The 21st International Conference on Modelling and Applied Simulation (MAS), 022
19th International Multidisciplinary Modeling & Simulation Multiconference

2724-0037 © 2022 The Authors.
doi: 10.46354/i3m.2022.mas.022

Digital Twins for Developing Innovative Industrial Autonomous Systems

Agostino G. Bruzzone[1,2,3*], Kirill Sinelshchikov[2,3], Antonio Giovannetti[1,2],

Javier Pernas[2,4]

[1] STRATEGOS, Simulation Team, Genoa University, via Opera Pia 15, 16145 Genova, Italy
2Simulation Team, via Magliotto2 , Savona, 17100, Italy
[3]SIM4 Future, via Trento 34, Genova, 16145, Italy
[4] University of A Coruña, Campus Industrial de Ferrol, Grupo Integrado de Ingeniería, Campus de Esteiro s/n, Ferrol, 15403, Spain

[*]Corresponding author. Email address: agostino.bruzzone@simulationteam.com

Abstract

The paper addresses the development of an innovative solution based on Autonomous Systems to operated within Industrial Plants based on the advance of technologies in this sector and investing new operational frameworks. Indeed the authors propose the adoption of digital twin approach in order to support the design of this new solution as well as on the development of new procedures and policies applied to iron & steel facilities. A real-life case study with relative system architecture and common control of the real and virtual replica is analyzed. Synthetic description of obtained results is presented.

Keywords: Digital Twin, Simulation, Autonomous Systems, Autonomous Systems, Iron&Steel

1. Introduction

Diffusion of autonomous systems is constantly growing. Indeed, due to availability of cheaper and better components, advancements in control mechanisms and facilitation of production, these systems become always more common. For instance, as of 2022 self-driving cars are not so rare, while interest in self-driving taxis and delivery drones is rapidly growing all around the world. Similarly, various prototypes are also in development in more specific contexts, such as in Iron & Steel industry (Bruzzone et al., 2021; 2016a; Mazal et al., 2019a).

Considering the nature of steel production facilities, it is clear that one of the most important goals of such project is the improvement of safety, in particular, by automated handling of most dangerous activities (Bruzzone et al., 2017; 2016b).

Apart from innovation in autonomous systems themselves, it is necessary to consider advances related to their development and testing. Indeed, while in the past the development cycle used to include preliminary evaluations and construction of a physical prototype, even more than one, nowadays it is more common to rely on virtual prototyping as well as on digital twin approach. Digital twin is a high fidelity replica of a system, characterized by elevated level of detail and hence suitable even for experimentation on a virtual counterpart of a real world system (Bruzzone et al., 2019a; Massei & Tremori, 2011). Availability of this kind of precise models allows testing of virtual equipment in virtual environments, reducing times and risks as well as introducing possibility to perform experimentations which otherwise would not be possible to perform on a physical vehicle. Furthermore, high fidelity model allows to foresee future state of the system by simulating evolution in various boundary conditions.

For example, while a virtual prototype could be used to evaluate different types of propulsion systems and accessibility constraints, the twin could be suitable for much more detailed development of procedures and testing of the system's behavior.

At the same time, digital twin embedded in a properly designed virtual environment, could be used for training of personnel, taking advantages of MS2G (Modeling & Simulation for Serious Games) approach (Bruzzone et al., 2014) and empowering Strategic Engineering approach (Mazal & Bruzzone, 2019b) as well as for giving possibilities to employ more compelling solutions based on Artificial Intelligence and intelligent agents (Bruzzone et al., 2018) and for integrate it in a common simulation environment using High Level Architecture (Longo et al., 2015).

Considering this, the authors propose an example of utilization of the digital twin to support finalization of development of an autonomous system capable to operate in an Iron & Steel facility. The twin is suitable for testing of various procedures that the system is expected to carry out; in the past the authors already used virtual prototyping to support initial steps of development of the unmanned vehicle.

2. State of the Art

Nowadays the digital twin approach is commonly used in order to support development and exploitation of robotic systems (Lo et al., 2021; Bruzzone et al., 2019b). In fact, in the past years there has been a marked increase in publications related to digital twin frameworks for autonomous robots, human-robot collaboration and co-simulation proof of concepts (Lumer-Klabbers et al., 2021; Ramasubramanian et al., 2022), As (Chen et al., 2020) states, the rational use of this technology requires not only the connections between the digital and the physical twin but "also information and physical integration, twin-driven data, dynamic interactive connections and service applications", among others. For instance, (Lumer-Klabbers et al., 2021) presents a proof of concept for a digital twin framework that acts simultaneously on the robot and the virtual digital twin. When in the case of certain controls like the emergency stop both systems must be able to act independently for safety reasons, they discuss the level of supervisory control within the digital twin. Another example related to common control of a system and of its digital twin can be found in (Kuts et al., 2019). Indeed, this approach is taken in the present paper as it is deemed very suitable for different industrial applications.

In some cases, a carefully synchronized digital twin could be used to improve capability of a system to handle collaborative operations with human personnel (Bilberg & Malik, 2019). This synchronization demands also for a precise replication of the real system's perception, movement, feedback and other real capabilities on the digital twin (Chen et al., 2020).

Moreover, digital twins coupled with proper simulation models could be used to predict system behavior (Qiao, 2019). The combination of data obtained from modern Industry 4.0 facilities, coupled with simulation and digital twin is known as one of enablers for creation of next generation systems (Longo et al., 2019). On top of this, 3D visualization techniques like virtual reality may ease the process of testing robot trajectory programs (Garg et al., 2021).

It must be noted that digital twins and simulation could also be used to support preparation of systems based on reinforcement learning and on other algorithms (Campodonico et al., 2021). The digital replica of our robot can be used as the training subject so save time, cost and safety concerns that would otherwise imply a training process on the real robot (Y. Liu et al., 2022). Once trained, the algorithm would be deployed on the physical robot with a reasonable level of confidence on its expected behavior. Besides, genetic programming may be used to optimize the robot trajectories in the virtual world to later correct the movement trajectory of the physical robot (X. Liu et al., 2022).

3. System Architecture

The overall system is composed of 3 principal components: the robot, its digital twin and their control system, as shown in the following figure

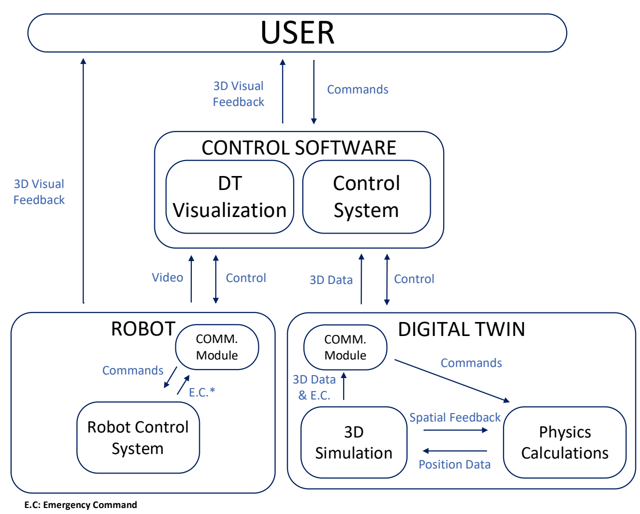

Figure 1. System architecture.

Considering this, the same common control system can be used with both the robot and its digital twin. Indeed, as communication with both is done via network and uses the same communication protocols and message structure, the control system treats both equally, as it is not aware if it is connected to physical robot or to its virtual counterpart. Hence, it becomes possible to perform various types of tests on the simulator, such as: communication correctness and stability, basic operations, autonomous navigation, complex sequences of operations etc.

Indeed, both robots have the same capability to elaborate and execute commands as well as to send sensor data and telemetry, including video feed and obstacle detection data from a LIDAR (Light Detection and Ranging). Hence, both systems even have the same level of spatial awareness in respective worlds.

At the same time, the two systems have slight differences in their behavior, caused mostly by stochastic factors and uncertainties in boundary conditions. For example, based on exact location of testing and relative conditions of terrain, the behavior of the robot changes in terms of precision and dynamics of movements. In fact, presence of gravel or sand influences propulsion dynamics of the system due to constantly changing grip, while even on asphalt or concrete the behavior could vary based on its conditions, e.g. dry, wet, dusty etc.

The control system is designed to be used for high-level commands, typically given by an operator without any particular knowledge about functionality of the robotic system. Indeed, it allows to the user to perform certain regular inspections and maintenance operations while leaving the logic of its execution to the software. However, the interface allows activation of manual controls on propulsion and other systems of the robot; at the same time, it is possible to order semi-automatic operations, such as movement to specific location.

The controller takes information about spatial state of the system and status of all its subsystems, which is then used to manage required activities. For example, it is possible to handle detection of obstacles which are not present on original map of the zone of interest; in this case, the system could order the robot to stop, change route or to ignore the obstacle, e.g. if it has no interference because is out of reach.

At the same time, the user has access to a map of the zone of interest with displayed position of the robot and detected obstacles, overview of state of the robot's systems and subsystems, including graphical representations, as well as video feed, obtained either from the on-board cameras or from the virtual cameras in the simulator.

4. Experimentation

The virtual simulation was used in the project since the beginning; for example, to support evaluation of different types of propulsion systems and auxiliary equipment, check accessibility constraints in a virtual model of several target facilities as well as to check principal considerations related to procedures.

With advancements in construction of a physical prototype it became possible to improve various parameters of the virtual model, leading finally to the digital twin, capable to replace its physical counterpart in development of command and control procedures.

At this moment it is possible to perform contemporary testing on both physical and virtual robots, in order to fine tune the twin as well as to improve control algorithms. Considering this, it was conducted a series of testing runs, in which a remote connection was used to control both physical and virtual robots. Based on outcome of the runs it was discovered that:

- A regular network connection with utilization of a VPN (Virtual Private Network) tunnel provides sufficient performance and stability for the operation, even if the control system and the robot are geographically distant; the latency of the network was negligible in all tests; in case of any introduced disruption of connection, the systems were able to reconnect to each other once the network conditions were acceptable.
- Behavior of the physical robot and of its digital twin is very similar, with minor differences related to movements in different terrains (asphalt, concrete, gravel) and in its different conditions (dry, wet, dusty).

Based on these findings, it was possible to proceed with testing of basic operations of the robot:

- Follow given path, detecting obstacles.
- Perform operations using manipulator.
- Combine movements of the platform and manipulator actions, in order to perform a complete working mission.

During the experimentation, particular attention is devoted to the safety and security. Indeed, all commands are exchanged through secure tunnel, while the location of testing was under constant supervision of personnel in order to interfere in case of risk of collision with passing people and/or other vehicles. Indeed, a robotic system could be dangerous even in a dedicated testing location, while in case of its utilization in an industrial environment attention to its safety and security must be especially high (Bruzzone et al., 2013).

5. Conclusions

Utilization of digital twins for development of new procedures and to design new systems is confirmed to be very efficient approach; indeed, it allows to reduce time and cost of experimentation, improve reliability and drastically cutting risks of failures; the testing and commissioning as well as exploitation and demonstration are strongly enhanced by this approach. In this paper the authors presented a real-life case study which confirms effectiveness of proposed approach. Due to high level of confidentiality of the project, it is not possible to present quantitative results of testing neither photo/video material related to it.

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