Intelligent Agents and Multi Agent Systems for Modeling Smart Digital Twins

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Abstract. Recent years witnessed a significant digital transformation in most aspects of life and various disciplines. A new technology concept named a Digital Twin has emerged. Digital Twin is mainly utilized to create a virtual representation (digital assets) of physical components (physical assets) which are connected and synchronized with each other. Digital Twin could be used in multiple tasks like diagnosing, forecasting, and visualization, decreasing the cost of designing, implementing, and using the physical assets. Nevertheless, because of the complexity level encountered when merging both cyber and physical parts, building a Digital Twin is considered a quite challenging job, as many requirements should be addressed during the design and the implementation processes. Thus, it's crucial to choose a reliable approach that can implement such a complex system. Therefore, this paper aims to introduce an intelligent approach driven by using the Multi-agent System architecture that could reduce the level of complexity while building a Digital Twin. Intelligent agents enabled us to deal with the challenges imposed by building CPS as well as the integration with the Digital Twin. In this approach, different components of CPS are represented as autonomous agents in the Digital Twin environment. Every individual agent represents a specific part of the system and acts intelligently and cooperatively with other agents to achieve the system's objectives.

Keywords: Digital Twin · Intelligent Agent · Multi-agent System · Agent-based Modelling · Cyber-Physical System

1 Introduction

Due to the lack of advanced technologies in the past, physical systems were working independently and most of the operations like testing, monitoring, validating and analyzing are conducted in the real-world (physical environment) and this approach could be not efficient, unsafe, unpredictable and very expensive. In the latest years, technologies have improved significantly, which led to the start of the era of digital transformation where the systems' requirements are becoming higher than before due to the large-scale components the CPS might have, and also they are hybrid and dynamic and could have exceedingly complex processes

[1]. For This reason, old and conventional solutions are being replaced by smart and intelligent solutions to satisfy such demands and achieve many goals like efficiency, accuracy, speed, reliability, etc. The digital transformation, specifically in the industrial sector, was propelled by the fourth industrial revolution (Industry 4.0), which changed many concepts in the industry and manufacturing and replaced them with intelligent approaches. Cyber-Physical Systems (CPS) and the Internet of Things (IoT) are the core paradigms for fulfilling the requirements for building complex and smart systems and achieving the desired digitization.

CPS and IoT are distributed systems that comprise many interrelated parts and sub-components, and which make them inherit some characteristics from the system-of-systems (SoS) that increase the level of their complexity which grows as more subsystems and sub-components are included in the system. Implementing smart and intelligent systems comes with a cost, which is represented in dealing with a higher level of complexity than in conventional systems [2]. Thus, a new generation of technologies are emerged to deal with such complexities. When it comes to physical systems, simulation tools, emulators, and performance monitors are proposed to tackle some of the challenges and complications encountered while building and deploying those physical systems. Despite all the existing technologies, achieving the full integration and interaction between the physical components and their digital counterparts still face some challenges due to the complexity of such systems. The primary motivation to reach such integration and interaction between the physical and digital worlds is to control, monitor, improve, predict and manage the physical systems in order to guarantee more flexible, scalable, and robust system performance.

Anyhow, a new emerging cutting-edge technology called Digital Twin has emerged. Due to its potential capabilities, Digital Twin has become a compelling topic in recent years and attracted many scientists and engineers in academia as well in the industry. Since the formulation of the technology and its initial concept, many interested researchers tried to adopt and reform the concept according to their domains from the smart manufacturing to the aerospace industry and many other disciplines that have not been mentioned here [3]. Digital Twin can be defined as a technology that enables the integration and real-time synchronization between physical and digital parts. The technologies provided in Industry 4.0 facilitate the operation of synchronizing the sensed data from the physical elements with a digital environment. In this context, building a Digital Twin can offer many benefits especially in the field of smart manufacturing. As mentioned in the definition of the Digital Twin, a real-time flow of information and data between physical and digital parts is essential. This continuous data can be used in development, improvement and management tasks like analyzing, inspecting, monitoring, predicting and reasoning about the current behaviour of the system and make decisions accordingly for future scenarios. Also, this continuous data could be beneficial in the product life-cycle [4]. In addition, the integration of the physical and digital parts in the Digital Twin could ease the process of extending, modifying and customizing the system based on the insights gained from the generated data.

2 State of the art

In the context of agents in the cyber-physical systems (CPS), several researchers have adopted the Agent-based Modeling (ABM) and Multi-agent System (MAS) based approach to develop, build and deploy smart designs and solutions to handle complex systems and the interactions that could happen inside those systems. Also, the use of MAS to build CPS has been seen often in the research community; also, companies developed and introduced industrial implementations.

Digital Twin is a popular trend among the research community. Hence, several literature reviews [5, 6, 7, 8, 9, 10] have been conducted to investigate the potentials and enabler technologies, and also, the main challenges and the barriers are pointed out and discussed. In the same context, building a Digital Twin for CPS/IoT system requires collecting information about the physical components to define them as virtual representatives. The complex nature of CPS, which resulted from the distributed and the heterogeneity of the interrelated components in the CPS and its sub-systems, sub-parts, and sub-elements, may trigger numerous challenges when dealing with these systems, such as uncertainty and ambiguity of its behavior. With this regard, this paper adopts an intelligent Agent-based approach to deal with the complexity and the challenges (distributed and heterogeneous components and the complex communication mechanism among them) that are encountered when building a Digital Twin for CPS by programming intelligent agents that can take self-action and smart decisions to reach their goals.

In the literature, and in general, there are a considerable number of studies that investigated the implementation of Digital Twin using different methods and techniques. Also, some of these works considered using Agent-based Modeling and simulation approaches to realize a Digital Twin. Most of the studies that utilized the Agent-based and Multi-agent System are relatively scarce and new. In the following paragraph we summarize the state-of-the-art in Digital Twin domain.

Alam and El Saddik in the [11] introduced an architecture reference model (C2PS) for Digital Twin for cloud-based CPS. The main properties of this model help to identify the degree of interaction of basic and hybrid modes (computation, communication, and control). In their implementation, they connect every physical component (thing) with its counterpart representative that is hosted in the cloud. With the help of a Bayesian belief network that is integrated with a fuzzy rule base, the system is capable of making self-reconfiguration.

In the study conducted by Ambra and Macharis [12], the paper shows the proof-of-concept of Digital Twin and how can be constructed by integrating virtual and physical spaces, which can be achieved by feeding the real-time data from the physical environment to the virtual GIS environment. Agent-based modelling (ABM) and multi-agent system (MAS) are utilized to provide the agents in the system with a self-awareness capabilities.

Braglia M, et al. present in [13] an Agent-based simulation model to operate a paper products warehouse. Their implementation integrates the Ultra High-Frequency Radio Frequency Identification (UHF RFID) technology in a Digital

Twin fed with data received from sensors and works to optimize the routes, minimize the traveled distance, and handle the potential congestion.
Implementing a Digital Twin in smart cities was discussed in [14] which utilizes the Internet of Things (IoT) and modeling and simulation approaches. In their presented work, they implemented the Digital Twin using the MARS framework for large-scale Multi-agent Systems. In the Digital Twin simulation, they presented the entire process where they incorporated the model description, and also the real-time data is retrieved from IoT sensors.
In another study introduced by Croatti A. et al. [15] discussed the integration of agents in Digital Twin for the healthcare sector. The authors presented their vision for integrating the Multi-Agent System (MAS) technology in Digital Twin for healthcare applications. Also, they presented a case study of agent-based Digital Twin for application that manages severe traumas.
Agriculture and farming are vital for humans. Thus, advanced technology can be utilized to improve farming approaches and introduce intelligent methods and techniques. The study carried out in [16] discussed developing a Digital Twin for a plant by utilizing the multi-agent technology and the knowledge base on macro stages which allowed to monitor and control the plant in many stages (plant development, vegetation quality, timing of following stages, and recalculation of forecast).
The study in [17] proposed a method for modeling a Digital Twin based on the architecture of a Multi-agent System. The study focuses on quality control in manufacturing, providing relevant information, and analyzing the product quality during the manufacturing processes. The basis of the DT model is on the physical entities, virtual models, DT data, services, and connections between the components.

Despite the efforts put into integrating and utilizing agents on Digital Twin, still, there are other aspects and capabilities of the Agent-based and Multi-agent Systems that are not covered and explored in the context of building a Digital Twin for CPS, for instance, having an ABM simulation to simulate the real-time situation or applying advanced and intelligent decision-making and reasoning mechanisms [18] such using the Belief–desire–intention (BDI) software model.

In this paper, we just focused on exploring the potential and capabilities of agents to realize and develop intelligent Digital Twin. The main contribution of this work is to provide a proof-of-concept of an intelligent agent-based Digital Twin implementation realized with the JADE platform for a complex and distributed system. Furthermore, advanced features and capabilities such as learning, reasoning, monitoring, and simulation will be added to agents in a modular way in future work.

3 Challenges and requirements in Digital Twin

In principle, Digital Twin represents physical assets that operate in the physical environment and mirrors these assets as a digital representation container. The granularity level of a Digital Twin for a particular physical system can vary from one system to another and depends on which components of the physical system are considered and represented in a Digital Twin. This means that in some systems, services in one physical component could be represented as an independent and single Digital Twin; this leads to having a hierarchical and distributed architecture for Digital Twin. Likewise, we will have atomic Digital Twins that might be coupled into a unified Digital Twin. To explain it in more detail, assume a system with multiple physical components (sensors and actuators), and every component has several micro-services that interact with other services. Consequently, all these services should be encapsulated and mirrored in the Digital Twin. In this scenario, the representation of components and their micro-services in Digital Twins can be immensely painful and time-consuming due to the heterogeneity and complexity of the interactions that might happen between the different components and their internal services. Therefore, it's necessary to provide a high-level and intelligent approach to tackle these challenges, complexities, and difficulties accompanied by realizing such integration and interaction in a Digital Twin.

To follow this objective, there are some efforts focused on providing solutions by offering frameworks and environments that facilitate the realization of Digital Twins. Yet, these frameworks lack straightforward, reusable, scalable, extendable, reliable, intelligent abilities which could tackle the complexities such as the hierarchical distributed architecture, components' heterogeneity, and multidisciplinary produced from the integration of CPS with Digital Twin [19]. For that reason, in the following we enlist several research questions that have been put on our table, and we try to provide answers; for instance, to what extent is the intelligent agent paradigm capable of tackling the complexities of the integration of CPS with Digital Twin? to what extent can agent-based solutions be utilized and provide reliable, scalable, and robust Digital Twin for complex CPS?.

However, the recent literature review study which has been published in [6] enumerated and discussed key challenges that are facing practitioners while implementing and constructing a Digital Twin, from technical difficulties, and computational barriers to the shortage of well-founded approaches. In the table 1 provided below, these challenges are summarized, discussed, and explained.

By taking into consideration all these emerging challenges and obstacles, an intelligent approach based on Multi-agent System is considered as the core paradigm to build flexible, reliable, and intelligent Digital Twin. Multi-agent Systems have shown significant potentials and capabilities to manage complexities and achieve a good level of intelligence. MAS technology is a promising paradigm and is adopted as an enabler for CPS, and its objectives [20]. Also, in the literature, surveys and systematic literature reviews are carried on to discuss the MAS technology in many aspects. The authors in [21] discussed the agent paradigm and its impacts and main factors that has led the industrial sector to accept it in manufacturing. The conducted review showed promising results for accepting and leveraging industrial agents because of their characteristics such as intelligence, flexibility, extendability, agility, modularity, responsiveness and

Table 1. Digital Twin Requirements and challenges.

Requirements In Digital Twins	Challenges & Explanations
1) High-fidelity representation	Uncertainty, unpredictability, and changeability of the physical environment behaviour make the virtual representations inconsistent with their physical counterparts and this limits the validity of these representations
2) Efficient Data gathering and processing	In CPS there are multiple and heterogeneous types of data that are produced from various sources (components and sensors). This data should be collected, processed and stored. Handling tremendous amount of data and dealing with its heterogeneity could be quite challenging task
3) Real-time synchronization and communication	In time-critical systems, the real-time synchronization between the physical and the digital assets in the Digital Twin should be ensured, achieving this criteria could be challenging especially with the expected delays and latency if a huge amount of data is generated in two-way direction
4) Development environments and tools standardization	Current available development environment and tools for Digital Twin are not standardized, due to the multidisciplinary and heterogeneity of the domains, protocols, formats in the implementations of Digital Twins
5) Techniques and approaches for tight coupling and integration	The complete representation of the physical assets into their digital counterparts is still not fully achieved, as they lack embodying the full behavior and the interactions of physical assets in their environment.
6) Intelligent and autonomous behaviour	Digital representations could have an enormous number of sub-services, those services could be individual and independent. Every sub-service should work autonomously and intelligently to achieve their internal goals as well as work cooperatively towards achieving the global goal.

a robustness that could have a significant effect while implementing intricate, complex and distributed systems for CPS [21].

We believe that the combination of the suitable methods, technologies, and tools is the optimal weapon to minimize the high level of complexity, and tackle the challenges that emerged from combining physical and cyber parts of CPS and Digital Twin. Ultimately, our aim and vision for this research is to provide an intelligent multi-paradigm approach for modeling a Digital Twin that combines using Multi-agent System (MAS), Agent-based Modeling, and Simulation (ABMS). In our proposed approach, the technologies and techniques will be used and applied incrementally as every technology will be deployed to counteract a specific challenge or part of it in the Digital Twin. In our implemented approach and the current version of the Digital Twin, we have somehow alleviated the complexity of the challenges (3,5, and 6) mentioned in the table 1.

4 Methodology and the proposed architecture

Researchers and engineers in different information technology fields need a standard, systematic, organized, and well-structured research methodology to help them conduct their research.

4.1 Design Science Research Methodology

The methodology that has evolved through the years, called design science research methodology (DSRM), provides a set of practices, tactics, principles, and procedures to conduct methodical research for a defined and formulated problem.

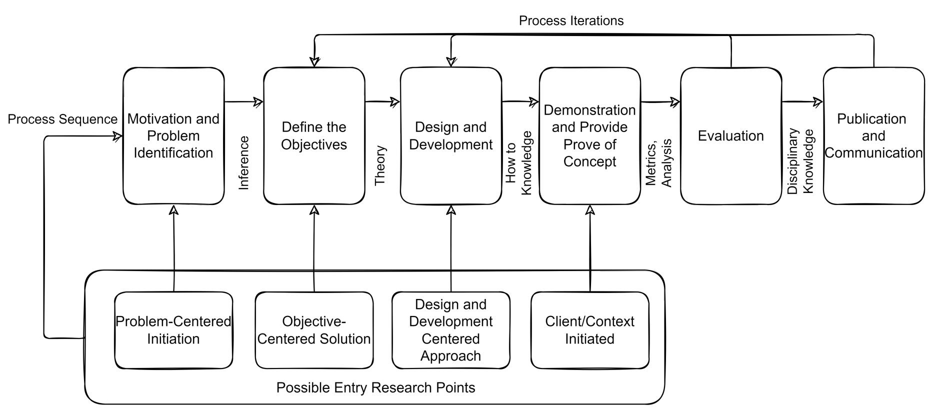

Fig. 1. DSRM Process Model

DSRM guides and directs researchers to manage their research to produce research results and initiate systems' building. As a consequence, DS methodologies evolved over time, and many guidelines, characteristics, and rigorous processes for carrying out high-quality DS research are proposed. For this reason, we are adopting a DSRM presented in [22] to conduct our research as we follow the guidelines and instruction that governs DSRM. In the following figure 1 the processes and the road map of the DSRM model are depicted and explained later. The processes starts with identifying the problem and ends in with communication and publishing the results from the artifacts. We will just summarize the key processes should be followed in the DSRM model. The most important when following the DSRM is to outcome artifacts that should address the relevant and the identified problem at the first stage. Also, the produced artifacts should be evaluated rigorously to prove their efficiency, quality, and usability. And finally, the researchers should communicate and present their resulted artifacts to a appropriate audience [22].

4.2 Intelligent agents

The core element in Agent-based Modeling approach and Multi-agent System paradigm is the agent. The architecture of agents provides powerful features that can make the implemented system by using this paradigm more intelligent. This intelligence is formed and composed by merging several characteristics, properties and behaviours of agents. For instance, in MAS systems, agents are autonomous entities, which means they operate without external intervention to reach their internal goals, and they can decide to collaborate, interact, negotiate and communicate with other agents directly or indirectly if there is a mutual benefit that can be achieved for the level of the agent itself or for the higher level in the whole system. Also, agents are considered social entities because they are located in a specific environment and they need to interact with other external agents (e.g., humans or computer agents) at some point to achieve global goals or their own goals. In addition, agents are reactive units, they perceive the environment and their surroundings, and accordingly, they respond to the changes that occur promptly, and on time. Agents don't just act as responsive; instead, they can work in a goal-directed fashion which make them proactive, and they can take the initiative to achieve things. Furthermore, agents can adapt to the changes in some uncertain situations or in a dynamic environment and take the best available actions according to the context [23] [24]. Additionally, agents may use the available knowledge from other agents to make better choices and decisions. Agents could be described as rational. Rationality in agents is required, and rational agents could be described as the ones that reason about the situation and select the appropriate and logical actions at any given time instant according to the context. In concept, rational agents should be aware of the environment, and they should select the right action from the pool of actions that increases its performance[24].

All the features mentioned above enrich and equip agents with powerful capabilities that enable to cope with the complexities in the CPS and fulfill the requirements for integrating it with a Digital Twin. Therefore, we are using agent paradigm and specifically Multi-agent System (MAS) as the main model for programming agents in the CPS layer as well as in the Digital Twin layer.

At the conceptual level, we have provided a metamodel for our proposed approach. In this meta model we provide a high level overview of the relation between the `Domain`, adopted `Architecture` and `Digital Twin`. Initially, our main objective is building a Digital Twin system by exploiting the agent paradigm. Also, the implemented Digital Twin targets a specific domain, and the Digital Twin is constructed according to this domain. In theory, once the domain is changed, Digital Twin implementation will be modified, adapted and adjusted according to the changes. So, the Digital Twin can be almost the same at a high level, and the only modifications are required when the domain changes are the technical and low-level details and implementations. Thus, flexible architecture is required to implement the Digital Twin and to provide easy steps to conduct the modifications when required. The metamodel for our approach is illustrated in figure 2.

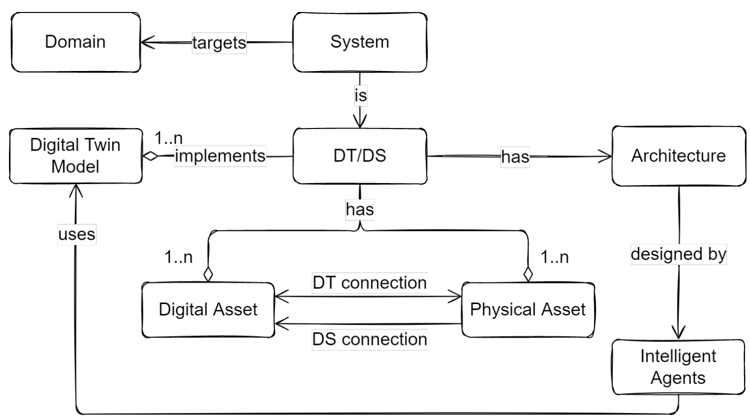

Fig. 2. A metamodel for intelligent Agent-based Digital Twin

In the metamodel provided in the figure 2, the Digital Twin system implements a `Digital Twin Model` that contains the essential details of the integration of the digital and physical assets based on the applied architecture and which uses Intelligent Agents as the core paradigm and, more specifically uses JADE MAS platform. Moreover, the system can be a fully functional Digital Twin (DT) or a Digital Shadow (DS) depending on the type of connection between the `Physical Asset` and `Digital Asset`, as depicted in the figure 2, the Digital Twin assures bi-directional channel between the Physical and Digital Assets, in contrast Digital Shadow provides just uni-directional channel between the Physical and Digital Assets.

In Figure 3, the architecture model for the Agent-based approach is provided. In this figure, we describe the main components of the Agent-based Digital Twin architecture.

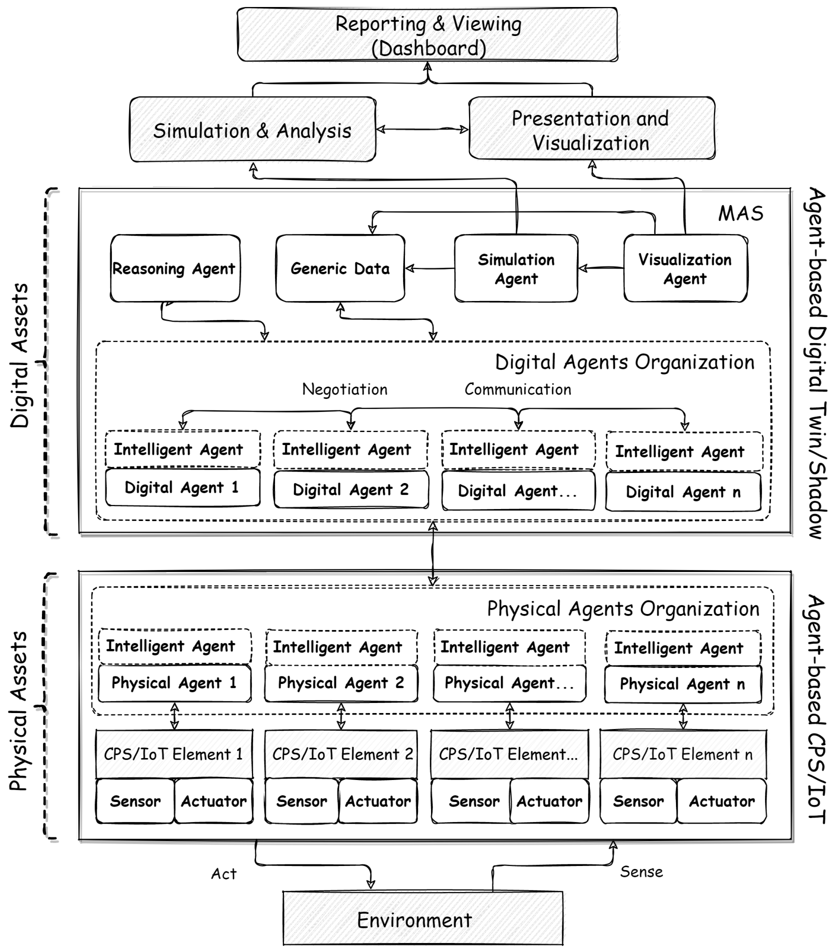

Fig. 3. A high-level overview of the intelligent Agent-based Digital Twin architecture

Two main regions draw the borders of the two integrated worlds (cyber and physical) that compose the Digital Twin. First, the *Digital Assets* layer that is empowered by multi-agents systems and contains the digital agents. In the Digital Assets, several agents are included; for instance, there is a separate part *Digital Agents Organization* that comprises agents who are in response to communicating and negotiating with the physical software agents from the agent organization in the *Physical Assets* layer. *Digital Assets* layer includes other agents with other functionalities; *Reasoning Agent* which is responsible for reasoning and making a context-aware decision in the Digital Twin, *Simulation Agent*; in charge of conducting simulations about specific context or scenario depending on the data collected from the *Physical Assets* and its agents, *Visualization Agent*, it is in control of viewing, visualizing and presenting all the important information collected from the *Physical Assets* and which will be accessed by other agent, external application or human agent. For the *Physical Assets* layer, CPS/IoT components such as sensors and actuators also are enabled by Multi-agent System. Thus, physical software agents control and operate the physical components that are targeted in the Digital Twin. Every software agent specified for a certain physical component located in the (*Physical Agents Organization*) communicate with its counterpart software agent located in the *Digital Agents Organization*. All physical and digital agent are coupled in a single unit system as a Digital Twin.

Digital Twin can be utilized for many purposes, and generally, reporting, analyzing, predicting and visualizing the state of the physical assets are very common in Digital Twins. Thus, to provide these services, other technologies must be used to enrich the experience for the user in the Agent-based Digital Twin.

5 Work in progress: prototyping a smart warehouse case study

In the development and deployment phase, it's essential to provide an initial prototype of the proposed system to demonstrate a proof-of-concept and show its potential and the degree of its effectiveness and success. To achieve all that, we have designed and built an automatic guided vehicle (AGV) robot prototypes with LEGO[1] technology [25, 26, 27] and integrated it with other technologies and hardware components. we have used Raspberry Pi-BrickPi[2] as the brain and processing unit of the robots to provide high processing capabilities.

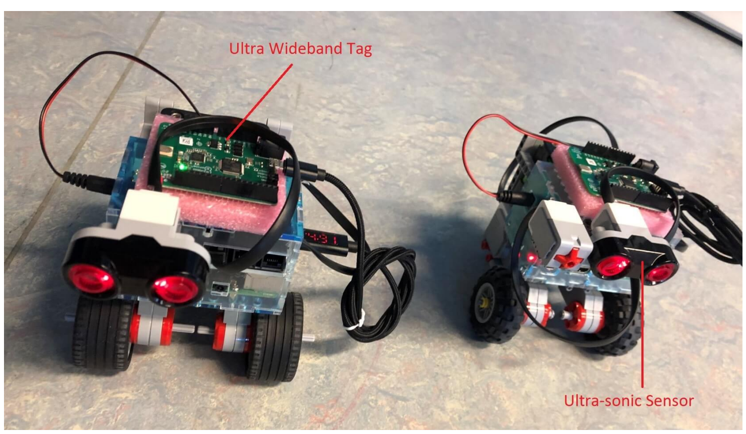

Fig. 4. Overview of robots prototype used in the smart warehouse

[1] https://www.dexterindustries.com/brickpi
[2] https://www.ev3dev.org/

As illustrated in the figure 4, the robots are equipped with an ultra-sonic sensor in the front, which measures the distance of the front object by sending sound waves that will be reflected and estimate the distance from this object. Using this sensor will make the robot aware of obstacles in the environment. Also, the tag attached above the robot uses ultra-wideband technology, and hence we can localize and determine the robot's position when it navigates through the world; by following this approach, we can obtain the coordinates of the running robots and process them in the Digital Twin to make robots avoid collisions.

Smart Factory Warehouse is the idea behind our case study. The essence of the idea is to build a Digital Twin for a factory warehouse where many robots operate and do all the work autonomously without human intervention. Digital Twin is based on the proposed architecture, and therefore, robots inherit the characteristics of agents and provide the system with a level of intelligence and autonomy. By implementing this case study, we aim to imitate the industrial-like environments, scenarios, and requirements in order to advance and adjust the implemented system to be adequate and build a smart fully-fledged Digital Twin for a factory warehouse in reality. In the implemented system, we have considered obstacle avoidance and collision detection requirements. We have equipped the AGV with ultra-sonic sensors to enable robots to detect objects and obstacles; moreover, we integrated Ultra-wideband (UWB) technology for positioning and localization of the robots. Also, time constraints requirements for picking and dropping off packages are considered to achieve high accuracy, speed, and reliability.

Following the proposed architecture to realize the Digital Twin. We have created two layers of agents; one is the physical layer, which contains agents for `Physical Assets` (i.e., robots and their sensors). The other layer is the digital layer, and it includes digital agents (i.e., representatives of physical agents) that operate in the `Digital Assets` within the Digital Twin. All agents in the Digital Twin whether are in `Physical Assets` or `Digital Assets` are implemented and programmed with the JADE[3] framework and use the FIPA[4] agent communication language as the mean of the communication [28].

The figure 5 gives a clear overview of how physical and digital agents are communicating and interacting inside the JADE platform to compose the Digital Twin implementation. The figure shows the two layers in the Digital Twin that contain the physical and digital agents, and this is also illustrated more while executing the JADE platform as in the figure 6 which shows the instantiated and created physical and digital agents in the graphical interface of the JADE platform. In fact, the layers are called containers in the JADE platform, and thus we have *Digital-Layer-Container* that comprises all the digital agents, while we have two physical layers; *Physical-Layer-Container* and *Physical-Layer-Container-1* which contain the agents of the robot 1 and the robot 2. The physical agents are running in separated robots, and they communicate with the main container in

[3] https://jade.tilab.com/
[4] http://www.fipa.org/repository/aclspecs.html

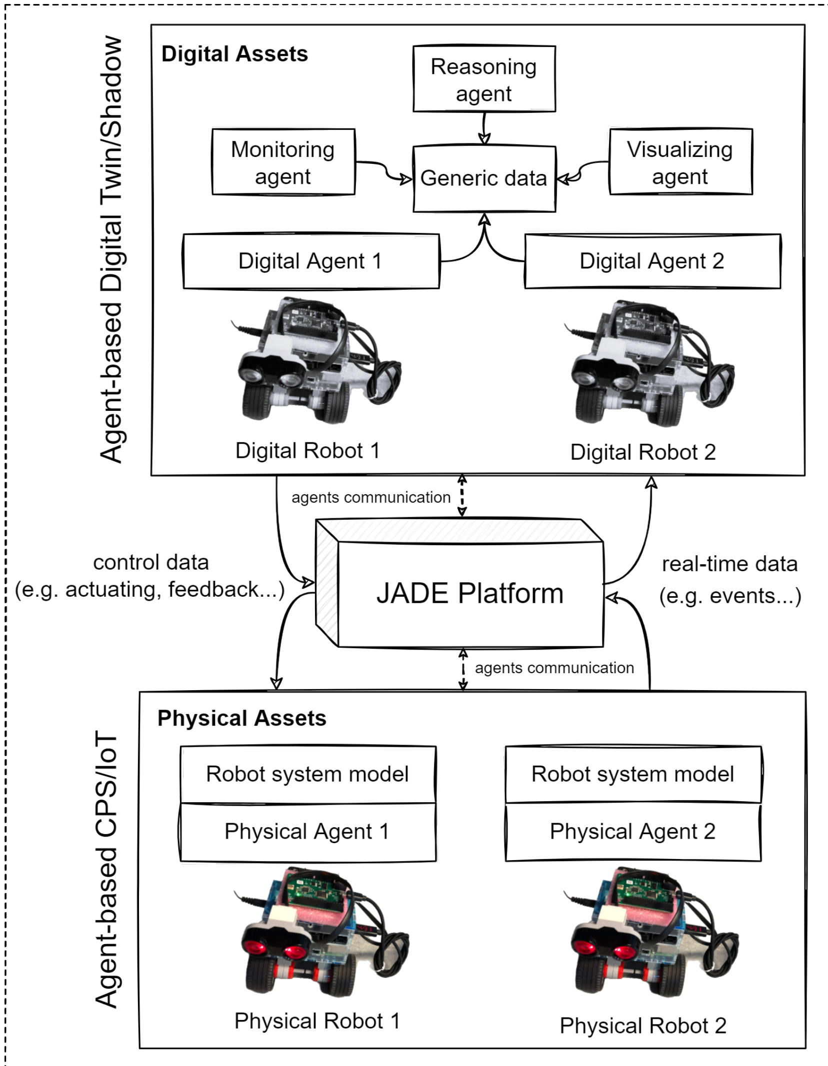

Fig. 5. Digital Twin implemented in JADE for the robot case study

the JADE by creating a new individual container which is the reason why we have two physical containers for the two robots.

In our conducted experiments, we have two running physical robots (physical agents) in the `Physical Assets` as well we have their counterparts (digital agents) in the `Digital Assets` of the Digital Twin. The two physical agents communicate with themselves if required or with their counterparts; digital agents or with other agents located the `Digital Assets` throughout the FIPA communication standard that provided the Digital Twin with a reliable communication mechanism. The physical layer and digital layer can operate in separate machines and have different IP addresses, or they can work in the same machine. Still, they should be executed in different containers, and one container should be the main, so the other containers can connect and then communicate with other agents inside the whole platform. Representing physical elements as agents and designing their digital representatives as agents in the JADE platform takes advantage of the tight coupling and the agent language communication standard used in JADE, and with this implementation we have managed to tackle 5th challenge mentioned in the table 1. In addition, the 3rd challenge has been addressed too, and by using agent communication language, we provided our implementation with real-time synchronization between physical and digital agents. Anyhow, achieving real-time requirements for time-critical systems may require adding more layers and special technologies to handle such needs specifically.

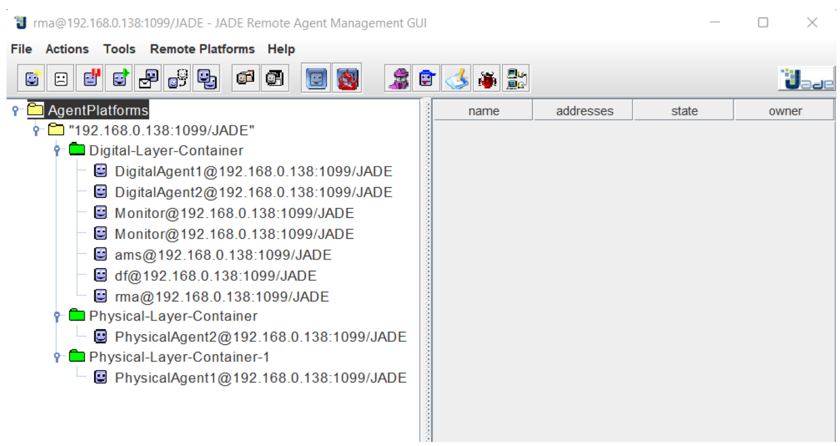

Fig. 6. JADE interface that contains agents of the Digital Twin

In the implementation of agents in the two Digital Twin layers, we designed and programmed the physical agents to control the robots in the physical assets while the digital agents organize and manage the tasks for the robots in the digital assets. For instance, if the robot encounters an obstacle, it responds autonomously and stops, and this is processed internally inside the physical agent. While if two robots are coming closer to each other, we have a higher level agent (coordinator) in the Digital Twin, which communicates with agents in the digital assets and oversees the whole picture and can predict a possible collision, and if there is a possible collision, it sends an alert message to the robots (physical agents) trough (digital agents) to stop and then give a priority according to the priority mechanism. In this phase of Digital Twin implementation, we have separated the concerns between physical and digital agents, and we provided agents with autonomous behavior, which makes them able to make self-decisions. Thus to a certain degree, we managed to tackle the 6th challenge mentioned in the table 1 and make Digital Twin more autonomous and intelligent to solve complex issues and interactions of CPS components in Digital Twin. To this end, and by considering and deploying all these requirements and features, we have made the agent-based Digital Twin for the factory warehouse more intelligent, safe, and autonomous.

6 Conclusion & Discussion

Digital Twin is a tight integration between physical and cyber parts. Realizing this integration imposes many issues and challenges. Besides, CPSs are naturally decentralized and distributed, and this increases the level of complexity while integrating them into Digital Twin. Several approaches and technologies have been proposed in the literature to tackle these challenges and build, create, deploy, and adjust Digital Twin for CPS systems. In this regard, In this regard, the lack of intelligence in many proposed methods and approaches limits the use of these approaches in very complex systems; thus, we need more intelligent and robust solutions. Consequently, in this study, we have proposed a new architecture for realizing a Digital Twin for CPS/IoT systems by leveraging the features, potentials, and intelligence offered by the Agent-based approach and the Multi-agent Systems and specifically using the JADE programming model and platform for programming agent-oriented Digital Twin for smart warehouse as a case study. We have managed to design and program agents in the physical assets (AGV robots) and their representatives in the digital assets as well.

The use of MAS provided our Digital Twin with a good level of intelligence and autonomy, where robots behave autonomously in certain situations. Also, by using the JADE platform, the communications between physical and digital agents in physical and digital assets respectively are organized, controlled, and managed adequately and smoothly. In addition, the use of MAS and exactly JADE platform could help us to extend and improve our current Digital Twin to be more resilient and robust by adding other agents such as reasoning, learning, monitoring, and simulation agents in the future work.

For example, we intend to extend this work and apply intelligent methods and algorithms such as fuzzy logic or Belief–desire–intention [29] software model (BDI) agent-based to reason about complex situations. This will enable the robot to make better decisions and deal with probable deviations to get more accurate results.

We also want to address the challenges of handling massive amount of data generated with high frequency from physical components in Digital Twin. This data is usually generated from sensors and other physical components during operation. Faults and defective readings, delays, or inaccuracies in data processing may cause undesirable results and damages. In our future works, we will provide the Digital Twin with dependable mechanisms to process and extract the information from the streams. [30].

Like most modeling approaches, there are pros and cons of implementing a Digital Twin with agents. For instance, most agent-based and multi-agent system programming languages and frameworks are not trivial to use and deploy. They need much effort, time, and programming skills to utilize. In this regard, research questions such as how to implement Digital Twin with these platforms faster with less time and effort could be achieved?. To tackle such issues, we are considering using model-driven engineering [31] concepts and techniques to add another layer of abstraction for our agent-based Digital Twin, which could simplify and speed up the process of building Digital Twin by having a multi-purpose model that can be altered and used for new Digital Twin implementations.

The use of MAS and agents offers an organized and well-structured approach that will enable us to implement and deploy more advanced agents to our proposed architecture incrementally and in a modular way.

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