operational analysis of the autonomous vehicle, is used to generate the boundary conditions feeding the thermal model in order to determine the exposition and maximum temperature respect different engineering solutions. This allows to support design of new potential robotic systems able to work in such areas. The virtual simulation has been developed by the authors to support complex scenarios involving industrial plants and critical infrastructures and it resulted as a valuable model available for this research (Bruzzone et al. 2016); the simulation architecture is based on interoperable HLA (High Level Architecture) simulation environment that originally it was developed to evaluate the effectiveness of new autonomous systems for protection of critical infrastructures and emergency management in industrial plant; the reuse in this context allows to create a simulation of the new industrial autonomous system to be used in virtual prototyping as well as digital twin during integration and field tests and for supporting installation, commissioning and service.

In facts the adoption of interoperable standards here is devoted mostly to couple models of different components with plant simulation; from this point o view there also standards such as FMI (Functional Mock-up Interface) devoted to support data exchange and that could incorporate HLA features (Garro et al. 2015). In this paper the digital twin is used specifically for supporting engineering of a suitable light HVAC system (Heating, Ventilation and Air Conditioning) as well as heat shields for protecting the UGV components and to guarantee the working temperature along all the operational models. Obviously on this vehicle space availability, weight distribution and limitation, dynamic stability and efficiency during the operations, power consumption and autonomy, vehicle size for area accessibility, thermal and electromagnetic interference among systems and subsystems are all crucial elements that need to be taken into considerations.

4 PRODUCTION PHASES, TASKS AND INDUSTRIAL ENVIRONMENT

In our case the goal is to consider the introduction of the new industrial unmanned ground vehicle (UGV) to be able to substitute humans for carrying out most dangerous operation within hot metal plants. Obviously, it is required, among other aspects, also to define a specific case study scenario including the description of the industrial environment and production phases as well as task to be covered by the robotic system. The focus is on a cast iron production facility, representing a big and complex industrial plant where casting is periodically carried out to extract the hot metal (slightly overestimated, conservatively, around 1500C°). This plant is characterized by some major production phases respect the use of UGV:

- Phase A: Closed Tap hole (vertical hot spot) without any casting flow, but presence of hot slags residuals in the runner (horizontal hot zone) at lower temperature respect casting
- Phase B: Open Tap hole and hot metal flows in the runner that: corresponding to extreme irradiation conditions (T=1500C°)
- Phase C: Open Tap Hole but no casting flow; in this phase there are flames and hot slag in horizontal hot zone and there are gas escapes corresponding to a risk of “whiffles” including hot metal drops

There are several tasks currently carried out by humans including among others the sampling during Phases A and C in different parts of the plants, Inspections during all phases as well as cleaning during phase A just at the end of phase C (Sarcar et al. 1982; Mailliet and Metz 1993; Nelson 2014; Nelson and Hundermark 2016); these task have been considered to be potentially transferable to UGV. Considering these activities, it is necessary to identify and design heat exchange solutions able to guarantee that all on board UGV subsystems are operational during movements in different plant areas, as well as when it carries out required tasks, especially in proximity of strongly irradiating hot metal. In our simulation architecture the models of heat exchanges and vehicle components are coupled to create a digital twin within the MS2G environment and used to support the engineering of most suitable thermal control system as well as the definition of most convenient operational procedures and upgrades to the plant processes and related automation. Indeed, the integration of the different models within an Interoperable Simulation allows to transform a virtual prototype into a digital twin including the models, characteristics and performance of the different elements of the robotic system and corresponding operational models along production phases.

In relation to the thermal aspects, the simulation environment allows to interact with the UGV digital twin including all its components as well as to determine the thermal radiation in the near-tap-hole zones in the different phases of the production cycle (phases A, B and C). Indeed, the simulator consider dynamically the heat transfer from the different heat sources to assets, which move and perform assigned tasks in the area as well as consequent effect on the assets' components. So simulation considers the spatial location and orientation of the UGV; in this case 3D Simulation, coupled with virtual prototype allows to support the computation of the UGV trajectory P(x_g,y_g,z_g,α,β,γ,t) including the working distance and the orientation of the UGV respect to the heat sources. Indeed, parameters x, y and z represent position of the UGV, while angles α, β and γ represent its rotational state at moment t. Furthermore, it is possible to measure dynamically during the virtual experiments the exposition time based on the different tasks and on the different configurations of the UGV itself. (i.e. geometrical dimension, irradiating surface, different kind of robotic arms that may affect the mission time, the power consumption as well as heat internal production).

5 PROBLEM FORMULATION

As mentioned, it is very important to define the problem and to find a suitable thermal model capable to determine the heat exchanges with and within the UGV. Indeed, the digital twin allows to change elements (e.g. robotic arm configuration) and to evaluate dynamically the different system interactions; in this way it is possible during simulation to analyze the performance as well temperature levels respect different UGV configurations that determine not only best vehicle configuration, but also the operational modes to be adopted respect assigned tasks. Obviously these aspects affect also the heat exchange considering importance of UGV distances and orientations respect to hot spots sources in the industrial plant (see Figure 1). For the aim of this project, among most important heat sources there are identified the horizontal and vertical zones. Considering the layout and the UGV's mission tasks, the heat exchange phenomena are the following:

- Heating of UGV by thermal irradiation from the horizontal hot zone
- Heating of UGV by thermal irradiation from the vertical hot zone
- Heating of UGV by internal heat generation
- Cooling (or heating) of UGV by convection
- Cooling by UGV by internal cooling unit

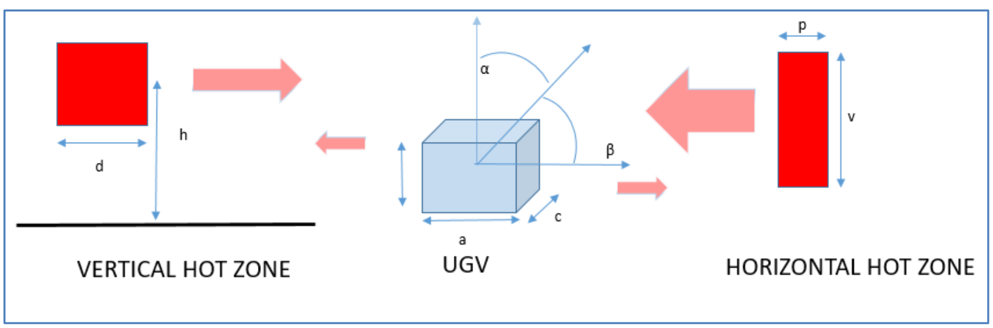

Figure 2: Thermal exchange between vertical and horizontal hot zones and UGV.

Vertical and horizontal hot zones are in a fixed position, while the UGV is characterized by different possible trajectories P_(i,UGV) (X_g,Y_g,Z_g, α, β, γ, t) and spatial states, which depend on i-mission task which can be performed in the three different production phases A, B, C, as defined in the previous table. Since there is no direct contact between the different hot zones and the UGV, the heat exchange is based on convection (1) and thermal radiation (2).

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

With:

h_c: Conduction Coefficient

S: Surface

T: Temperature of the surface

T_{env}: Environment temperature

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

With:

ε_x: Emissiveness coefficient

A_x: Area of the Emitting Body

F_{1-2}: Shape Factor

⍰: Boltzmann constant $5.669 * 10^{-8} \frac{W}{m^2\ K^4}$

T_x: Temperature of emitting body

The problem of determining the heat flow Q_UGV directed to the UGV is challenging, since both convection and thermal irradiation are function of UGV trajectory and orientation. The solution proposed is based on Modeling & Simulation (M&S) techniques able to represent the behavior of the UGV in a 3D Environment: the creation of a digital copy of the real plant is used for the calculation of the trajectory P and exposure to hot spots respect their status during the different production phases. Consequently, it is possible to evaluate the different components required by heat exchange equations (1,2), as presented in figures 2 and 3. Finally, in order to keep internal UGV temperature below the maximum working temperature a thermal control system is defined operating over a light HVAC.

In this case M&S is extremely powerful since it offers a flexible instrument to test the different possible configurations of the UGV in term of size, task performed, heath protection etc. Indeed, each different activity need different abilities in term of geometry, size, power, manipulation, degree of freedoms, maximum force applied as well as thermal protection. All these variables affect the geometry, the power consumption since it is function of the total weight. By using M&S it is possible to create a virtual prototype and test it in the real layout testing the different configurations and alternatives in the same environment, with the same initial conditions, considering also the stochastic factors affecting the process and the different missions.

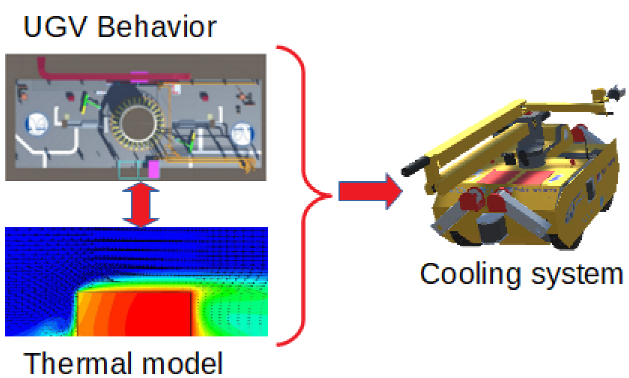

Figure 3: 3D Simulation and heat transfer model for the calculation of the UGV thermal control.

In order to achieve the required precision, it is necessary to feed the model with reliable data regarding environmental conditions. To acquire such information, the authors performed measurements in a real plant. In particular, the temperature of different surfaces during the different phases of casting process have been registered by means of a laser pyrometer, a thermometer and integrated with the available measurements obtained from the SCADA system, as summarized in the table 2.

Table 1: Temperature measurement for determining boundary conditions.

Variable	*Temperature*	*Description*	*Acquisition Mode*	*Error*
$T_{c,B}$	1500C°	Hot metal temperature during casting (phase B)	SCADA System + Pyrometer	0,5%
T_{env}	-20 C° $<T_{\text{env}}<$ 45 C°	External Air Temperature, it depends on the location of the plant	Thermometer/Historical Data Set	1%
$T_{Slag}(\text{t})$	$T_{\text{env}} < T_{Slag}(\text{t}) <$ 1500 $C°$	Temperature of the slag residual, assumed to be known. Time dependent due to natural cooling of the hot metal	SCADA System + Laser Pyrometer	3-5%
T_{VHS}	$T_{\text{env}} < T_{VHS} <$ 400C°	Vertical Hot Surface Temperature, assumed to be know from SCADA system	SCADA System + Laser Pyrometer	3-5%
T_{ground}	$T_{\text{env}} < T_{ground} <$ 120C°	Ground temperature, assumed to be known	Laser Pyrometer	5-10%

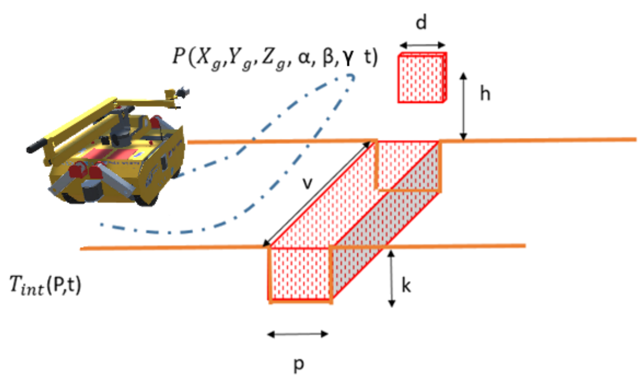

Figure 4: UGV and hot temperature zones.

6 THERMAL CONTROL DESIGN

The role of a thermal control system is to regulate the temperature of specific part of the system in order to maintain the ideal temperature range for each component. A good example of small systems which need small and efficient thermal control systems is offered from satellite applications (Humphries and Griggs 1977; Tsai 2004). Indeed, sophisticated systems, such as for instance satellites, are characterized by their small dimensions and they have several obvious limitations for power consumption as well as the need of low-power thermal control system able to preserve the optimal temperature with a periodic exposition to the sun radiation. Scientific literature offers several documents describing the technological foundation of low-power thermal control system in the different branches: software, hardware, active and passive systems as well as special reflecting materials (Fortescue and Stark, 1995; Swanson and Birur 2003). A further interesting example is provided by Osiander et.al 2004, where louver array thermal protection structure and a movable shutter solution are compared and tested. Other solutions, particularly interesting in case of absence of gravity are capillary pumped loops (CPLs) and loop heat pipes (LHPs) (Faghri 1995; Maydanik 2005). Considering the iron & steel plants and UGV mission inside hot zone, there is quite interesting analogy with micro-satellite heat exchange (Baturkin 2005). Indeed, as well as the satellite in space, the main heating source is represented by Irradiating Power. In fact, in some specific part of the plant, the temperature of the hot metal can reach the 1500C° making the irradiating power the main heating source. In general, a thermal control system can be distinguished into two main categories:

Passive Systems. This category do not need any source of external power supply to operate, and they are typically cheaper; this is one of the easiest mean to influence the internal temperature. For doing so, special materials as well as paints have to be identified, in order to have a high emissive power and good reflection from external thermal irradiation:

- Surface Coating
- Paints
- Insulation
- Thermal Straps
- Radiators

Active Systems. this category require external power to operate, and they often have a more precise temperature regulation. Such system are active systems, and they need an external power to a possible example is the multi-layer insulation.

- Heat exchanger
- Heat pumps

The typical working temperatures of different systems as well as their peak power consumption are summarized in the table 2.

Table 2: UGV components, and their typical working temperatures.

Component name	**Working temperature range [C°]**	**Peak power consumption [W]**
On-board computer	-5 up to 40	20
Camera	-20 up to 55	40
Lidar	-20 up to 55	50
Anti-collision sensors	-20 up to 60	35-50
Controller	-20 up to 45	100-200
Auxiliary systems (lights, siren etc)	-20 up to 45	30
Communication Systems	-20 up to 50	<5
Robotic arm controller	-20 up to 45	100-200
Propulsion system	-20 up to 50	1000
UGV total	**-5 to 40**	**1700**

As it is possible to note, the inside temperature must be maintained between -5…40C°, while the peak power consumption $E_{gen}$is expected to be around 1700W.

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

With:
E_{in}: Total incoming energy
E_{out}: Total outgoing energy
E_{gen}: Total generated energy
E_{Stored}: Total stored energy
(In order to keep the internal temperature constant, cooling system should be designed with a cooling power $E_{cool} > E_{Stored}$

7 SIMULATION AND RESULTS

As presented, the thermal model takes into account spatial states of the UGV (position, Euler angles) and coordinates and parameters of the heat sources, combining them with the boundary conditions generated by high fidelity models validated by on site measurements. In addition, the thermal models of platform components take into account such factors as natural convection, heating due by irradiation as well as impact of different active and passive cooling systems. The simulation engine has been developed mostly in C# (operational models, industrial processes and procedures), Matlab (thermal physical models), Java (HLA gateway) using a graphic user interface based on Unity 3D and they allowed to obtain Key Performance Indicators and numerical results over the different configurations. Using the digital twin within the simulation, it was found that the specific task and production phase strongly affect the capability to absorb heat and corresponding external and internal temperatures that varies in wide ranges. In fact, the UGV different tasks (e.g. cleaning, sampling, inspections) have specific characteristics that change along the different productions phases and require distinct times and modes to be successfully completed. At the same time, utilization of proper heat protection reflective material allows to save power of on-board cooling unit mostly halving consumptions. Furthermore, external environmental conditions and plant indoor temperatures impact strongly on HVAC characteristics and they require specific tuning to optimize the UGV design, due weight and space constraints, requires. Obviously, to make system capable to carry out any type of activity it is necessary consider conservative hypotheses related to the different factors affecting the consumptions and absorbed power. In particular, in this study the most critical conditions correspond to the hot metal cleaning phase, which requires significant time respect other activities and it is done when the runner is still full of molten metal, while the surfaces are extremely hot. In this case, considering facilities of interest for this research located in equatorial areas it is necessary to consider also a potential maximum environmental temperature arriving up to 45C. So using the simulation of the digital twin and considering the virtual experimentation, it was found that in order to operate at high temperature for a sufficient period of time it is necessary to employ an on-board cooling system with a capacity around 500W.

8 CONCLUSION

The paper presents an innovative approach where a simulation of a new UGV was created to carry out interoperable simulations combining the effects of different internal elements and external plant components over different operational modes and production phases of a cast iron productions facility. These models have been wrapped into a digital twin coupled with a thermal simulation in order to evaluate the heat exchange and to support engineering of an ad hoc lean HVAC able to keep adequate temperature inside the UGV, while it operates within the plant. The simulation allows to evaluate feasibility and effectiveness of the different alternative solutions used to protect the autonomous system and to properly design these components. Virtual prototyping applied to autonomous systems will follow not only design phase, but also installation, commissioning, operations and services being kept aligned with the real UGV and plant configuration and updated based on measures on the field. The severe working conditions in this industrial sector are pretty common in many different hot metal production facilities and represent dangerous elements for human workers that could enable in future to extend the use of these new UGVs also to other facilities and roles, resulting very useful for improving operations and safety at once; in such sense the creation of digital twins and simulators able to model these elements is a crucial factor to support diffusion of these solutions in effective and efficient way. Indeed, the MS2G approach allows to integrate additional elements and to substitute different models. In this case it was integrated a set of heat exchange models devoted to consider the different factors (internal exchange, external hot spots, cooling system) to create a digital twin for fast engineering new autonomous systems for industrial plants. The simulation environment created for this research represents an interesting example of digital twin respect the new robotic systems that will be further used by the authors during real tests and installation and commissioning phases in near future.

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