IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 14 November 2023, accepted 1 December 2023, date of publication 5 December 2023,
date of current version 13 December 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3340132

RESEARCH ARTICLE

Distributed Digital Twins as Proxies-Unlocking Composability and Flexibility for Purpose-Oriented Digital Twins

ABDULLAH AZIZ, SHAILESH SINGH CHOUHAN, OLOV SCHELÉN, (Member, IEEE), AND ULF BODIN
Department of Computer Science, Electrical and Space Engineering, Luleå University of Technology, 971 87 Luleå, Sweden

Corresponding author: Abdullah Aziz (abdullah.aziz@ltu.se)

This work was supported in part by the projects Arrowhead flexible Production Value Network (fPVN) [EU Key Digital Technologies Joint Undertaking (KDT JU)] under Grant 101111977, in part by the Mine.io (Horizon Europe) under Grant 101091885, and in part by AIMS5.0 (EU KDT JU) under Grant 10111208.

ABSTRACT In the realm of the Industrial Internet of Things (IoT) and Industrial Cyber-Physical Systems (ICPS), Digital Twins (DTs) have revolutionized the management of physical entities. However, existing implementations often face constraints due to hardware-centric approaches and limited flexibility. This article introduces a transformative paradigm that harnesses the potential of distributed digital twins as proxies, enabling software-centricity and unlocking composability and flexibility for purpose-oriented digital twin development and deployment. The proposed microservices-based architecture, rooted in service-oriented architecture (SOA) and microservices principles, emphasizes reusability, modularity, and scalability. Leveraging the Lean Digital Twin Methodology and packaged business capabilities expedites digital twin creation and deployment, facilitating dynamic responses to evolving industrial demands. This architecture segments the industrial realm into physical and virtual spaces, where core components are responsible for digital twin management, deployment, and secure interactions. By abstracting and virtualizing physical entities into individual digital twins, this approach lays the groundwork for purpose-oriented composite digital twin creation. Our key contributions involve a comprehensive exposition of the architecture, a practical proof-of-concept (PoC) implementation, and the application of the architecture in a use-case scenario. Additionally, we provide an analysis, including a quantitative evaluation of the proxy aspect and a qualitative comparison with traditional approaches. This assessment emphasizes key properties such as reusability, modularity, abstraction, discoverability, and security, transcending the limitations of contemporary industrial systems and enabling agile, adaptable digital proxies to meet modern industrial demands.

INDEX TERMS OT virtualization, distributed digital twin as proxy, edge, cloud, composition, flexibility.

I. INTRODUCTION

The emergence of the Internet of Things (IoT) has introduced a new era of connectivity and data-driven decision-making across various domains [1], [2]. In this context, the Industrial IoT (IIoT) has surfaced as a transformative force, reshaping the landscape of industrial processes and systems [3], [4]. Central to this evolution is the concept of digital twins [5], a technology that has gained notable dominance in the context of IIoT. Digital twins represent the virtual counterparts of physical entities, offering an accurate depiction of their real-world counterparts, enabling real-time monitoring, analysis, and control [6].

As digital twin technology continues to evolve, it plays a pivotal role in the field of industrial cyber-physical systems (ICPSs) [7], bridging the gap between the physical and

The associate editor coordinating the review of this manuscript and approving it for publication was Stefano Scanzio.

digital worlds. Digital twins serve as dynamic, data-rich representations of physical entities, providing valuable insight and facilitating decision-making across industries such as manufacturing [8], [9], [10], [11], healthcare [12], [13], transportation [13], [14], IoT and CPS [15], [16], [17], [18], [19], [20], [21], and more [22], [23], [24], [25], [26], [27], [28].

Although the foundational role of digital twins in industries is evident, advancements in this technology have paved the way for even more intricate systems. This paper sets the stage for our exploration of the concept of distributed digital twins as proxies and their role in unlocking composability and flexibility for the development and deployment of purpose-oriented composable digital twins.

Despite the promises of IoT and digital twins, their complexities are deeply embedded in the history of industrial evolution, and as such, several challenges persist in the industrial domain [29], [30], [31]. Traditionally, industrial systems have been hardware-centric, characterized by isolated, vendor-specific, and purpose-built solutions [32]. These systems often suffer from vendor lock-in, limited interoperability, and high development costs [33].

The convergence of Information Technology (IT) and Operational Technology (OT) not only brings challenges of integration but also requires a shift to a new paradigm from hardware-centric to software-centric solutions. Hence, introducing new functionalities or adapting to changing industries involves extensive investigations into hardware entities, interfaces, protocols, and integration mechanisms, making the process time-consuming and resource-intensive [34], [35]. This underscores the constant change in the industrial domain, where adaptation and innovation are imperative.

In the context of enabling a significant shift from hardware-centric to software-centric industrial systems, the concept of virtualization functions as a key catalyst [36]. Just as virtualization has revolutionized IT [37], with the widespread use of virtual machines (VMs) and containers, it plays a transformative role in the OT landscape. Virtualization in OT facilitates the abstraction of physical entities into digital counterparts, allowing for standardized communication, interoperability, and the seamless integration of devices, even when they may not be inherently IP-ready. This approach aligns perfectly with our software-centric philosophy, where distributed digital twins, acting as proxies, bridge the gap between the physical and virtual spaces at the edge [38], [39], [40], unlocking composability and flexibility in industrial systems.

Thus, the scope of our work focuses on addressing challenges in existing industrial systems. These challenges largely result from the limitations of hardware-centric approaches. Hence, by advocating for a shift from hardware-centric to software-centric solutions empowered by digital twins, we explore how digital twins, acting as proxies, can serve as modular software representations of physical entities. This facilitates the development of flexible and composable digital twins for evolving industrial needs. By doing so, we aim to harmonize the IT and OT domains, fostering interoperability, flexibility, and composability in industrial systems. This shift not only addresses current challenges but also holds the promise of more agile, adaptable, and cost-effective industrial systems [35].

Our solution is built on the foundation of the fundamental properties of a digitalized environment: reusability, modularity, loose coupling, adaptability, dynamism, autonomy, discoverability, abstraction, scalability, openness, and development cost [41], [42]. These properties not only drive the design and development of advanced digital systems but also collectively form the backbone of a composable and flexible architecture [43]. To attain this objective, we adopt the principles of Service-Oriented Architecture (SOA) [44], [45] and microservices [46], [47], which are renowned for their modular and scalable nature. Additionally, we employ the Lean Digital Twin Methodology (LDTM) to create and develop distributed digital twins efficiently [48]. To expedite the process, we employ the Packaged Business Capability (PBC) approach [49] to rapidly construct and deploy digital twins as proxies.

In this article, our innovations and contributions are as follows:

- We propose an architecture that incorporates the principles of composability and flexibility. It effectively categorizes the industrial space into two domains: a physical space (PS) and a virtual space (VS). The architecture allows for the development and deployment of purpose-oriented digital twins, utilizing distributed digital twins as proxies.
- Our Proof of Concept (PoC) implementation showcases the practical realization of the proposed architecture. It features VS core components such as the Digital Twin Registry (DTR), Orchestrator, Authenticator, and Digital Twin Image Repository (DTIR), along with a PBC application template for the creation and deployment of digital twins as proxies.
- We exemplify our proposed architecture through a practical use-case scenario, showcasing its application in achieving purpose-oriented digital twin development and deployment.
- To conclude, we provide both quantitative and qualitative analysis, showcasing the potential benefits of our approach in addressing both contemporary and future industrial challenges.

Each of these contributions represents a stepping stone towards harnessing the capabilities of distributed digital twins as proxies and furthering the domain of composable digital twins. Drawing from these contributions, our work presents a solution to the challenges facing modern industrial systems, empowering them to transition from hardware-centric to software-centric adaptability. In doing so, we offer a plan for how purpose-oriented digital twins can be designed and applied to effectively address the demands of a constantly changing industrial landscape.

The article is organized as follows: Section II provides a summary of related research efforts on digital twin architectures. Next, Section III presents the conceptual model for the demarcation of industrial space and types of digital twins. Building on this groundwork, Section IV introduces the proposed distributed digital twin architecture and its key components. To demonstrate feasibility, Section V details a proof-of-concept implementation. The architecture's utility is then showcased through a practical use-case scenario in Section VI. Finally, Section VII provides both quantitative and qualitative analysis to evaluate the architecture and its benefits.

II. RELATED WORK

In the discipline of distributed digital twins, several research endeavors have explored diverse architectural models and applications. In this section, we summarize related work in the context of our proposed architecture.

The work [50] focuses on utilizing Industrial Internet of Things (IIoT) technologies to design a digital twin architecture. It emphasizes the importance of IIoT for sensing and actuating in physical processes and proposes the use of the OPC UA communication protocol for data exchange. While this work addresses IIoT integration, it does not delve into the composability and flexibility aspects that our architecture emphasizes.

Another significant contribution [51], introduces the concept of Edge Digital Twins and highlights a flexible and modular architecture. This architecture extends the role of digital twins to support last-mile digitalization and interoperability. While it addresses modularity and flexibility, our proposed architecture specifically targets purpose-oriented digital twins.

The architecture [52] aims to enable collaborative digital ecosystems through composite digital twins. It focuses on addressing challenges related to trust, interoperability, and security in collaborative environments. Our work also supports composable digital twins but emphasizes purpose-oriented development and deployment.

Open-source approaches have also been explored for the design and implementation of digital twins in smart manufacturing [8]. By providing flexible, open-source solutions, researchers aim to overcome the limitations associated with closed systems. These initiatives encourage a more open and adaptable approach to digital twin development in smart manufacturing contexts.

Furthermore, the advent of cloud-based Cyber-Physical Systems (CPS) has led to the development of the C2PS digital twin architecture reference model [19]. C2PS demonstrates its versatility through the generation of complex system-of-systems and practical applications, such as vehicular domain assistance.

The concept of Digital Twin as a Proxy (DTaaP) has been proposed to address challenges in industrial cyber-physical systems (ICPSs) [53]. By implementing a four-layer architectural model, DTaaP aims to enhance energy efficiency, security capabilities, and device availability. The integration of Eclipse Ditto as an open-source digital twin framework showcases the potential of DTaaP in improving ICPSs.

Moreover, empowering existing frameworks with digital twin capabilities is also a recognized trend. For instance, the Eclipse Arrowhead Framework (EAF) [54] has been augmented with DTaaP, aiming to enhance energy efficiency, service availability, and security capabilities for industrial automation [55].

The Digital Twin as a Service framework introduced in [56], offers a platform for creating and using digital twins efficiently. While it streamlines digital twin operations, our architecture extends beyond this, concentrating on the composability and flexibility of digital twins for various purposes by enabling software-centricity.

The importance of achieving interoperability among digital twins is addressed in [57], where a flexible transformation system is proposed. This system enables file- and API-based information exchange among digital twins, offering a bidirectional approach. The customization of transformation systems enhances interoperability and supports advanced IIoT use cases [57].

A generic digital twin architecture for industrial energy systems, known as the Generic Digital Twin Architecture [24], has been developed to align with industry standards such as the Reference Architecture Model Industry 4.0 (RAMI4.0) [58]. This technology-independent architecture demonstrates its relevance to the purpose-oriented deployment of distributed digital twins [24].

The OpenDT framework introduces a novel approach to service publication and discovery using remote programmable digital twins [59]. This framework, designed to support entity publication and discovery, allows users to create mashups and applications using digital twin services.

The IoTwins project, discussed in [60] and [11], aims to develop hybrid digital twins for manufacturers, primarily focusing on predictive maintenance. By integrating data from various sources and creating virtual representations of physical products and processes, manufacturers can benefit from advanced maintenance capabilities.

In summary, while the aforementioned research contributions are significant in the field of digital twins, our proposed architecture distinguishes itself by placing particular importance on the concepts of composability, flexibility, and purpose-driven development and deployment

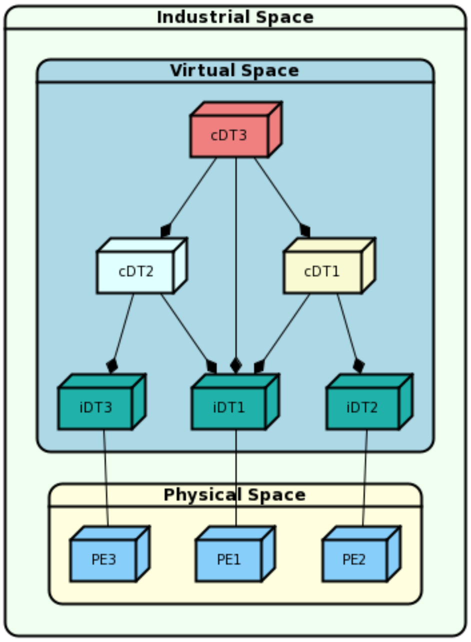


FIGURE 1. Concept model of digital twins within industrial space.

of digital twins facilitated through distributed digital twins as proxies.

III. CONCEPTUAL MODEL

This section aims to elucidate our interpretation and perception of foundational constructs, establishing a coherent basis for the subsequent articulation of the proposed architecture's core tenets. The conceptual model can be seen in Fig. 1.

A. INDUSTRIAL SPACE DEMARCATION

A distinguishing facet lies in the demarcation of the industrial space into two realms: the Physical Space (PS) and the Virtual Space (VS). This division serves as a fundamental cornerstone for facilitating the seamless integration of physical and digital elements within the industrial landscape. The following key attributes highlight the essential characteristics of each space:

- **Physical Space (PS):**
  - Comprises tangible entities, including physical devices, machinery, and equipment.
  - Serves as the foundational layer for the integration of hardware components within the industrial ecosystem.
  - Represents the physical manifestations of the operational characteristics and functionality of industrial infrastructure.
- **Virtual Space (VS):**
  - Encompasses digital counterparts of physical entities, operational models, and computational frameworks.
  - Provides a digital emulation of the industrial landscape, facilitating digital representations of physical elements.
  - Serves as the medium for deploying digital twins, enabling virtualized representations of physical entities and processes.

This clear demarcation of the industrial space into distinct physical and virtual realms lays the groundwork for the subsequent delineation of types of digital twins and their dynamic interplay within our proposed architecture.

B. DIGITAL TWIN

The concept of the digital twin (DT) has garnered significant attention in industrial applications, representing the virtual counterpart of physical entities. While the literature presents various conceptions of digital twins, our work categorizes them into two distinct types: Individual Digital Twin (iDT) and Composite Digital Twin (cDT).

- **Individual Digital Twins (iDT):** These DTs are tailored for one-to-one mappings of singular physical entities into their corresponding digital counterparts. By capturing the essence of individual physical entities, iDTs form the foundation for establishing a software-centric industrial landscape.
- **Composite Digital Twins (cDTs):** In contrast, cDTs emerge from the composition of multiple iDTs. These cDTs employ a many-to-many (N:N) mapping strategy, uniting several iDTs to create a comprehensive and multifaceted digital representation. They serve specific purpose-oriented solutions, symbolizing the collaboration of diverse industrial elements. For example, a cDT might represent an entire manufacturing line by combining the iDTs of its constituent machines, sensors, and control systems.

The division of DTs into iDTs and cDTs offers several advantages within our proposed work. This division enables a fine-grained and dedicated representation of individual physical entities, which is essential for realizing software-centric solutions. At the same time, the capability to compose these iDTs into cDTs enhances flexibility, reusability, and adaptability, thereby facilitating the development of versatile, purpose-oriented digital twins.

C. COMPOSABILITY & FLEXIBILITY

In the context of our proposed architecture, achieving composability and flexibility stands as a crucial objective, essential for adapting to the dynamic and evolving demands of the industrial landscape. Composability refers to the ability to seamlessly integrate and combine different components, allowing for the creation of multifaceted solutions from modular parts. Flexibility, on the other hand, signifies the capability to adapt and respond to changing requirements efficiently.

The utilization of service-oriented architecture (SOA) and microservices plays a pivotal role in facilitating composability and flexibility by enabling the construction of complex systems from discrete, independent services. SOA emphasizes the creation of loosely coupled, interoperable services that can be easily integrated to fulfill diverse industrial requirements. Microservices further reinforce this approach by advocating the development of small, independently deployable services that collaborate to deliver complex functionalities.

Composability and flexibility offer several key benefits, particularly in the context of software-centricity. They promote modularity, scalability, and agility, ensuring that the architecture remains adaptable to changes in the industrial environment and technology landscape. They also foster a high degree of autonomy and interoperability among digital components, facilitating seamless communication and data exchange, ultimately leading to enhanced software-centric solutions for industries.

IV. PROPOSED ARCHITECTURE

The proposed architecture is a strategic initiative geared toward unlocking the inherent potential of composability and flexibility for purpose-oriented digital twins. Building upon the conceptual groundwork established in Section III, which defines the industrial space and characterizes digital twin types, the architecture signifies a crucial advancement in the realization of a dynamic and adaptable industrial system. Fig. 2 provides an illustrative depiction of the key components and their interconnections within the proposed architecture, emphasizing the indispensable role of Individual Digital Twins (iDTs) as proxies, anchoring the transformation of software-centric industrial systems.

In this architecture, the industrial space is divided into two primary segments: the Physical Space (PS) and the Virtual Space (VS). The PS consists of physical entities (PEs), while the VS is the digital environment where digital twins reside. The interface between them is facilitated by Industrial Communication Gateways (ICGs), capable of handling various industrial protocols (e.g., OPC-UA, Modbus, and MQTT). These ICGs ensure uninterrupted and secure data exchange between the PEs in the PS and their corresponding digital twins in the VS, emphasizing the architecture's commitment to seamless integration and data interoperability across both segments.

A. VIRTUAL SPACE CORE COMPONENTS

Within the Virtual Space (VS), a suite of core components is instrumental in orchestrating the seamless amalgamation and oversight of digital twins (DTs) and associated services. Grounded in the tenets of SOA and microservices, these components provide a flexible system, catering to the sophisticated needs of modern industrial environments.

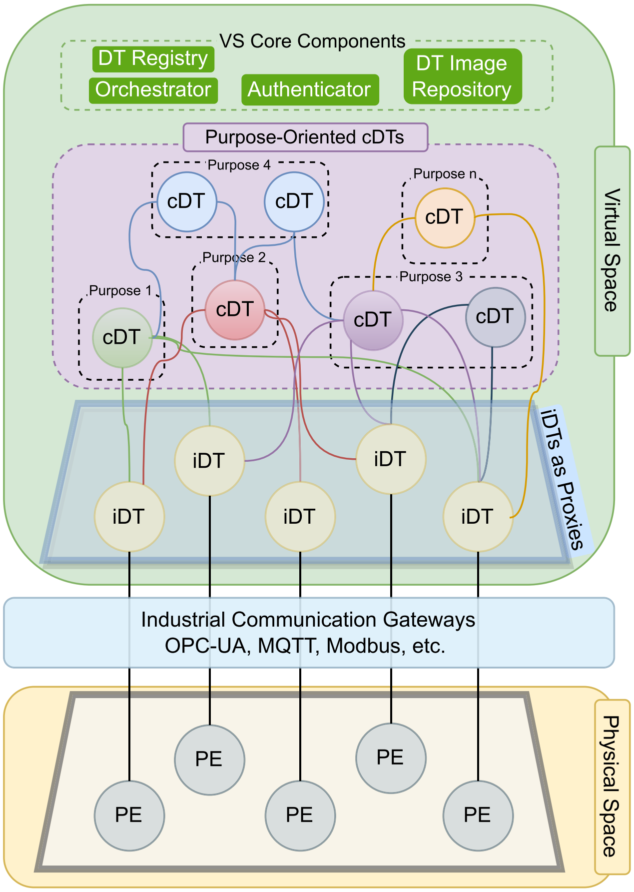


FIGURE 2. Illustrative representation of the proposed architecture.

1) DIGITAL TWIN REGISTRY (DTR)

The Digital Twin Registry (DTR) serves as a repository, facilitating the efficient cataloging and discovery of digital twins and their corresponding services within the architecture. It adheres to the principles of SOA, fostering loose couplings between digital twins and services, thereby promoting the composability of purpose-driven digital twins. The DTR extends the service registry concept in SOA by not only managing service endpoints but also encapsulating detailed digital twin information, facilitating efficient discovery and management in the VS.

2) AUTHENTICATOR

The role of the Authenticator within the architecture is paramount, ensuring robust authorization and authentication strategies for secure communication within the VS. In the realm of Microservices security, it surpasses basic authentication functions by securing interactions not only at the service level but also by ensuring authenticated & authorized access to digital twins, enhancing overall system security. This component aligns with the overarching goal of maintaining the stability and security of the VS, thereby fortifying the

TABLE 1. Summary of virtual space core components.

Component	Responsibilities	Benefits
Digital Twin Registry (DTR)	Cataloging and discovery of digital twins and associated services.	Streamlined access, management, and composability of purpose-driven digital twins.
Authenticator	Ensuring robust authorization and authentication strategies for secure communication.	Enhanced security and stability within the Virtual Space, safeguarding against potential threats and unauthorized access.
Digital Twin Image Repository (DTIR)	Management of microservices throughout the digital twin lifecycle.	Flexible versioning and access rights, promoting modularity and efficient management of digital twin functionalities.
Orchestrator	Coordination and oversight of microservices and digital twin components.	Streamlined deployment, automation, and scalability, fostering efficient communication and collaboration among digital components.

industrial ecosystem against potential security threats and unauthorized access.

3) DIGITAL TWIN IMAGE REPOSITORY (DTIR)

The Digital Twin Image Repository serves as a comprehensive management system, housing and supervising the lifecycle of microservices associated with digital twins. Unlike conventional microservices repositories, the Digital Twin Image Repository stores more than just service artifacts; it manages digital twin representations, enabling efficient versioning, retrieval, and deployment of digital twin instances, contributing to the flexibility and agility of the architecture. It fosters a structured approach to digital twin functionality, emphasizing modularity and management of these essential components.

4) ORCHESTRATOR

The Orchestrator in the proposed architecture functions as the central manager responsible for the deployment and management of microservices. Its role aligns closely with the principles of SOA and microservices, contributing to the overall software-centricity. By orchestrating the deployment of distributed digital twins as microservices, the architecture achieves a high degree of composability and flexibility, allowing individual components to be combined and reconfigured to fulfill specific industrial purposes.

Table 1 summarizes the key responsibilities and benefits of the core components within the VS, highlighting their pivotal roles in enabling the architecture's flexibility and robustness within the industrial landscape.

B. iDTS AS PROXIES

The key role that iDTs serve as proxies within the proposed architecture is essential for facilitating the transition from hardware-centricity to software-centricity, achieving a fundamental abstraction of physical entities within the virtual space (VS). Embracing the principles of virtualization and abstraction, iDTs establish a secure and adaptable interface that translates the complexities of physical entities into well-structured digital counterparts. It's important to note that there exists a one-to-one mapping between a specific iDT and its corresponding PE, ensuring a precise and tailored representation. The nature of this linkage can fluctuate, with some being unidirectional, while others require bidirectional communication, depending on the specific requirements of the PE being mapped as an iDT. We can define this association, $a(iDT, PE)$, as:

$$a(PE, iDT) = \begin{cases} PE \rightarrow iDT & \text{if unidirectional} \\ PE \leftrightarrow iDT & \text{if bidirectional} \end{cases} \tag{1}$$

Functioning as reusable and encapsulated microservices, iDTs promote a modular approach to the architecture, emphasizing their agility and adaptability in addressing specific industrial demands while laying the groundwork for the seamless composition of higher-level purpose-oriented digital twins, highlighting the importance of composability and flexibility. As integral components of the Virtual Space, iDTs serve as the nucleus, driving the architecture's software-centric ethos and enabling the efficient management and integration of digital twins for diverse industrial applications.

C. PURPOSE-ORIENTED cDTS

Within the proposed architecture, Purpose-Oriented Composite Digital Twins (cDTs) serve as the cornerstone for addressing industrial challenges, requirements, and objectives with precision and agility. The development of purpose-oriented cDTs is rooted in the seamless composition of a collection of iDTs, strategically integrated to create comprehensive digital representations tailored for industrial purposes. Formally, when confronted with a particular purpose denoted as (P), our cDT tailored for that purpose, referred to as cDT_P, is thoughtfully a composition ($\bigoplus$) of a collection of $iDTs$:

$$cDT_P = \bigoplus_{j=1}^{n} iDT_j \tag{2}$$

Operating as microservices, purpose-oriented cDTs provide high-level services by leveraging the composition of iDTs, effectively combining their functionalities to cater to complex industrial scenarios. The integration of iDTs into purpose-oriented cDTs, emphasizes the modularity and reusability of digital components within the architecture. By employing this, the architecture enables the seamless orchestration and deployment of purpose-oriented digital twins, ensuring a streamlined and efficient approach to addressing diverse industrial objectives and challenges.

V. PROOF-OF-CONCEPT IMPLEMENTATION

The Proof of Concept (PoC) of the proposed architecture represents the practical manifestation of our architectural vision, aligning with the core principles of service-oriented architecture (SOA) and microservices. In this section, we detail the implementation methodologies, VS core components development, and digital twin instantiation within the VS. Notably, it is essential to emphasize that our PoC focuses exclusively on the VS, while the Physical Space remains beyond the scope of this work. For the simplicity of our PoC, we chose MQTT as the industrial communication gateway (ICG) to establish communication between PE and DT as it is an efficient data integration choice in industries [61].

A. IMPLEMENTATION METHODOLOGY

The successful execution of the PoC necessitated the adoption of specific implementation methodologies, ensuring the effective development and deployment of the architecture's key components within the VS. Leveraging the distinctive nature of the PoC, we combined two essential methodologies to guide the development process: the Lean Startup Methodology (LSM) [62], [63], [64], [65] for VS core components and the Lean Digital Twin Methodology (LDTM) [48] for digital twin development. These methodologies provided a structured framework for efficient and iterative development, enabling us to harness the full potential of the proposed architecture.

In particular, the LSM guided the custom development of the VS core components, emphasizing rapid prototyping and an agile approach. This streamlined development expedited the process and maintained a sharp focus on necessary functionalities, ensuring their seamless integration.

Concurrently, the implementation of iDTs as proxies and purpose-oriented cDTs relied on the application of the modified LDTM. This methodology, visually represented in Fig. 3, is adapted from LSM and integrates the principles of the facets described earlier. The methodology involves the following formalized steps:

1) **Define Purpose:** Each digital twin, represented as DT_i, has a purpose, p_i. Let P represent the set of all such purposes such that $p_i \in P$. We begin by clearly identifying the purpose of the digital twin, and aligning it with specific use cases and objectives.
2) **Identify Solution and Technologies:** For each digital twin DT_i, there's a chosen subset of technologies T_i from a set T of all available technologies. Next, we prioritize existing solutions, but when necessary, create custom ones tailored to the unique requirements of each digital twin.

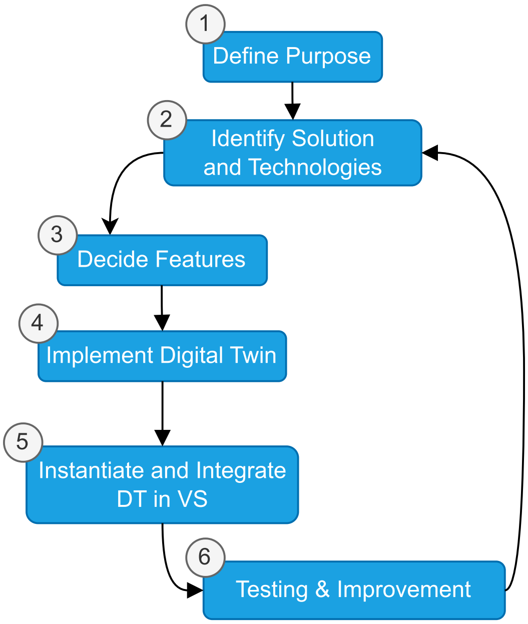


FIGURE 3. Modified lean digital twin methodology.

3) **Decide Features:** Each digital twin DT_i encompasses a specific set of features F_i. Let F be the set of all possible features, making $F_i \subseteq F$. At this stage, we decide on the essential features that the digital twin will need to fulfill its defined purpose.
4) **Implement Digital Twin:** This involves an implementation function $I(DT_i, T_i, F_i)$, which operationalizes the digital twin using the chosen technologies T_i and features F_i.
5) **Instantiate and Integrate DT in VS:** Once instantiated, each digital twin DT_i becomes an integral part of the Virtual Space VS, leading to $VS = VS \cup DT_i$. This ensures that the digital twin can seamlessly interact with other components and digital twins, reinforcing the principles of the proxy.
6) **Testing and Improvement:** This step involves a feedback loop. Let $R(DT_i)$ be a function that checks if the digital twin DT_i meets all set requirements. As long as $R(DT_i) \neq \emptyset$, improvements are continuously made to DT_i to ensure alignment with necessary architectural requirements.

In line with our core idea of promoting software-centricity through the concept of proxies, the LDTM provides a structured approach for developing and deploying iDTs as proxies for specific PEs. Instead of creating a single iDT as a proxy, we adopted the concept of Packaged Business Capability (PBC), where we conceptualize the iDT as a PBC for Proxies (PBC-iDT). This approach enables the efficient reuse and deployment of PBC-iDTs for various devices, customizes development costs, and aligns with a standardized yet adaptable development process

TABLE 2. Summary of implementation methodologies.

Methodology	Applied for	Reason for Selection
LSM	VS Core Components	Agile development, responsiveness to evolving requirements.
LDTM	Digital Twin Creation	Adopted for the systematic creation and deployment of digital twins, promoting modularity, reusability, and scalability.
PBC	iDT as Proxy	Streamlined iDT development and enhanced flexibility for iDTs creation.

Moreover, for the development of purpose-oriented cDTs, the LDTM offered a framework for the development. By following the defined steps of the LDTM, we ensured the systematic and purpose-driven development of each cDT. This strategic alignment with the LDTM fostered a holistic development approach, reflecting our commitment to delivering purpose-driven and adaptable digital twins within the proposed architecture.

B. IMPLEMENTING VS CORE COMPONENTS

The choice of implementing the core components of VS was guided by the principle of selecting the most suitable technology for each part according to the specific requirements. In doing so, we were able to utilize existing open-source solutions where applicable, thereby improving development efforts and fostering an environment of reusability and modularity. The implementation scheme for VS core components is shown in Fig. 4

For the VS core components, our requirements dictated different approaches. The Orchestrator and DTIR, integral to the setup process, were identified as components that would benefit from the use of containerization technologies. In this regard, we employed Docker technologies, including Docker Compose, and established a local Docker repository. These choices align with the architecture's emphasis on microservices, composability, and flexibility. Docker technologies provided the means to create portable, containerized instances of the orchestrator and DTIR, facilitating their deployment and ensuring compatibility with a diverse range of environments.

In contrast, the development of the Digital Twin Registry (DTR) and the Authenticator, which are actively used during runtime, warranted a tailored approach. Node.js was chosen as the development platform for these components, primarily due to its lightweight and efficient nature, perfectly aligning with the architecture's emphasis on composability and flexibility. The REST API endpoints provided by DTR are documented in Table 3, offering the foundation for managing digital twins and services efficiently. The development of a custom Authenticator, on the other hand, was focused on delivering authorization and authentication strategies to ensure secure communication within the VS.

Table 4 outlines the implementation approach for each VS core component, along with the rationale and benefits guiding the choice of each method.

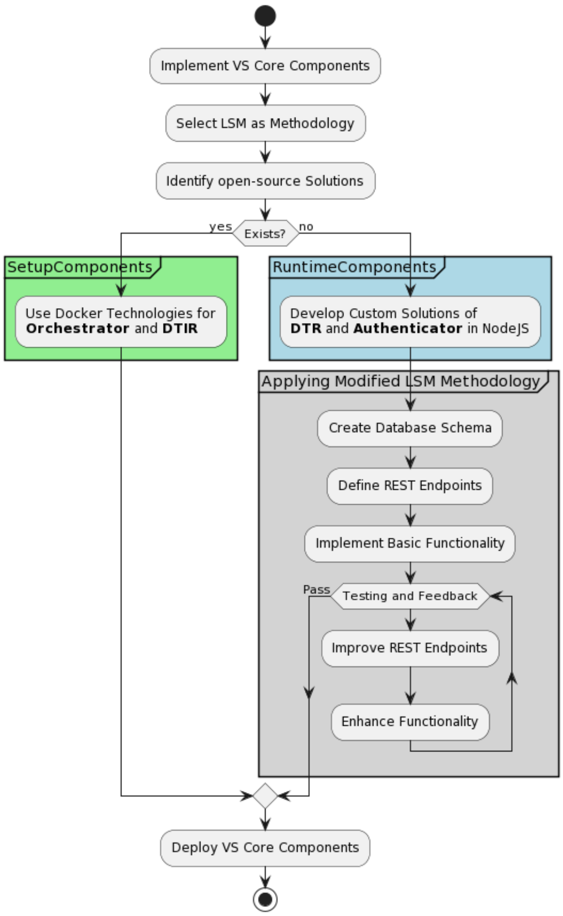


FIGURE 4. Implementation scheme for vs core components.

TABLE 3. DTR RESTful APIs.

API Endpoint	Description
POST /register	Registers a new digital twin instance.
GET /discover	Discovers all registered digital twin instances.
GET /discover/:dtId	Discovers a specific digital twin instance by ID.
GET /services/:dtId	Retrieves services provided by a specific digital twin.
PUT /update/:dtId	Updates the metadata and attributes of a digital twin.
DELETE /unregister/:dtId	Unregisters a digital twin instance.

TABLE 4. Summary of vs core components implementation, a = During run-time, b = During setup.

VS Core Component	Implementation Approach	Rationale for Approach	Existing Alternatives
Digital Twin Registry (DTR)^a	Custom Node.js Application	Tailored functionality and integration.	IoT platforms, Registries such as Consul [69]
Authentication^a	Custom Node.js Middleware	Simplified authorization and authentication strategies ensuring secure communication within the Virtual Space.	Third-party identity providers e.g., OpenID, oAuth 2.0
Orchestrator^b	Docker Compose	Portability, containerization, and compatibility with diverse environments, in line with SOA/microservices principles.	Kubernetes, Docker Swarm
DT Image Repository (DTIR)^b	Docker Local Registry	Facilitating deployment and management of DT images, aligning with the architecture's modularity and flexibility.	Docker Hub, Container registries

C. IMPLEMENTING PBC-iDT FOR PROXIES

In alignment with our emphasis on enabling software-centricity and fostering composability for higher-level, purpose-oriented cDTs, the implementation of iDTs as proxies plays a key role within the VS. The core rationale behind developing the Packaged Business Capability for iDTs (PBC-iDT) is to standardize the abstraction of diverse physical entities into the digital realm, ensuring a uniform representation in line with our software-centric approach. The adoption of PBC-iDT streamlines the process of developing and deploying iDTs while promoting consistency and reusability, facilitating efficient composability for creating purpose-oriented cDTs.

This PBC-iDT, developed using Node.js, serves as a crucial intermediary within the architecture. Operating based on a JSON model representing a Physical Entity (PE), the PBC-iDT module leverages this model to instantiate and seamlessly integrate the specific iDT within the VS. To ensure a cohesive and standardized approach to representing diverse PEs, we opted to standardize the structure of the JSON model, encapsulating essential attributes, properties, services, and required configurations. The JSON model of any PE should adhere to the format shown in the List. 1.

```
{
   "dtname": "DigitalTwinName",
   "dtid": "DigitalTwinId",
   "peid": "PhysicalEntityID"
   "attributes":{
       "owner" : "OwnerName",
       "version": 1.0,
       ...
   },
   "sensedProperties" :  ["AllSensingProperties", ... ],
   "controlCommands": ["AllControlCommands", ... ],
   "connectivity": {
       "host" : "localhost",
       "topic" : "someTopic",
       ...
   }
}
```

LIST. 1: JSON model of physical entity.

The description of the model is as follows:

- **dtname:** The name of the digital twin.
- **dtid:** A unique identifier for the digital twin.
- **peid:** A unique identifier for the associated *pe*.
- **attributes:** A dictionary of attributes, such as ownership, versioning, etc.
- **sensedProperties:** An array of sensing properties associated with the *pe*.
- **controlCommands:** An arraye of control commands for the *pe*.
- **connectivity:** Details for establishing connectivity, such as the host and topic.

The implementation of PBC-iDT lies at the heart of our strategy to enable software-centricity within the VS. Designed as a dynamic bridge between the PEs and their digital counterparts, the PBC-iDT functions as a comprehensive microservice. Its implementation is grounded in a detailed pseudo algorithm that systematically executes various functions, as described in Algorithm 1.

Algorithm 1 Pseudo Algorithm of PBC-iDT

```
Require: PE model as jsonModel
Ensure: iDT as Proxy of this PE is instantiated and
        integrated into the VS
 1: dtBaseModel ← Parse(jsonModel)
 2: sensedProperties ← dtBaseModel.sensedProperties
 3: controlCommands ← dtBaseModel.controlCommands
 4: connectionDetails ← dtBaseModel.connectivity
 5: mqttConnection ← ConnectMQTT(connectionDetails)
 6: for property in sensedProperties do
 7:     CreateDatabaseCollection(property)
 8: for property in sensedProperties do
 9:     CreateRestEndpoints(property)
10: for command in controlCommands do
11:     CreateRestEndpoints(command)
12: dtInstanceModel ← getDTInstanceModel()
13: RegisterDTinVS(dtInstanceModel)  ▷ Registering DT to
        Digital Twin Registry
14: StartListening()                 ▷ Listening for Requests
```

Initially, the provided *PE* model in JSON format undergoes parsing, transforming it into a structured data model, *dtBaseModel* (line 1). From this base model,

TABLE 5. Iterative improvements to PBC-iDT.

Iteration	Description of Improvements
1	- Initial implementation of PBC-iDT based on the decided PE JSON model. - Error handling for parsing and connectivity. - Integration of iDT into the VS.
2	- Integration of additional attributes of PE. - Enhanced JSON model parsing for improved data extraction.
3	- Authorized access for REST endpoints. - Fine-tuned database interactions. - Integration of iDT with VS.
4	- Extended JSON model to accommodate new PE attributes. - Authorized access improvements. - Integration with advanced VS functionalities.

essential elements such as sensed properties, control commands, and connection details are extracted (lines 2-4). Using the *connectionDetails*, an MQTT connection is established (line 5). To ensure efficient storage and retrieval of real-time data, a database collection for each sensed property is created, as shown in the loop in line 6. The purpose of the subsequent loops (lines 8 and 10) is to facilitate external accessibility and control. Specifically, line 8 focuses on creating RESTful endpoints for each sensed property, while line 10 does the same for each control command. Moving on from the base model, the *dtInstanceModel* is derived by augmenting the *dtBaseModel* with all the REST endpoints corresponding to its services (line 12). This enhanced model is pivotal as the *iDT* is then registered in the DTR, integrating it into the VS (line 13). In the final step, the *iDT* commences its listening mode (line 14), positioning itself to supply real-time data and action control commands upon the *PE*.

Designed in line with the LDTM, the PBC-iDT has undergone four cycles of iterative refinement to ensure its alignment with the broader architectural purpose. Such iterative refinement is crucial to keep pace with evolving requirements and to guarantee its robustness and adaptability. These four cycles of improvement are summarized in Table 5.

Although this PoC provides detailed insight into the creation of digital twins for the proxy purpose through the implementation of the PBC-iDT, the comprehensive implementation scheme for both iDTs as proxies and other cDTs, designed for diverse industrial purposes, can be found in Fig. 5.

This strategic approach not only streamlines the deployment of iDTs but also amplifies the architecture's agility and adaptability, emphasizing the transformative potential for software-centricity. Through the PBC-iDT implementation, we lay the groundwork for purpose-driven compositions and the seamless integration of diverse industrial elements, establishing a foundation for the development of purpose-oriented cDTs.

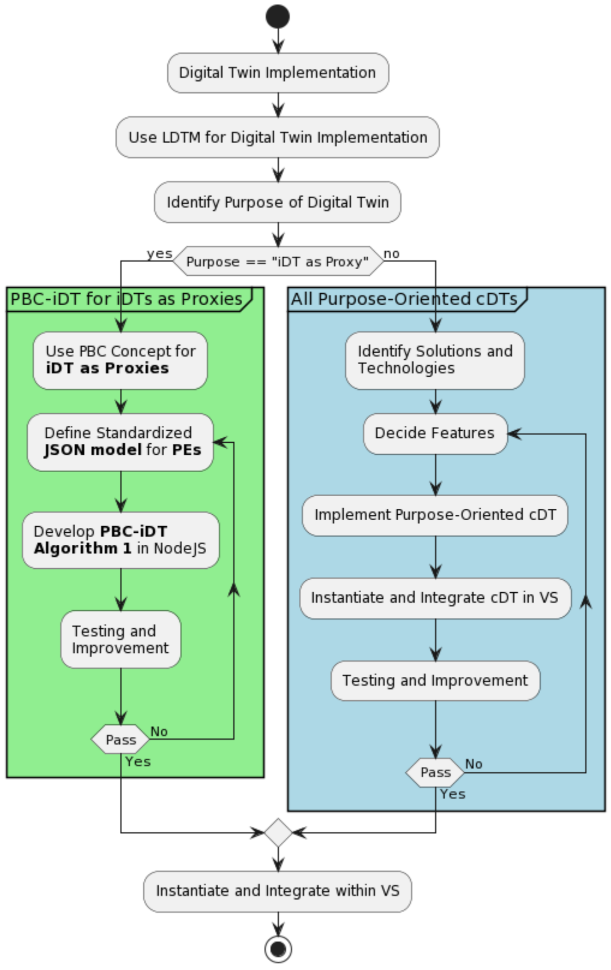


FIGURE 5. Implementation scheme for digital twins.

VI. USE-CASE SCENARIO: DYNAMIC SORTING OF PACKAGES

In this section, we delve into a use-case scenario that illustrates the practical application and advantages of our proposed architecture for composable purpose-oriented digital twins. This scenario centers on the dynamic sorting of packages on a conveyor belt within an industrial setting. This scenario is instrumental in showcasing the ability of the proposed architecture to foster software-centricity within industrial operations, thereby facilitating the development of purpose-specific digital twins. It embodies the central theme of the paper: enabling the creation of purpose-oriented cDTs through the implementation of distributed iDTs as proxies. We designed this use case to elucidate the pivotal concepts of composability and flexibility, core to the functionality of our architecture.

In a typical industrial operation, packages of diverse colors and dimensions traverse a conveyor belt. These packages need to be efficiently sorted and stored based on their material composition. Conventionally, this involves a robotic

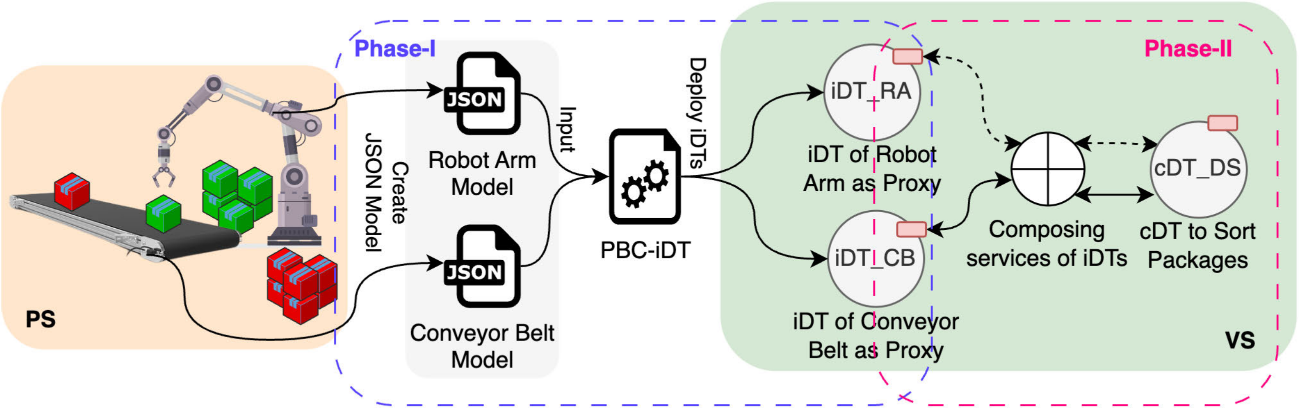


FIGURE 6. Dynamic sorting use case scenario.

arm picking and placing packages into stockpiles. Our chosen scenario setup, illustrated in Fig. 6, emphasizes the complexity of this task. It categorizes packages into two distinct groups: metallic (marked as "red") and non-metallic (marked as "green"). The primary objective is to optimize the operation of the conveyor belt and the robotic arm to ensure efficient sorting. The scenario can be summarized as follows:

- Metallic objects (marked as "red") are picked and placed into the "left" stockpile.
- Non-metallic objects (marked as "green") are picked and placed into the "right" stockpile.

Our proposed architecture facilitates the realization of this dynamic sorting scenario through a two-phase process, grounded in the principles of software-centricity, composability, and flexibility.

In the initial phase, we contemplate a situation where iDTs for the robotic arm and the conveyor belt may not yet exist in DTIR and need to be created. This creation and deployment process leverages the PBC-iDT, as detailed in the PoC (Section V). The PBC-iDT approach facilitates the rapid creation and deployment of iDTs, based on the provided models of the robotic arm and the conveyor belt. The description of the iDTs with their services is as follows:

1) **iDT_RA:** Represents the Robotic Arm PE.
    - *Control Command Service:* Enables the robotic arm to deposit objects in either the right or left stockpile.
2) **iDT_CB:** Represents the Conveyor Belt PE.
    - *Sensed Service:* Provides information about the color (red or green) of the current object on the conveyor belt.

The creation and deployment of these iDTs can be executed by directly providing their JSON models to a PBC-iDT Docker image and run by providing the specific model of PE or by using the PBC-iDT image as the base image to create

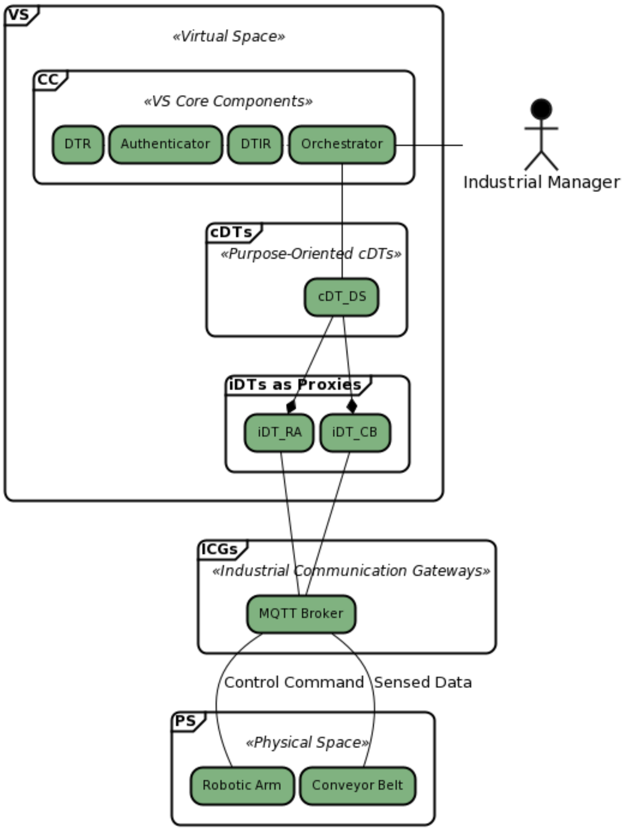


FIGURE 7. System setup for the dynamic sorting use case.

Docker images of iDT_RA and iDT_CB. These images can be stored in the DTIR for future use.

In the second phase, we create and deploy a cDT dynamic sorting, denoted as cDT_DS, while adhering to LDTM as suggested PoC (Section V). The implementation of cDT_DS leverages the step-by-step scheme described in Fig.5, highlighting the process involved in achieving the dynamic sorting purpose. This process involves the following steps:

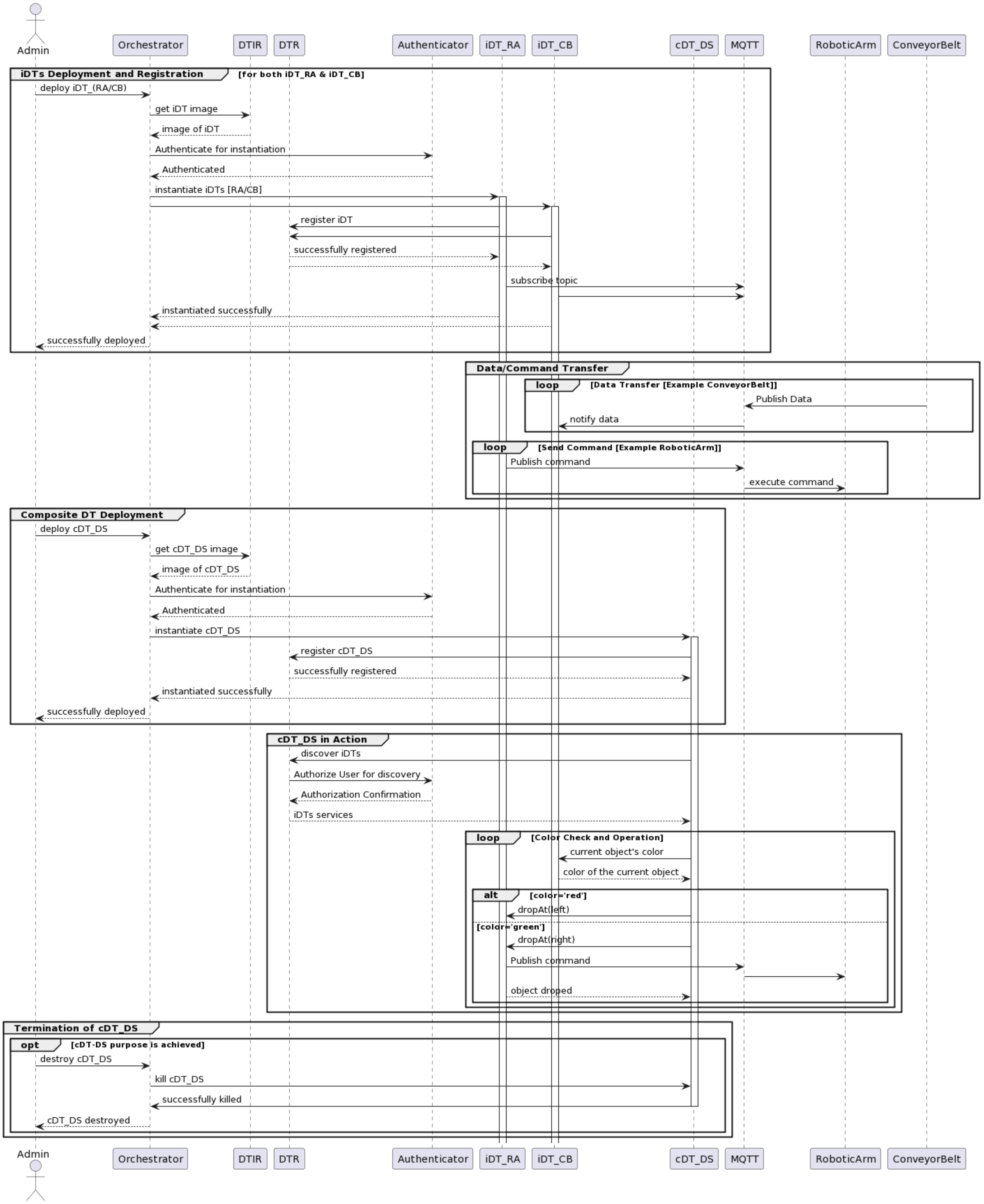


FIGURE 8. Sequence diagram.

1) **Define Purpose:** The primary objective is to achieve dynamic sorting, categorizing metallic and non-metallic packages based on color (red or green) into their respective stockpiles.

TABLE 6. Performance evaluation of PBC-iDT.

Device Models	Size	iterations	Mean	Std	Min	25%	50%	75%	Max
Model 1	378B	10.0	66.72	3.97	60.27	65.25	66.22	67.81	74.99
Model 2	575B	10.0	64.48	2.05	61.02	63.77	64.43	65.87	67.49
Model 3	635B	10.0	65.36	3.94	59.24	64.55	65.03	65.83	71.97
Model 4	675B	10.0	66.35	5.68	59.20	62.08	66.45	68.43	75.80
Model 5	736B	10.0	63.41	3.10	59.18	61.38	62.99	65.12	68.47
Model 6	776B	10.0	67.26	12.59	57.36	59.02	63.37	69.71	98.90
Model 7	817B	10.0	62.29	1.62	60.19	61.23	61.83	63.51	64.82
Model 8	858B	10.0	65.16	2.87	59.90	64.03	65.48	66.27	70.53
Model 9	969B	10.0	63.68	5.15	57.58	59.30	62.41	67.40	73.46
Model 10	1.11KB	10.0	64.41	6.59	56.49	60.51	62.54	66.86	79.22

2) **Identify Solutions and Technologies:** Leveraging the existing iDTs (iDT_CB and iDT_RA) and employing Node.js as the technology for minimal solution implementation.
3) **Decide Features:** The cDT_DS utilizes color information from iDT_CB to instruct iDT_RA, enabling the sorting of packages at specific stockpiles. It provides a feature for dynamic sorting.
4) **Implement cDT_DS:** The cDT_DS is developed using Node.js by composing services of iDT_CB and iDT_RA, allowing the execution of the dynamic sorting operation.
5) **Instantiate and Integrate cDT_DS in VS:** Leveraging the orchestrator, the cDT_DS is instantiated and integrated within the VS, ensuring seamless interaction with the VS core components and iDTs.
6) **Testing and Improvement:** Test to verify the operational validity of the cDT_DS. Continuous improvement efforts are suggested to enhance its performance and adaptability.

The complete use-case setup within the architecture is shown in Fig. 7. Lastly, considering that all the DTs including iDT_RA, iDT_CB, and cDT_DS, are stored in the DTIR, the complete deployment sequence of iDTs and cDT, along with their interaction with VS core components is represented as a sequence diagram in Fig. 8 to provide holistic application of the architecture.

VII. ANALYSIS

In this section, we delve into an analysis of the proposed architecture, aiming to provide both quantitative and qualitative insights into its practical implications and significance. We commence the evaluation with a quantitative examination of the PBC-iDT's operational efficiency and subsequently provide a qualitative assessment of its contributions to the broader industrial landscape.

A. PERFORMANCE EVALUATION OF PBC-IDT

The PBC-iDT stands as an essential element within our architecture, exemplifying the shift towards software-centricity and flexibility. It empowers the rapid creation and deployment of iDTs as proxies for physical entities, offering a path toward composability and purpose-driven digital twin development. The performance of PBC-iDT becomes an imperative metric, as it influences the speed and agility with which iDTs can be instantiated and integrated into the VS.

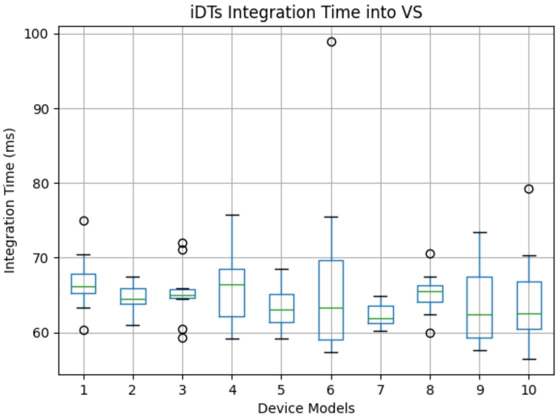


FIGURE 9. PBC-iDT performance analysis.

To evaluate the performance of PBC-iDT, we conducted a series of experiments focused on measuring the time it takes for the PBC-iDT to progress from initiating the creation of an iDT to the integration within the VS. These experiments involved running PBC-iDT with ten distinct device models represented in JSON format. Each device model was run ten times and the execution time was recorded. We conduct this quantitative analysis of PBC-iDT as a plain nodejs microservice without utilizing the docker image to offer a holistic perspective on the baseline performance of the PBC-iDT in its raw form, without the potential optimizations and overhead associated with containerization. The experiments were conducted on a Macbook Pro (2021) equipped with an Apple M1 Max chip and 32GB of RAM.

The results of our performance evaluation are presented in the Table 6, providing a summary of key performance metrics for each device model. The metrics include the count of experiments, the mean execution time, standard deviation, minimum and maximum execution times, and various percentiles. These statistics offer insights into the PBC-iDT's consistency and efficiency across different device models and scenarios. These quantitative results are further visualized in a box plot, shown in Fig. 9, to provide a

TABLE 7. **Qualitative comparison of architectural aspects with traditional approach.**

Aspect	Component(s)	Description	Qualitative Comparison
Reusability	iDTs, cDTs, PBC-iDT	iDTs, cDTs, and PBC-iDT are designed as modular, reusable entities that can be applied across various contexts, reducing redundant development efforts.	Traditional architectures are often characterized by rigid, single-purpose components, leading to redundant development for similar functionalities. The proposed architecture emphasizes modular design and standardized components, enabling efficient reuse and reducing development efforts.
Loose Coupling	All	The architecture facilitates independent interactions among components, reducing interdependencies and enabling localized modifications without affecting the entire system.	Traditional designs heavily rely on tightly integrated systems, making modifications complex and time-consuming. The distributed approach of proposed architecture allows components to interact independently, minimizing the impact of changes on the overall system.
Abstraction	iDTs	By representing physical entities as iDTs, the architecture enables software-centricity, allowing seamless integration and interaction with the VS.	Traditional designs often expose low-level system intricacies, leading to complicated system interactions and dependencies. The proposed architecture abstracts physical complexities into virtual representations, simplifying software interfaces and minimizing direct hardware interactions.
Discoverability	DTR	DTR provides a centralized platform for efficient discovery of digital twins, promoting easy access and streamlined interaction.	Traditional architectures lack standardized service discovery mechanisms. The proposed DTR employs a centralized registry making DTs and their services discovery efficient.
Security	Authenticator, iDTs	The Authenticator component ensures secure access, while iDTs abstract physical entities to secure them from various threats using robust security techniques.	Traditional systems often lack comprehensive security measures, leaving components vulnerable to cyber threats and unauthorized access. The proposed architecture enhances security by abstracting physical entities into secure digital representations and employs robust authentication mechanisms through the Authenticator.
Modularity	All	The architecture promotes modularity by allowing individual upgrades and replacements without disrupting the overall system, ensuring scalability and adaptability.	Conventional systems often rely on monolithic designs, making system modifications challenging and limiting scalability. The proposed architecture emphasizes service-oriented design, enabling the development of self-contained microservices that can be independently deployed and scaled, minimizing the impact of module modifications.
Openness	All	The architecture embraces open standards and interoperability, fostering collaboration and seamless integration with other systems and platforms.	Traditional systems tend to rely on proprietary solutions, leading to limited interoperability and hindering integration with external platforms. The proposed architecture prioritizes open standards and communication protocols, enabling seamless interaction with other systems and promoting data sharing and collaboration.
Development Cost	All	By emphasizing modular, reusable components and streamlined deployment processes, the architecture improves development costs and resource utilization.	Traditional development practices often involve high costs due to extensive custom development and complex integration processes for every challenge and purpose. The proposed architecture reduces development costs by leveraging reusable components and standardized design principles, promoting efficient resource utilization and cost-effective development processes.

comprehensive understanding of the execution times of PBC-iDT across the device models.

While there is inherent variability in the integration times and sizes of the device models, indicative of the complex dynamics at play, the PBC-iDT approach still exhibits a noteworthy degree of consistency. This is particularly evident in the median values and the compact interquartile ranges observed in several device models, such as Models 2, 3, and 10. Although the standard deviations reveal fluctuations in the instantiation and integration processes, suggesting diverse behavior across different device models, overall performance remains within a predictable range. This inherent variability is an expected characteristic of sophisticated systems, yet it does not significantly detract from the robustness of the PBC-iDT method. The approach demonstrates the ability to provide reliable integration times, which is crucial for the deployment of digital twins as proxies in industrial settings.

The consistency in the median integration times across most device models underscores the reliability of the PBC-iDT method, emphasizing its potential to handle various device models and sizes with a reliable baseline performance. While individual outliers and instances of increased variability are noted, they are an anticipated aspect of any system dealing with a range of device complexities and capabilities. These variations highlight the importance of a thorough analysis when implementing the PBC-iDT approach, ensuring that the unique characteristics of each device model are accounted for in the overall architecture. Moreover, the data derived from this evaluation empowers informed decision-making, fostering streamlined development and deployment practices within the proposed architecture.

B. QUALITATIVE ANALYSIS OF THE ARCHITECTURE

In this subsection, we present a qualitative analysis of the proposed architecture, comparing it with conventional industrial practices and their traditional limitations. Our architecture stands out by enabling software-centricity through the utilization of distributed iDTs as proxies, which in turn unlocks composability and flexibility for the purpose-oriented digital twins. This comparative analysis is based on the key properties and principles of SOA, microservices, and composable & flexible architectures. We shall assess how our architecture embodies these properties and which components within the proposed framework contribute to achieving them, providing a comprehensive understanding of its advantages in contrast to traditional practices.

As summarized in Table 7, our proposed architecture excels in key architectural properties, enabling reusability, loose coupling, abstraction, discoverability, security, modularity, autonomy, flexibility, automation, and composability. Compared to conventional industrial practices, our architecture offers advanced features in these aspects, providing a strong foundation for purpose-oriented digital twin development. This qualitative analysis underscores the substantial advantages our architecture brings when compared to traditional industrial practices, equipping industries with the agility and adaptability needed to thrive in rapidly evolving ecosystems.

VIII. CONCLUSION

In this article, we have introduced an innovative and transformative approach to address the evolving landscape of industrial digitalization. By leveraging the concepts of software-centricity, microservices, and composability, we have devised an architecture that facilitates the seamless integration of distributed iDTs as proxies, thereby fostering composability and flexibility in the development of purpose-oriented cDTs. Our approach has been validated through a PoC implementation, which includes the suitable selection and deployment of vital VS core components, such as the DTR, orchestrator, authenticator, and DTIR. Additionally, the introduction of the PBC-iDT has expedited the development and deployment of iDTs as proxies, further solidifying the practicality and effectiveness of our proposed architecture.

Through the employment of our architecture, the development of purpose-oriented cDTs has been made possible, showcasing the architectural excellence achieved by encapsulating distinct functionalities tailored for specific industrial purposes. This approach has been exemplified through a use-case scenario, showcasing its capacity to seamlessly orchestrate the actions of physical entities in response to dynamically changing requirements. The quantitative and qualitative analysis further highlighted the performance and architectural advantages, solidifying the significance of the proposed architecture in fostering a more agile and efficient industrial ecosystem.

While our proposed architecture introduces advancements in industrial digitalization, several inherent limitations warrant consideration. The distributed nature of digital twins introduces challenges related to data consistency, synchronization, and security that warrant further investigation. Furthermore, the integration of a broader range of legacy systems and protocols may present challenges, requiring comprehensive adaptation strategies to ensure seamless interoperability and integration with existing infrastructure.

Looking ahead, our research lays the foundation for numerous promising directions. The development of enhanced security mechanisms, real-time data synchronization strategies, and refined orchestration techniques will further strengthen the applicability of our architecture. By persistently exploring and innovating in these domains, we aspire to forge a future where composite digital twins redefine the boundaries of industrial possibilities. In conclusion, our work offers a compelling vision of how distributed digital twins can empower the industrial landscape with composability and flexibility. By embracing software-centricity and adaptability, we position industrial systems to meet the dynamic demands of the future. Through continued research and innovation, we aim to shape a future where cDTs redefine the boundaries of industrial possibilities.

ACKNOWLEDGMENT

AI-based tools have been used to improve the quality of English.

REFERENCES

[1] S. Mahmudova, "Intelligent systems for the Internet of Things: Essence, perspectives and problems," *Int. J. Natural Sci. Res.*, vol. 9, no. 1, pp. 17–25, Nov. 2021.

[2] S. Li, L. D. Xu, and S. Zhao, "The Internet of Things: A survey," *Inf. Syst. Frontiers*, vol. 17, no. 2, pp. 243–259, 2014.

[3] H. Jaidka, N. Sharma, and R. Singh, "Evolution of IoT to IIoT: Applications & challenges," in *Proc. Int. Conf. Innov. Comput. Commun. (ICICC)*, May 2020. [Online]. Available: https://ssrn.com/abstract=3603739

[4] S. Schneider, "The industrial Internet of Things (IIoT)," in *Internet of Things and Data Analytics Handbook*. Hoboken, NJ, USA: Wiley, 2017, ch. 3, pp. 41–81.

[5] Y. Jiang, S. Yin, K. Li, H. Luo, and O. Kaynak, "Industrial applications of digital twins," *Philos. Trans. Roy. Soc. A, Math., Phys. Eng. Sci.*, vol. 379, Aug. 2021, Art. no. 20200360.

[6] B. R. Barricelli, E. Casiraghi, and D. Fogli, "A survey on digital twin: Definitions, characteristics, applications, and design implications," *IEEE Access*, vol. 7, pp. 167653–167671, 2019.

[7] K. Zhang, Y. Shi, S. Karnouskos, T. Sauter, H. Fang, and A. W. Colombo, "Advancements in industrial cyber-physical systems: An overview and perspectives," *IEEE Trans. Ind. Informat.*, vol. 19, no. 1, pp. 716–729, Jan. 2023.

[8] V. Damjanovic-Behrendt and W. Behrendt, "An open source approach to the design and implementation of digital twins for smart manufacturing," *Int. J. Comput. Integr. Manuf.*, vol. 32, nos. 4–5, pp. 366–384, 2019.

[9] D. Georgakopoulos and D. Bamunuarachchi, "Digital twins-based application development for digital manufacturing," in *Proc. IEEE 7th Int. Conf. Collaboration Internet Comput. (CIC)*, Dec. 2021, pp. 87–95.

[10] Q. Qi, D. Zhao, T. W. Liao, and F. Tao, "Modeling of cyber-physical systems and digital twin based on edge computing, fog computing and cloud computing towards smart manufacturing," in *Proc. 13th Int. Manuf. Sci. Eng. Conf.* New York, NY, USA: American Society of Mechanical Engineers (ASME), 2018.

[11] A. Costantini, G. Di Modica, J. C. Ahouangonou, D. C. Duma, B. Martelli, M. Galletti, M. Antonacci, D. Nehls, P. Bellavista, C. Delamarre, and D. Cesini, "IoTwins: Toward implementation of distributed digital twins in Industry 4.0 settings," *Computers*, vol. 11, no. 5, p. 67, Apr. 2022.

[12] A. Ricci, A. Croatti, and S. Montagna, "Pervasive and connected digital twins—A vision for digital health," *IEEE Internet Comput.*, vol. 26, no. 5, pp. 26–32, Sep. 2022.

[13] A. Ricci, A. Croatti, S. Mariani, S. Montagna, and M. Picone, "Web of digital twins," *ACM Trans. Internet Technol.*, vol. 22, no. 4, pp. 1–30, Nov. 2022.

[14] A. Martínez-Gutiérrez, J. Díez-González, R. Ferrero-Guillén, P. Verde, R. Álvarez, and H. Perez, "Digital twin for automatic transportation in Industry 4.0," *Sensors*, vol. 21, no. 10, p. 3344, May 2021.

[15] K. Josifovska, E. Yigitbas, and G. Engels, "Reference framework for digital twins within cyber-physical systems," in *Proc. IEEE/ACM 5th Int. Workshop Softw. Eng. for Smart Cyber-Physical Syst. (SEsCPS)*, May 2019, pp. 25–31.

[16] C. Liu, P. Jiang, and W. Jiang, "Web-based digital twin modeling and remote control of cyber-physical production systems," *Robot. Comput.-Integr. Manuf.*, vol. 64, Aug. 2020, Art. no. 101956.

[17] J. Autiosalo, J. Vepsäläinen, R. Viitala, and K. Tammi, "A feature-based framework for structuring industrial digital twins," *IEEE Access*, vol. 8, pp. 1193–1208, 2020.

[18] A. J. H. Redelinghuys, K. Kruger, and A. Basson, "A six-layer architecture for digital twins with aggregation," in *Studies in Computational Intelligence*, vol. 853. Berlin, Germany: Springer, 2020, pp. 171–182.

[19] K. M. Alam and A. El Saddik, "C2PS: A digital twin architecture reference model for the cloud-based cyber-physical systems," *IEEE Access*, vol. 5, pp. 2050–2062, 2017.

[20] L. F. Rivera, H. A. Müller, N. M. Villegas, G. Tamura, and M. Jiménez, "On the engineering of IoT-intensive digital twin software systems," in *Proc. IEEE/ACM 42nd Int. Conf. Softw. Eng. Workshops*, Jun. 2020, pp. 631–638.

[21] Z. Jiang, Y. Guo, and Z. Wang, "Digital twin to improve the virtual-real integration of industrial IoT," *J. Ind. Inf. Integr.*, vol. 22, Jun. 2021, Art. no. 100196.

[22] X. Li, H. Liu, W. Wang, Y. Zheng, H. Lv, and Z. Lv, "Big data analysis of the Internet of Things in the digital twins of smart city based on deep learning," *Future Gener. Comput. Syst.*, vol. 128, pp. 167–177, Mar. 2022.

[23] W. Lohman, H. Cornelissen, J. Borst, R. Klerkx, Y. Araghi, and E. Walraven, "Building digital twins of cities using the inter model broker framework," *Future Gener. Comput. Syst.*, vol. 148, pp. 501–513, Nov. 2023.

[24] G. Steindl, M. Stagl, L. Kasper, W. Kastner, and R. Hofmann, "Generic digital twin architecture for industrial energy systems," *Appl. Sci.*, vol. 10, no. 24, p. 8903, Dec. 2020.

[25] P. Empl, D. Schlette, D. Zupfer, and G. Pernul, "SOAR4IoT: Securing IoT assets with digital twins," in *Proc. 17th Int. Conf. Availability, Rel. Secur.*, Aug. 2022, pp. 1–10.

[26] C. Gehrmann and M. Gunnarsson, "A digital twin based industrial automation and control system security architecture," *IEEE Trans. Ind. Informat.*, vol. 16, no. 1, pp. 669–680, Jan. 2020.

[27] B. T. Wang and M. Burdon, "Automating trustworthiness in digital twins," in *Automating Cities* (Advances in 21st Century Human Settlements). Berlin, Germany: Springer, 2021, pp. 345–365.

[28] J. Trauer, S. Schweigert-Recksiek, T. Schenk, T. Baudisch, M. Mörtl, and M. Zimmermann, "A digital twin trust framework for industrial application," *Proc. Des. Soc.*, vol. 2, pp. 293–302, May 2022.

[29] A. Fuller, Z. Fan, C. Day, and C. Barlow, "Digital twin: Enabling technologies, challenges and open research," *IEEE Access*, vol. 8, pp. 108952–108971, 2020.

[30] J. Michael, J. Pfeiffer, B. Rumpe, and A. Wortmann, "Integration challenges for digital twin systems-of-systems," in *Proc. IEEE/ACM 10th Int. Workshop Softw. Eng. Syst.-Syst. Softw. Ecosystems (SESoS)*, NY, NY, USA, May 2022, pp. 9–12.

[31] K. Wang, Y. Wang, Y. Li, X. Fan, S. Xiao, and L. Hu, "A review of the technology standards for enabling digital twin," *Digit. Twin*, vol. 2, p. 4, Mar. 2022.

[32] D. Berardi, F. Callegati, A. Giovine, A. Melis, M. Prandini, and L. Rinieri, "When operation technology meets information technology: Challenges and opportunities," *Future Internet*, vol. 15, no. 3, p. 95, Feb. 2023.

[33] A. Hazra, M. Adhikari, T. Amgoth, and S. N. Srirama, "A comprehensive survey on interoperability for IIoT: Taxonomy, standards, and future directions," *ACM Comput. Surv.*, vol. 55, no. 1, pp. 1–35, Nov. 2021.

[34] A. Khan and K. Turowski, "A survey of current challenges in manufacturing industry and preparation for Industry 4.0," in *Proc. 1st Int. Sci. Conf. 'Intell. Inf. Technol. Ind.*, A. Abraham, S. Kovalev, V. Tarassov, and V. Snasel, Eds. Cham, Switzerland: Springer, 2016, pp. 15–26.

[35] Y. Cohen, M. Faccio, F. Pilati, and X. Yao, "Design and management of digital manufacturing and assembly systems in the Industry 4.0 era," *Int. J. Adv. Manuf. Technol.*, vol. 105, no. 9, pp. 3565–3577, Dec. 2019.

[36] F. Rodríguez-Haro, F. Freitag, L. Navarro, E. Hernánchez-sánchez, N. Farías-Mendoza, J. A. Guerrero-Ibáñez, and A. González-Potes, "A summary of virtualization techniques," *Proc. Technol.*, vol. 3, pp. 267–272, Jan. 2012.

[37] J. Daniels, "Server virtualization architecture and implementation," *XRDS, Crossroads, ACM Mag. Students*, vol. 16, no. 1, pp. 8–12, Sep. 2009.

[38] R. Morabito, V. Cozzolino, A. Y. Ding, N. Beijar, and J. Ott, "Consolidate IoT edge computing with lightweight virtualization," *IEEE Netw.*, vol. 32, no. 1, pp. 102–111, Jan. 2018.

[39] Y. Mansouri and M. A. Babar, "A review of edge computing: Features and resource virtualization," *J. Parallel Distrib. Comput.*, vol. 150, pp. 155–183, Apr. 2021.

[40] S. R. U. Kakakhel, L. Mukkala, T. Westerlund, and J. Plosila, "Virtualization at the network edge: A technology perspective," in *Proc. 3rd Int. Conf. Fog Mobile Edge Comput. (FMEC)*, Apr. 2018, pp. 87–92.

[41] S. W. Choi and S. D. Kim, "A quality model for evaluating reusability of services in SOA," in *Proc. 10th IEEE Conf. E-Commerce Technol. 5th IEEE Conf. Enterprise Comput., E-Commerce E-Services*, Jul. 2008, pp. 293–298.

[42] B. Shim, S. Choue, S. Kim, and S. Park, "A design quality model for service-oriented architecture," in *Proc. 15th Asia–Pacific Softw. Eng. Conf.*, 2008, pp. 403–410.

[43] H. Bu, "Metrics for service granularity in service oriented architecture," in *Proc. Int. Conf. Comput. Sci. Netw. Technol.*, vol. 1, Dec. 2011, pp. 491–494.

[44] N. M. Josuttis, *SOA in Practice: The Art of Distributed System Design*. Sebastopol, CA, USA: O'Reilly Media, Aug. 2007.

[45] N. Niknejad, W. Ismail, I. Ghani, B. Nazari, M. Bahari, and A. R. B. C. Hussin, "Understanding service-oriented architecture (SOA): A systematic literature review and directions for further investigation," *Inf. Syst.*, vol. 91, Jul. 2020, Art. no. 101491.

[46] X. Larrucea, I. Santamaria, R. Colomo-Palacios, and C. Ebert, "Microservices," *IEEE Softw.*, vol. 35, no. 3, pp. 96–100, May 2018.

[47] A. Bucchiarone, N. Dragoni, S. Dustdar, P. Lago, M. Mazzara, V. Rivera, and A. Sadovykh, *Microservices: Science and Engineering*. Cham, Switzerland: Springer, 2020.

[48] P. van Schalkwyk and D. Isaacs, "Achieving scale through composable and lean digital twins," in *The Digital Twin*, N. Crespi, A. T. Drobot, and R. Minerva, Eds. Cham, Switzerland: Springer, 2023, pp. 153–180.

[49] Y. Natis, D. Gaughan, M. O'Neill, B. Lheureux, and M. Pezzini, "Innovation insight for packaged business capabilities and their role in the future composable enterprise," Gartner Res., London, U.K., Tech. Rep., 2019.

[50] V. Souza, R. Cruz, W. Silva, S. Lins, and V. Lucena, "A digital twin architecture based on the industrial Internet of Things technologies," in *Proc. IEEE Int. Conf. Consum. Electron. (ICCE)*, Jan. 2019, pp. 1–2.

[51] M. Picone, M. Mamei, and F. Zambonelli, "A flexible and modular architecture for edge digital twin: Implementation and evaluation," *ACM Trans. Internet Things*, vol. 4, no. 1, pp. 1–32, Feb. 2023.

[52] P. Kuruppuarachchi, S. Rea, and A. McGibney, "An architecture for composite digital twin enabling collaborative digital ecosystems," in *Proc. IEEE 25th Int. Conf. Comput. Supported Cooperat. Work Design (CSCWD)*, May 2022, pp. 980–985.

[53] A. Aziz, O. Schelén, and U. Bodin, "Digital twin as a proxy for industrial cyber-physical systems," in *Proc. 10th Int. Conf. Wireless Commun. Sensor Netw.*, New York, NY, USA, Jan. 2023, pp. 85–92.

[54] J. Delsing, *IoT Automation: Arrowhead Framework*. Boca Raton, FL, USA: CRC Press, 2017.

[55] A. Aziz, O. Schelén, U. Bodin, L. Römer, S. E. Jeroschewski, and J. Kristan, "Empowering the eclipse arrowhead framework with a digital twin as a proxy service," in *Proc. 22nd Int. Conf. Control, Autom. Syst. (ICCAS)*, Nov. 2022, pp. 1716–1721.

[56] P. Talasila, C. Gomes, P. H. Mikkelsen, S. G. Arboleda, E. Kamburjan, and P. G. Larsen, "Digital twin as a service (DTaaS): A platform for digital twin developers and users," 2023, *arXiv:2305.07244*.

[57] M. Platenius-Mohr, S. Malakuti, S. Grüner, J. Schmitt, and T. Goldschmidt, "File- and API-based interoperability of digital twins by model transformation: An IIoT case study using asset administration shell," *Future Gener. Comput. Syst.*, vol. 113, pp. 94–105, Dec. 2020.

[58] *Reference Architectural Model Industrie 4.0 (RAMI4.0)—An Introduction*. Accessed: Mar. 15, 2023. [Online]. Available: https://www.plattform-i40.de/IP/Redaktion/EN/Downloads/Publikation/rami40-an-introduction.html

[59] M. R. Shahriar, X. F. Liu, M. M. Rahman, and S. M. Nahian Al Sunny, "OpenDT: A reference framework for service publication and discovery using remote programmable digital twins," in *Proc. IEEE Int. Conf. Services Comput. (SCC)*, Nov. 2020, pp. 116–123.

[60] A. Borghesi, G. Di Modica, P. Bellavista, V. Gowtham, A. Willner, D. Nehls, F. Kintzler, S. Cejka, S. R. Tisbeni, A. Costantini, and M. Galletti, "IoTwins: Design and implementation of a platform for the management of digital twins in industrial scenarios," in *Proc. IEEE/ACM 21st Int. Symp. Cluster, Cloud Internet Comput.*, May 2021, pp. 625–633.

[61] A. Aziz, O. Schelén, and U. Bodin, "Data integration models for heterogeneous industrial systems: A conceptual analysis," in *Proc. 26th IEEE Int. Conf. Emerg. Technol. Factory Autom. (ETFA)*, Sep. 2021, pp. 1–8.

[62] S. Baloutsos, A. Karagiannaki, and I. Mourtos, "Business model generation for Industry 4.0: A 'lean startup' approach," *Int. Technol. Manag. Rev.*, vol. 9, no. 1, pp. 34–45, Jul. 2020.

[63] P. Hines, M. Holweg, and N. Rich, "Learning to evolve: A review of contemporary lean thinking," *Int. J. Oper. Prod. Manag.*, vol. 24, no. 10, pp. 994–1011, Oct. 2004.

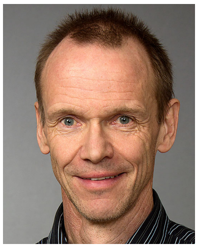
[64] S. Blank, "Why the lean start-up changes everything," Harvard Bus. Rev., USA, May 2013.

[65] E. Ries, *The Lean Startup: How Today's Entrepreneurs Use Continuous Innovation to Create Radically Successful Businesses*. New York, NY, USA: Crown, 2017.

[66] *Consul by HashiCorp*. Accessed: Aug. 22, 2023. [Online]. Available: https://www.consul.io/

ABDULLAH AZIZ received the master's degree from Sejong University, Seoul, South Korea. He is currently pursuing the Ph.D. degree with the Luleå University of Technology. He contributed to the standards' technical specifications. His research interests include the IIoT, IT/OT convergence, digital twins, the IoT, distributed systems, edge/cloud computing, virtualization, and orchestration.

SHAILESH SINGH CHOUHAN received the D.Sc.(Tech.) degree in microelectronics from Aalto University. He is currently a Senior Researcher in CPS with the Luleå University of Technology. He works to bridge the gap between electronics and IT to achieve the vision of CPS. His research interest includes chiplet design and computational hardware integration into microsystems and microservice paradigms.



OLOV SCHELÉN (Member, IEEE) is currently a Professor with the Luleå University of Technology and the CEO of Xarepo AB. He has more than 25 years of experience in industry and academia. His research interests include mobile and distributed systems, the Industrial IoT and CPS, software orchestration, computer networking, artificial intelligence, and blockchain.

ULF BODIN is currently a Professor with the Luleå University of Technology, where he is conducting research on the Industrial IoT, distributed system of systems, computer communications, distributed ledgers, and applied machine learning. He has more than 15 years in software industry, ETSI, and several other standardization organizations.

• • •