From the Cyber-Physical System to the Digital Twin: the process development for behaviour modelling of a Cyber Guided Vehicle in M2M logic

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Abstract: This paper describes a research whose aim was to prototype a Digital Twin (DT) which meets the logistic behavior of a new family of automated guided vehicles (AGVs), based on the Cyber-Physical System (CPS) paradigm. The research consists of two steps. First, the implementation of CPS logic on an existing micro-controlled rover is examined; then, a traditional discrete event simulation (DES) software is used to simulate different environment application for the DT, including some modifications that allow identifying the most suitable solutions for the research aim. The specific design process has limited the stochastic variability of the simulated system to the mechanical component of the CPS-AGV. This because of the absolute identity of the logistic logic, operating both in the code used by the CPS-AGV micro-controller and in the code of simulating the system. The results show that the combined CPS-DT architecture allows a strategic optimization of the plant resources in Industry 4.0 configuration. To this end, different policy have been implemented to optimize the auto-adaptive behavior of CPS-AGV, and each one of them has proven to be effective in a specific scenario. Outcomes of this study provide an industrial justification to the design and managing costs of Digital Twin implementation in an Industry 4.0 production system.

Keywords: Industry 4.0, Cyber-Physical Systems, Digital Twin, Machine to Machine

1.Introduction

The current industrial world is characterized by a significant evolution which increasingly leads large areas of manufacturing systems to the Industry 4.0, thanks to its greater perspective of sustainability (Stock and Selige 2016). To the best knowledge of the authors, several works in literature tried to define this revolutionary production approach, but none of them provided a clear and unique ontology. Therefore, it is possible to identify some pillars for all the different possible vision of Industry 4.0: Machine-to-Machine (M2M), IoT (Internet of Things), Big Data, Cyber-Physical Systems (CPSs), Digital Twins (DT), Augmented Reality, Additive Manufacturing, Cybersecurity and Cloud Cooperation.

Each pillar represents a component of the new theorized architecture. Although, only some of these are strictly required to characterize a production system as a 4.0 configuration. In particular, an Industry 4.0 production system is typically featured by the attribution of an advanced capability of machines in an autonomous decision-making process.

This new machine's ability can be realized exploiting different computational architectures and technological solutions. Each equipment could be set up in a particular configuration, depending on the required objective, features, aims or designs. However, in any of this case, they are all characterized by a CPS architecture. This new class of equipment is expected to replace the so-called production centers (e.g. generic automated machine or flexible manufacturing systems), integrating the traditional production features with the capability of communicating with other interconnected CPSs and of embodying algorithms oriented to an independent decision-making. This integration leads to a proactive equipment able to execute and optimize the production goals using a self-adaptive behavior.

In this scenario, it is important to outline a path for effectively introduces the design of this innovative behavior, primarily from a technological point of view. The novel relationship between DT and CPSs, with the help of the acquired knowledge from the analysis of the Industrial Big Data, makes possible to build a first attempt of the CPS's self-adaptive behaviour. In this sense, this paper shows the first prototype of Digital Twin in the complete step for building its architecture and logic. In particular, we focused on the development of a Cyber-Physical Automated Guided Vehicle Digital Twin for solving the typical Material Handling problem of a Job-Shop manufacturing system. We investigated about the simulation logic to be implemented in a DT and analysed the benefits that the introduction of self-adaptive behaviour (and, more in general, of the Industry 4.0) will bring in the current manufacturing system.

2. State of the art

Even if the Industry 4.0 is only a recent industrial topic, an extensive literature is already focused on this topic and its hypothetic scenario evolution (Hermann et al. 2015). In some of the available studies, a significant diffusion of enabling technologies for Industry 4.0 is predicted (Wan 2015). Nonetheless, just their implementations are not expected to be able to transform the old production systems in Industry 4.0 ones (Posada 2015). In particular, according to (Jian et al. 2016), the main element featuring a 4.0 system is the presence of the CPS paradigm, the Industrial Big Data, Internet of Things in the M2M interaction logic and the Digital Twin. The relationship between these components is characterized by a high complexity and different configurations, each one of them connected to a specific objective (Oesterreich and Teuteberg 2016). In this context, the most important feature is the empowerment of the equipment with the above decision-making capability, which definitely transforms a simple automated machine in a CPS (Jazdi 2014).

However, to make possible this behaviour, it is recommendable and necessary to implement three capabilities to the CPS: an intercommunication ability between CPS through the IoT for allow a continuously exchange of data, a comprehensive knowledge of the system state and, most of all, a computational and autonomous ability (Galaske and Anderl 2016). As said above, Industrial Big Data (Thiede et al. 2016), DT (Schroeder et al., 2016) and M2M logic (Guizzi et al. 2016) play a critical role in embodying all these capabilities in a CPS.

Some example of hardware and CPS architecture are carefully and specifically developed in the literature (Lee et al., 2015), even if a hierarchical relationship between the components of the system seems to be always necessary to solve the potential conflicts caused by the adoption of M2M logic. In fact, without such configuration, the continuous communication between the industrial equipment and the consequent cooperation in the decision-making processes would be impossible at this stage (Bagheri et al. 2015). With the Industry 4.0 and the introduction of the CPS's capability, emerges the old dichotomy between a centralized or decentralized production logic of the manufacturing system. (Schuhmacher and Hummel 2016). To the best knowledge of the authors, even doing a careful literature review, neither policies and procedures for designing nor a systematic theory for evaluating the performance of the two different logic is available in order to solve the proposed dichotomy.

According to (Rosen et al. 2015) and (Monostori 2014), a CPS may achieve its autonomy in industrial production process decision-making with the help of a DT which could replace the production system time by time. In this context, arise the importance of the DT in the Industry 4.0 revolution, as a necessary step for improving the self-adaptive behaviour of the interconnected CPSs.

As a matter of fact, despite the substantial investment, it is possible to show that the implementation of a DT allows an exponential improving of production quality (Grieves 2014).

Several authors describe the implementation of DTs developed with different mathematic methods. Grounding a DT modelling on the use of simulation software is not an original idea. For example, (Schluse et al. 2016) focused their attention on an agent-based simulation approach with the introduction of "Experimentable Digital Twin" concept. The results have been very encouraging and, the proposed approach, show its feasibility and promises in a manufacturing environment. In short, the use of the DTs concept, allow a practical integration of the simulation, like the Discrete Event Simulation (DES) (Converso et al., 2015) or System Dynamic Approach (Ascione et al. 2014), in the manufacturing context. In the opinion of the authors, there are three innovative scenarios for the DT uses.

First of all, it is possible to use the DT for the development of the future system. In this context, the DT have itself the same rules and structure of the future equipment (i.e.,.it represent the virtual substitutes of the real object with the same code and behaviour). This scenario allows simulating, developing, characterizing and verifying, the behaviour that the real equipment will show inside the manufacturing system.

Secondly, the DT bring all the simulation technology available for use in the real system, allowing the self-adaptive behaviour of the equipment. The machine, in this scenario, can simulate the different environment, establishing the best decision to take in a particular situation. In this scenario, the environment is simulated. However, the DT replicates the same decision that the real equipment would have taken (without introducing another stochastic event).

Thirdly, the DT helps to populate relevant Industrial Big Data with the support of the simulation tools. In fact, simulating the different environment in which the real equipment could work, a large set of data could be collected and analysed.

3. The CPS-AGV's Digital Twin experiment

To build, implement and apply a DT proof of concept focused on the Industry 4.0 paradigm, a simple Job-Shop production system was built. It consists of four processing stations, three of them configured as Manual Assembling Station and the other as a Warehouse/Source. All the stations are connected through a predefined circuit in which the AGVs can move between the different Processing Station (Fig. 1). It should be noted that the three Manual Assembling Station was enabled with a various and a different number of operations, depending on the setup costs supposed to simulate. In this environment, it is necessary to solve the scheduling problem of the plant. Due to its layout, it is a typical Job-Shop scheduling problem in which the AGV are responsible for the Material Handling (MH) of the plant. In Industry 4.0, the AGV considered should be based on the Machine-To-Machine (M2M) interaction logic. For this reason, it is a CPS-AGV or, more concisely, a Cyber Guided Vehicle (CGV) with a self-adaptive behaviour for solving the Material Handling problem of the plant.

Industrial Material Handling (MH) is one of the most exciting Industry 4.0 application field (Seitz and Nyhuis 2015). The innovation of a supply chain in a 4.0 scenario needs the achievement of a 4.0 configuration for each logistic component (Santillo et al. 2013). Scientific literature highlights a large set of examples of AGV use: all the application shows the same common feature: the capability of carrying a load of material, running an automated guiding schedule (Gallo et al., 2012). In the following paragraph, we investigate on all the process necessary for the development of the AGV's DT.

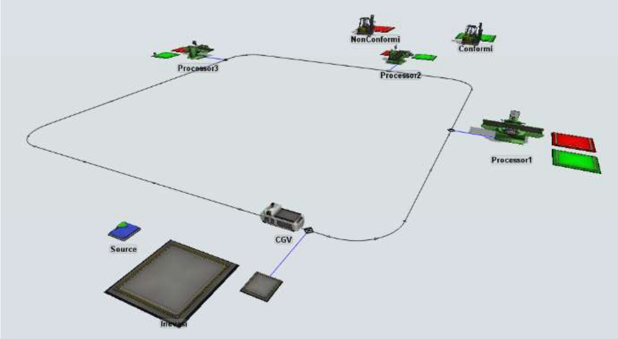


Fig. 1 – The Job-Shop Production System built

3.1 The Cyber Guided Vehicle

For the real construction of the above theorized CGV, the Zumo Robot (Pololu Robotics, 2017) has been selected and chosen. Zumo is an automated rover able to follow a track on the floor. The choice of Zumo Robot was motivated by the wide programming library, usable to control the rover, and most importantly, by the opportunity to implement the control tools developed for Arduino UNO microcontroller, assembled on the rover (Fig.2).

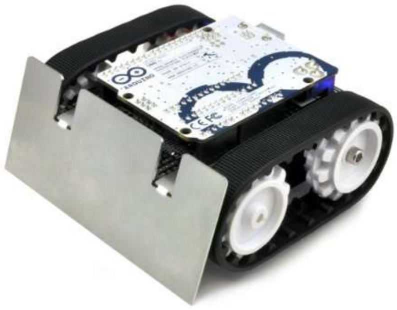


Fig. 2 – Zumo Robot

The Rover is equipped with a proximity sensor, which allows detecting the way line (i.e. the path of the CGV). This feature is handy, even if in its traditional configuration Zumo is just an AGV. Its behaviour can be programmed and elaborated by an algorithm on the microcontroller. In this context, Arduino UNO allows an easy implementation of the algorithm, thanks to a C++ interpreter. This feature allows writing the same algorithm in both the real CGV and the simulation software (the DT). The code ensures that the CGV makes decisions autonomously, on the basis of the data provided in real-time by the other CPSs and the use of industrial Big Data, through a dedicated Wi-Fi software infrastructure (access point). It should be noted that the utilization of the same code in both the real CPS and the DT avoid inserting another stochastic variable inside the simulation. The CGV is not simulated in its behaviour during the simulation. The Simulation will simulate only the environment, but the answer of the CGV are the same of the real system because the behaviour is an exact copy of it, not a simulated one.

3.2 The Conceptual Design of the experiment

This research has been focused on the conceptual design shown in (Fig.1).

The conceptual model consists of the following items:

- an Input Station that generates orders (source);
- a virtual backlog warehouse;
- a warehouse with unitary capacity that hosts the order ready to be worked;
- the vehicle for handling the orders/items that are termed the CGV to recall that it belongs to the CPS class;
- three Manual Assembling Station for the manufacturing of the item (named Processor 1, 2,3);
- six buffers for compliant (green) and not compliant (red) items;
- two big warehouses to collect the finished items, again one green for compliant and one red for non-compliant items;
- two pallet trucks that pick up the finished items;
- twelve pairs of proximity sensors to map the logistic state of the system.

The plant layout of the establishment in question is designed in such a way that the CGV driven vehicle can move on a predefined circuit to which the unit storage capacity and the three machineries belong. The path, on which the two transpallets move, being guided by man, is irrelevant to our discussion.

To implement the whole system, the DT runs the following processes:

1) The source serves as the input station and generates orders using a known statistic frequency.

2) The orders generated by the source are moved using baskets to the buffer with unitary capacity, where they are ready to be picked up.

3) The CGV receives the order of loading of the generated basket.

4) The CGV interacts with the three machines (Processor 1, 2, 3) arranged on the circuit and selects the equipment where to deliver the basket. Then, it entrusts processing,

according to a chosen production criterion and the known self-detected state of the machinery.

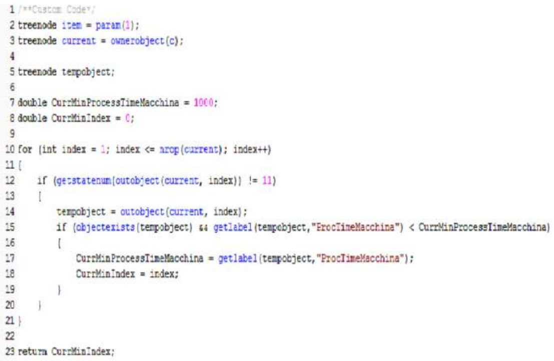
5) The chosen machine processes the materials basing on the known stochastic behaviour of time, reliability and quality.

6) Downstream of the production, the processed basket is moved to one of the buffers (either red or green).

7) The pallet trucks move, through the action of an operator, picking up the processed items and carrying them to the respective main buffers, located outside the path.

8) Meanwhile, the CGV repeats its path, receives a new order of loading and makes a new decision. Such a decision is based on the self-adaptive algorithm that considers the new data of each workstation and the status of the equipment updated during the simulated process.

The rover process the tasks four and eight using self-adaptive decision-making algorithms (Fig.3-4), which optimize the chosen policy for the system:



```
/**Custom Code*/
treenode item = param(1);
treenode current = ownerobject(c);

treenode tempobject;

double CurrMinProcessTimeMacchina = 1000;
double CurrMinIndex = 0;

for (int index = 1; index <= nrop(current); index++)
{
    if (getstatenum(outobject(current, index)) != 11)
    {
        tempobject = outobject(current, index);
        if (objectexists(tempobject) && getlabel(tempobject,"ProcTimeMacchina") < CurrMinProcessTimeMacchina)
        {
            CurrMinProcessTimeMacchina = getlabel(tempobject,"ProcTimeMacchina");
            CurrMinIndex = index;
        }
    }
}

return CurrMinIndex;
```

Fig. 3 - Algorithm for Minimization of the Process Time

```
/**Custom Code*/
treenode item = param(1);
treenode current = ownerobject(c);

treenode qualobject;

double CurrMaxQualityMacchina = 0;
double CurrMaxIndex = 0;

for (int index = 1; index <= nrop(current); index++)
{
    if (getstatenum(outobject(current, index)) != 11)
    {
        qualobject = outobject(current, index);
        if (objectexists(qualobject) && getlabel(qualobject,"QualityMacchina") > CurrMaxQualityMacchina)
        {
            CurrMaxQualityMacchina = getlabel(qualobject,"QualityMacchina");
            CurrMaxIndex = index;
        }
    }
}

return CurrMaxIndex;
```

Fig.4 - Algorithm for Minimization of the Logistic Time

In both codes, the self-adaptive behaviour of the system is achieved using a simple exponential smoothing algorithm, applied to the workstation behaviour time series, retrieved from the Industrial Big Data of the system.

3.2 The Simulated Policy

The real CGV and the correspondent DT is designed for operating in three different decision-making logics, correspondent to three different behaviour:

1. Pre-Planned Policy, in which the CGV represents the AGV without its ability to think. It represents the old traditional scenario of Industry with a centralized planner.
2. Minimization of the Processing Time Policy, in which the CGV will cooperate in the scheduling of the plant, preferring to assign less consequential job possible to a Processing Station, minimizing the continuous use of each station with a more flexibility of the plant. Even this plan represent an Industry 4.0 scenario, in which CGV is a part of the CPSs network with the common goal of minimizing the continuous utilization time of Station.
3. Minimization of the Logistic Time Policy, in which the CGV will cooperate in the scheduling of the plant, preferring to assign more consequential job possible to a Processing station, minimizing the movement and the time for the internal logistic. It represents an Industry 4.0 scenario, in which every CGV is a part of the CPSs network with the common goal of minimizing the Logistic Costs and Time.

4. Results

In the simulation, ten tests for each Policy were performed, and the values obtained as a result of the individual simulations were reported in the following Figures.

The different scenarios will be determined by the variation of two parameters:

1. The frequency with which Source generates pieces (a type of Demand).
2. Selling Price.

The obtained data are reported in the table, and we have charted each the value of the objective function "Gross Profit" for each scenario in both the Policy applicable

The aim of the analysis is to understand what decision-making policy to set on the rover, to maximize *Gross Profit* of the system, i.e. the objective function in eq.1 below:

$$F(€) = p_v * n_c - p_{nc} * n_{nc} - p_{in} * n_{in} - \sum_{i=1}^{3}(ch_i * tp_i)$$

where:

- p_v= selling price;
- n_c= number of compliant items;
- p_{nc}= penalty for non-compliant items;
- n_{nc}= number of non-compliant items;
- p_{in}= penalty for out-of-stock items;
- n_{in}= number of out-of-stock products;
- ch_i=production hourly cost of machine *i*;
- tp_i= production time of machine *i*.

The policies chosen for comparison by the DT arise from two big issues, i.e.: the variability of (external and uncontrolled) production factors and the trade-off between logistics and production costs. In order to highlight the effectiveness of coupling a DT with a CPS-CGv, we compared a traditional centralized (pre-planned) policy (Policy 1) with the two Industry 4.0 Policy shown in the previous paragraph (i.e., Minimization of the Logistic Time (Policy 2) and the Minimization of the Processing Time Policy (Policy 3)).

4.1 Simulation and policy comparison

The first scenario is representative of a situation where demand has a low variation, and the selling price is high. Under this condition, the plant material handling tasks is likely to be rescheduled several times. Running simulations with DT in the loop, the gross profit for each short period was estimate, with ten simulations per policy, computing their average values and comparing them by recording the results in proper tables and graphs. Fig. 5 presents the results of the first scenario.

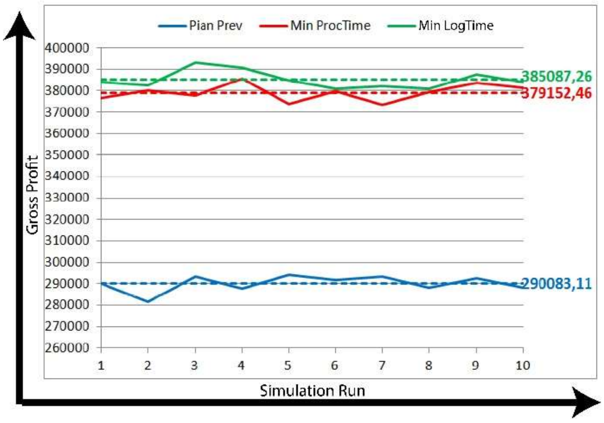


Fig. 5 - First Scenario results

What we notice right away is that by implementing a logic 4.0 and then implementing in our CGV an auto-adaptive decision-making autonomy, the average profit is higher. Under these conditions, the winning policy is the Minimization of the Logistic Time Policy.

The second scenario is representative of a situation where demand has a high variation, and the selling price is low. Even in this scenario, compared to a preventive schedule and therefore to a static scheduling, logic 4.0 prevails. In particular, compared to what has been obtained before, the variation of the scenario will also lead to a variation of the best criterion. In fact, in that scenario where the part generation frequency is low as well as the cost of the work piece worked, the best logic is the Minimization of the Processing Time Policy. The Fig. 6 shows the results of the second scenario for each policy considered

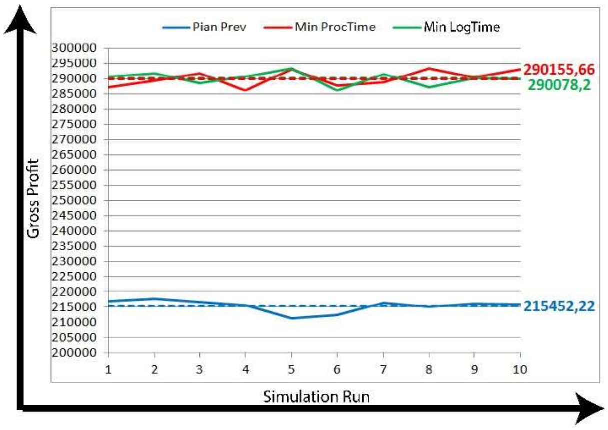


Fig. 6 - Second scenario results

In the third scenario, the MH system operates in a process plant where the production equipment reliability, the market demand, and the selling price are characterized by a low degree of variability. Under this conditions, the process rescheduling of the plant MH system decreases significantly. In this scenario, every Policy applied in the DT do not make a significant change in the objective function. Instead the situation of the other scenario, in this case the use of Industry 4.0 hasn't a competitive impact on the Production goal. The Fig. 7 shows the results relating to each policy applied to this scenario.

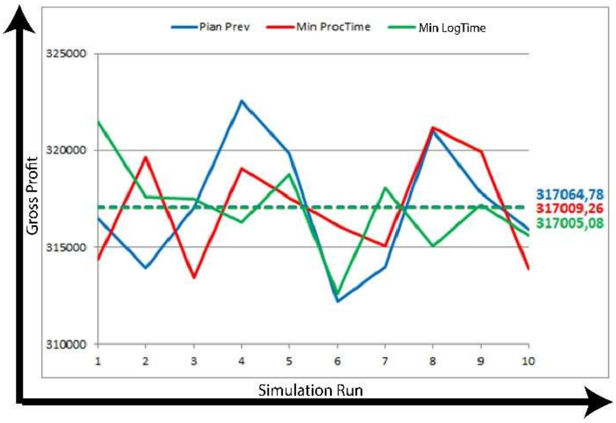


Fig. 7 - Third scenario results

4.2 Results analysis

From an analytic point of view, it is appropriate to summarize the recorded behaviour in the following (Table 1), where the average gross profit (in €) is reported:

	Policy 1	Policy 2	Policy 3
Scenario 1	290083,11	379152,46	385087,26
Scenario2	215.452,22	290.155,66	290.078,2
Scenario3	317.064,78	317.009,26	317.005,08

Table 1: Scenario vs. Policy behaviour

The main consideration that arises from the above Table is that when changing the demand typology and the industrial contingencies, the policies should be changed as well. To this end, the implementation of a DT expands the operation opportunities and the industrial potential of

CPSs. As a matter of fact, using the results of the DT, not only CPSs can apply a decision-making autonomy (to optimize their goal), but they can choose "autonomously" between their optimized available policies.

5. Conclusions

This paper highlights how CPSs, DT and industrial Big Data are strongly connected in an Industry 4.0 manufacturing system. The combination of these three pillars allows meeting the concepts of decision-making autonomy and self-adaptation of machines operating in an industrial plant. This conclusion is supported by the possibility of determining (and, therefore, choosing) the optimal production schedule depending on the market scenario, by different possible choices on the tactical criterion concerning the short period considered.

The experimental approach also demonstrated that Industry 4.0 is not always the "best" configuration for a production system. When the strategic positioning of an industrial plant highlights operating conditions characterized by uniformity of performance and behaviour, both internal and external to the production domain, the tactical approach can be managed with greater convenience without implementing autonomous decision-making algorithms in the machines.

In the case of equipment reliability or (high) production variability, the self-adaptive reaction feature of a "4.0 plant" is a non-negligible competitive factor. In this context, M2M logics are a fundamental pillar on which the reaction and optimizing capacity of the system should be based. Considering a strictly M2M oriented system, the results achieved highlight that the application of DES to the DT logic allows a complete and well-performing operations of the model.

With this aim, exploiting a general simulation model to develop a DT is a cheap and, at the same time, useful and suitable solution, agreeable to the industrial needs and design purpose. As a matter of fact, our results highlight that, under the project hypothesis of developing a plant system (or subsystem), strictly M2M oriented, built and managed with the use of CPSs, the DT built is effective in reproducing the CGV and helpfully in optimizing its schedule.

The main innovative idea of this paper consists in basing the DT implementation on the use of same operational software code of self-adaptive behaviour and scheduling optimization routine, both in the CPSs microcontroller, both in the DT (that is). The simulated experiment shows that the adopted design process just reduces the stochastic variability of the simulated system to the natural variations of the physical factors not controlled by the DT. This conclusion implies that, under the hypotheses made, the simulation software can be implemented in practice to support industrial DT. On the one hand, in fact, using the proposed process there is no variability introduced by the operational code of simulation; on the other hand, all the graphic and computational tools used in a simulation software make it possible to achieve several advantages.

The AGV systems fall within the hypothesis of the system provided for the proposed model. In a particular way the rover used in work, already able (as every automated equipment) to perform an assigned path, may be transformed with success in a CGV, by writing the code items relating to the transfer of decision-making autonomy to the machine in its microcontroller.

As a discussion theme for future developments, it is appropriate to underline that the results of this work depend strictly on the hypothesis of a production system operating in M2M logic. This assumption is very restrictive for most of the real production plants, which need tools that centralize at least partially the flow of decisions. The original aim of this research was to build and implement a concrete example of DT, usable for small industrial subsystems oriented to the smart manufacturing and Industry 4.0 approaches. This aim has been completely achieved; nonetheless, the complexity of the real industrial contexts could generate more structured equipment interactions. This involves conflicts between resources, which cannot be managed using a rigorous M2M logic. In this circumstance, implementing a plant, system or subsystem DT requires the introduction of production centralization tools and the careful review of the DES logic, which would probably need to be replaced with an Agent-Based logic.

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