

DETC2026-190478

STANDARDS-BASED DIGITAL TWIN COMPOSITION: ROBOT ARM AND GRIPPER

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ABSTRACT

Digital twins are used to monitor, diagnose, predict, and optimize systems' performance, often for the purpose of informing human decision-makers or automatically controlling systems. However, it is impractical to create a large-scale, monolithic digital twin for each factory floor or to develop a digital twin from scratch for every new production unit. To reduce the complexity and cost of the development, such digital twins can be created through the composition of multiple-component digital twins to enable modular design and facilitate the digital twin reuse. Individual digital twins can be reused in various configurations to form digital twins of larger systems with various purposes. Deciding how these component digital twins should talk to each other, consolidating multi-vendor data formats, and ensuring lifecycle validity of the composed digital twins, and ensuring scalability and consistency are very challenging tasks. A new international standard (ISO 23247-6) has been developed to address these challenges. This research involves implementing an integrated digital twin of a robot arm and a gripper, following procedures outlined in the standard to demonstrate an Integrated Digital Twin Composition (DTC) approach. The implementation is analyzed to identify the benefits and challenges following the standards. Future topics of standardization are identified and discussed.

Keywords: ISO standards, digital twin, digital twin framework, digital twin composition (DTC), component digital twin, composed digital twin, manufacturing, robot, gripper

1. INTRODUCTION

The concept of a digital twin is highly applicable in the manufacturing industry, promising to advance the industry's productivity through better monitoring, analysis, prediction, optimization, and automation. However, creating digital

representations of large-scale physical systems is a challenging task. A design pattern that could reduce development complexity and cost is composing digital twins from modular components.

There are examples of digital twins being created through the combination of software services and digital models [1, 2, 3]. A less explored strategy is to combine existing independent digital twins to become a composed digital twin through the process of digital twin composition (DTC). The motivation behind this approach is that manufacturers can reuse existing digital twins that could be developed in-house or obtained from third parties, such as solution providers and equipment vendors, and then combine them to formulate a larger digital twin for a complex system. This avoids the duplicated effort in developing digital twins from scratch. Even third party-provided digital twins that utilize standard formats or interfaces are unlikely to be fully interoperable with others due to differences in design criteria and development platforms. To address this variability in digital twin implementations, a generic guideline and procedure for digital twin composition would establish common concepts, principles, structures, and approaches for composing digital twins, independent from implementation details.

The ISO 23247 standard, Digital Twin Framework for Manufacturing, provides a common set of terms and a framework for developing digital twins for manufacturing. According to ISO 23247, a digital twin is a "fit-for-purpose digital representation of an observable manufacturing element (OME) which is synchronized with the state of the physical object [3]." Part 6 of ISO 23247 is currently in its final draft international standard (FDIS) stage, it defines principles, methodologies, and use case examples for digital twin

composition in manufacturing [4]. This FDIS adopted the interoperability approaches, defined in ISO 11354, Requirements for Establishing Manufacturing Enterprise Process Interoperability, which includes three kinds of integration approaches for models: integrated, unified, and federated [5].

This paper focuses on the validation and demonstration of the framework standard by evaluating one of the three integration approaches - the integrated DTC, along with the utility and clarity of the framework for digital twins in manufacturing. An integrated DTC is a type of composition that guides the development of a larger digital twin by combining multiple component digital twins with centralized control and centralized communication [4]. The implementation of an integrated DTC is illustrated through the case study of composing digital twins of a robot arm and a gripper. These two components were selected for integration because a robot arm or a gripper would not be useful without working together; therefore, integrating their digital twins would be necessary to digitally replicate the intended purpose of the whole robot arm system for picking and placing objects. In addition, the system can benefit from the modularity offered by representing the gripper as an independent digital twin, allowing different gripper digital twins to be swapped in the digital representation as desired.

In addition to the application of the standards, this paper also provides lessons learned in terms of new insights on DTCs, discusses DTC benefit (e.g., lower development time and cost) and key challenges (e.g., interoperability, semantic mismatches, synchronization, latency, and error accumulation), and specifies third-party digital twins specific opportunities and complexities for digital twin compositions.

Section 2 discusses related work, followed by research questions. Section 3 provides a brief introduction to the high level procedures the FDIS provided when implementing an integrated digital twin composition. Section 4 describes the use case of composing the digital twins of a robot arm and a gripper. Section 5 discusses the use case results and lessons learned, and finally Section 6 concludes the paper with discussion of future work.

2. RELATED WORK AND RESEARCH QUESTIONS

Mitigating the difficulty and costs of digital twin development has been a focus for researchers and industry, as it is one of the major factors limiting digital twin adoption. Using modular architectures for digital twin development is a critical approach for addressing this challenge. Research on DTC has been focusing on how individual component digital twin can be integrated into larger, cohesive ecosystems [6, 7]. This is essential for large-scale industrial systems where a single digital twin is often too big and insufficient to represent complex, multi-vendor environments [7].

A core challenge in DTC is ensuring that heterogeneous component digital twins, often provided as “black-box” applications by different vendors, can interact correctly. Ontologies would help formalize domain knowledge and unify data models [8]. Current literature classifies digital twin ecosystems by how isolated digital models scale up into larger, multi-domain systems-of-systems. Research highlights several organizational patterns [9], including centralized where a single master digital twin manages all subordinate data (e.g., a “Robot Workcell Digital Twin”), hierarchical where digital twins are nested (e.g., a “Machine Digital Twin” within a “Production Line Digital Twin”), and heterarchical and holonic: Peer-to-peer relationships where digital twins collaborate autonomously (e.g., a “Supply Chain Digital Twin”).

Researchers are also investigating formal methods to verify the correctness of composed digital twins, as the interaction between complex data and dynamic models can lead to “emergent” behaviors that are difficult to predict [7]. Generative AI and Machine Learning (ML) can assist in orchestrating digital twins for real-time optimization [10, 11, 12]. This includes the development of hybrid digital twins that compose physics-based models with AI-driven methodologies to improve predictive accuracy in sparse-data environments.

Researchers are exploring “Executable Digital Twins” (xDT), which are self-contained, high-speed simulation models that run outside of traditional Computer-Aided Design (CAD) software (Siemens xDT Framework). Reduced Order Modeling (ROM) and AI are used to package complex physics such as robot gripper friction and joint torque into lightweight apps that run on edge devices for real-time decision-making [13]. A major hurdle in robot digital twins has been the “Virtual-to-Real” gap, where the digital twin’s perfect math doesn’t account for the physical robot’s mechanical wear or gravity-induced bending. The digital twin trains the robot arm in the cloud using reinforcement learning, while a Fuzzy PID (Proportional-Integral-Derivative) controller on the physical robot arm corrects mapping errors in real-time [14]. Cognitive digital twins do not just represent the robot arm but also predict human intention during collaborative tasks. Augmented Reality (AR) headsets are used to overlay the robot’s “planned trajectory” from the digital twin onto the human’s vision. These digital twins include three functionalities (1) Virtual Twin: In-situ monitoring, (2) Hybrid Twin: Intuitive control and interaction, and (3) Cognitive Twin: Optimized operation through human intelligence integration [15, 16].

ISO 23247 is increasingly cited as essential for promoting the composability and reusability of digital twin components, particularly for small-to-medium enterprises [17]. For robotic applications, a recent use case demonstrates an ISO 23247-compliant digital twin for a large-scale robotic welding in an additive manufacturing cell [18]. A digital twin of a KUKA robot arm equipped with a Meltio LMD nozzle was developed using ISO 23247-3, which includes the digital representations

of the robot's kinematics and the end effector's thermal deposition properties. By following the standard, they enabled "near real-time" monitoring of the bead geometry in the cloud using Message Queuing Telemetry Transport (MQTT), ensuring that the data remained consistent even if they swapped the KUKA robot for a different brand. Another application is the immersive AR robotic digital twins [19], which focuses on the "User Entity" of ISO 23247, integrating AR with robotic twins. They used the standard to govern how gesture-tracking data (from a user) is sent back through the Digital Twin Entity to control a physical sorting robot.

Interoperability for digital twins is not just about connecting data but also about semantic orchestration, e.g., ensuring that a robot arm digital twin from one vendor can understand the capabilities of a gripper digital twin from another without effort from scratch. The Asset Administration Shell (AAS) framework can support the implementation for DTC in Industry 4.0. It acts as a standardized "digital envelope" that wraps around an asset's data and models. Instead of one massive digital twin, the AAS uses "submodels." DTC can be achieved by linking these submodels across different digital twins [20]. To enable semantic mapping between Digital Twins Definition Language (DTDL) to AAS, a research effort developed algorithms to translate the "properties" and "relationships" defined in DTDL into the "submodels" of AAS to allow engineers to build digital twins in user-friendly commercial platforms but export them into a standardized format to facilitate composition [21].

A commonly used modular approach is to segment the digital twin into specialized software modules that each perform a specific set of functions, mimicking how physical components with specialized functions, such as actuators, sensors, and mechanisms, are composed into a machine [1, 2]. The structure of this type of modular system encourages the use of a central controller that organizes communication between all functional modules and the physical system [1, 2]. This approach is well-suited for creating digital twins of single systems due to the correspondence between functional modules and the physical, functional components from that the systems are constructed. A similar approach, motivated by creating a digital twin of a factory, involves segmenting the digital twin by machines in the production process, with each machine completing a specific production task [22]. Both approaches create software modules that correspond to physical modules, each performing a distinct function. The primary difference between the per-machine and per-factory approaches is the granularity and scope of the modules.

To summarize the related work, individual research efforts are made to facilitate the digital twin development and composition. Standards such as ISO 23247, AAS, and DTDL are helping create and integrate digital twins. However, systematic definitions, principles, methodologies, and procedures for digital twin composition are still needed for

manufactures to follow and practice DTC. ISO 23247-6 is such a standard that provides step-by-step guidance for digital twin composition in manufacturing. This work takes a robot arm and a gripper as a use case to implement the integrated DTC following the guideline. Naturally, this study aims to address the following questions relating to the implementation of a robot arm and gripper-integrated DTC, in the case where the individual digital twins are developed by unaffiliated third parties:

- What procedures need to be followed when creating an integrated composition of digital twins?
- Are the procedures provided in Part 6 FDIS sufficient and clear?
- How did the third party-developed individual digital twins influence the development of the integrated system?
- What features of digital twins facilitate composability?

3. MOTIVATION FOR NEW ADDITIONS

ISO 23247-6 is a critical expansion of the original four-part framework. While Parts 1 through 4 established the basic architecture framework, data representation and data exchange. Part 6 focuses on interoperability and composition of digital twins [23]. This part was specifically drafted to address the "system of systems" problem, e.g., how to combine digital twins of a robot arm and a gripper to formulate a functioning robot.

The core objective of ISO 23247-6 is to provide a standardized methodology for digital twin composition. It moves the standard from describing individual digital twins to describing composed digital twins.

- This part defines how independent Digital Twin Entities (DTEs) can be assembled using others. It introduces the concept of component twins and composed twins.
- This part provides guidelines for ensuring that data shared between component digital twins is contextually understood. For example, if a robot arm digital twin outputs a coordinate in mm, the gripper twin must be able to interpret that coordinate within the same reference frame automatically.

Part 6 address the functional, structural, behavioral, and informational composition of digital twins. Three types of DTCs in Part 6 are defined: (1) Integrated DTC that consolidates all data and functionalities from its component digital twins by using a common data model and a centralized control. (2) Unified DTC that uses a centralized interoperability layer, such as middleware or APIs, to facilitate data mapping and exchange between independent component digital twins, allowing them to remain loosely coupled while maintaining their own unique models and formats. (3) Federated DTC that enables independent component digital twins to interact and exchange data directly via peer-to-peer coordination, eliminating the need for a central manager while providing a flexible, autonomous architecture suited for decentralized

environments. Figure 1 shows the three digital twin composition types in the standard and Table 1 shows the comparison of a few key aspects of these types.

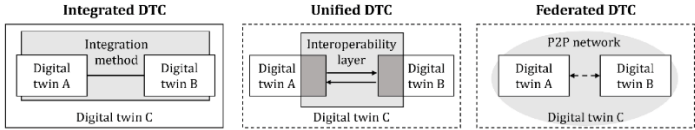


FIGURE 1. Different Types of Digital Twin Composition [4].

TABLE 1. KEY ASPECTS COMPARISON FOR DIFFERENT DTC TYPES.

Aspect	Integrated DTC	Unified DTC	Federated DTC
Architecture Style	Single tightly integrated digital twin system	Common platform with harmonized models and interfaces	Multiple autonomous digital twins collaborating across systems
Scalability	Low–Moderate	Moderate–High	Very High
Flexibility	Low	Moderate–High	Very High
Latency	Very Low	Low–Moderate	Moderate–High
Data Governance	Centrally controlled	Shared governance model	Distributed/local governance

The development of a composed digital twin using DTC has four lifecycle phases: specification, design, development, and operation of the DTC [4]:

- The specification phase defines the overall purpose of the composed system, the functions that the desired composed digital twin performs, and metrics governing the integrity of the system’s performance. These requirements help determine the optimal DTC type for the application.
- The design phase involves translating the selected DTC type into a technical execution strategy by defining the system architecture, data standards, and a phased deployment plan. It also involves designing software and hardware components to ensure the DTC fulfills its purpose and requirements, including selecting existing digital twins or developing them to incorporate and determine the data required to link them together.
- The development phase focuses on the technical implantation, integration, and development of component digital twins by mapping data, building interfaces, and validating the composed digital twin before cataloging it for use. It involves iteratively developing and evaluating the design to ensure it meets requirements throughout its life cycle.
- The operation phase focuses on the live deployment and execution of the composed digital twin, synchronizing it with physical manufacturing operations through continuous data updates and systematic monitoring. It also involves maintaining the composed digital twin in a production environment to ensure it continues meeting requirements throughout its usage.

Since the use case is for Integrated DTC, in this paper, we only briefly discuss the structured development procedure for the integrated DTC, which is shown in Figure 2. The procedure uses a lifecycle-based approach to illustrate the activities from initial requirements to continuous operational maintenance.

- Specification phase: Defining requirements, identifying existing digital twin assets, and creating composed digital twin metadata.
- Design phase: Building the technical foundation through common data models, shared ontologies, and centralized architecture.
- Deployment phase: Implementing the DTC by creating strict data mapping rules and functional modules to merge the component digital twins into a composed digital twin.
- Operation phase: executing the composed digital twin with continuous data synchronization and a dedicated maintenance process for reliability.

Note that because the system is tightly coupled, adding a new component often requires complex re-coding of the central control logic and interface adaptations.

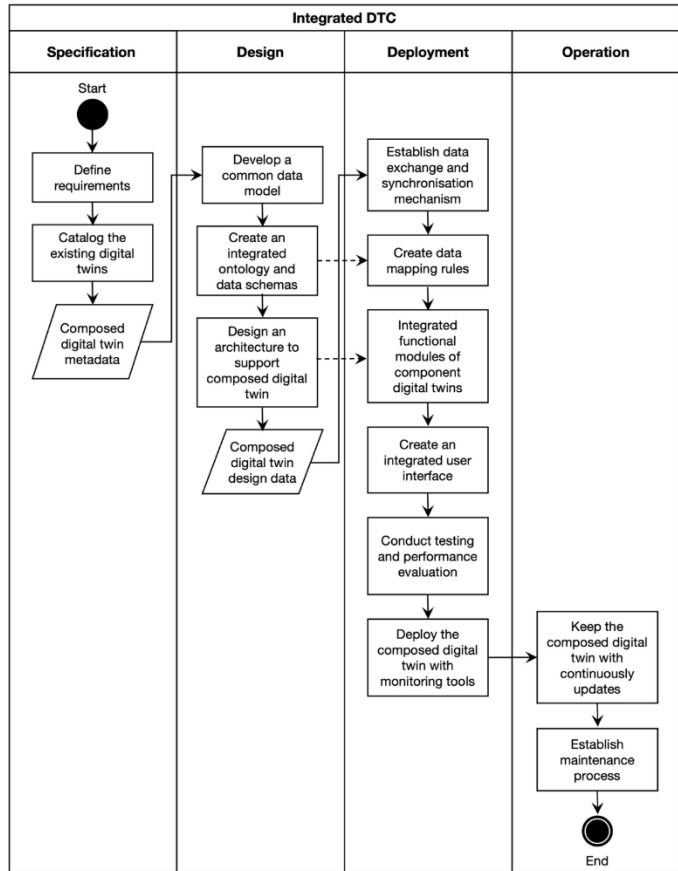


FIGURE 2. Development Procedure for Integrated Digital Twin Composition [4].

4. USE CASE IMPLEMENTATION – COMPOSITION OF DIGITAL TWINS OF A ROBOT ARM AND A GRIPPER

The use case involves creating a larger digital twin composed of two component digital twins, i.e., one for a robot arm and one for a gripper, to safely complete pick-and-place operations. The physical robot arm and gripper in the NIST Digital Twin Lab were a Universal Robots UR5e robot arm and a RobotIQ 2F85 gripper.

4.1 Specification

A robot arm and a gripper digital twins have limited capabilities when used independently. A digital twin that simulates the whole robot arm with the gripper system as a single entity shall be developed. However, creating a single monolithic digital twin for every configuration is costly and inefficient since robot arm and gripper digital twins are often developed by different vendors using different platforms. This is a perfect case for the integrated DTC. The purpose of the physical system was to perform pick-and-place operations safely. In this case, safe operation involved avoiding collisions with known obstacles and warning human operators when physical movements did not match the intended path. Performance metrics for accuracy were chosen to be a tolerance for the difference in position and rotation between the physical system and its digital twin. Based on the robot's capabilities, the positional tolerance was chosen to be 1 mm, and the rotational tolerance was set to 1 degree.

4.2 Design

Based on the requirements, the individual digital twins informed the design of the composed digital twin through their individual capabilities, data requirements, and digital interfaces. Universal Robots provided URSim, an idealized simulation of a robot arm, serving as a digital twin and mirroring UR5e's configuration and control signals, it is controlled by the same software used for the physical device. Executing the same movement commands results in synchronization between the physical robot arm and URSim. RobotIQ did not provide a digital twin for their gripper, but they did offer resources, such as 3D models, kinematic information, and a detailed manual describing the gripper's behavior, to support a digital twin implementation. With that information, a digital twin of the 2F85 gripper was developed according to the vendor's specifications and synchronized with the 2F85 gripper. This allows for the decoupling of control between physical systems and digital twins. Controlling just the digital twins enables virtual commissioning, where actions are simulated before being executed physically. This also allows for monitoring, where synchronized execution is compared in real time for checking discrepancies.

The two digital twins need to communicate with each other for composition, but they have different data formats and interfaces. The data for each digital twin needed to be

transformed into a format that the other could understand. Without the standard, an ad hoc approach might be direct conversion, where a data conversion operation is performed for every interface between the digital twins. This does not scale well when more component digital twins are involved, since the number of conversion operations would be multiplied by the number of interfaces for each added digital twin. According to the guideline provided in ISO 23247-6, the digital twins and additional modules that comprise a composed digital twin through the integrated DTC process have data and interface requirements that constrain the common data model, as the model must be able to represent the data types used by all component digital twins [4]. Using this approach, each digital twin is less coupled with others, as the required interfaces are not directly between the digital twins but rather between the digital twins and the common data model. As a result, digital twins can be added or removed as desired with less development effort.

For this use case implementation, ROS 2 is chosen as a core framework to support the common data model. ROS 2 is an open-source project that is widely used for robotics development [24]. Both Universal Robots and RobotIQ support ROS 2 in various forms, including methods for modeling, communication, and control within their products. ROS 2 utilizes the Interface Definition Language (IDL), which enables the definition and use of data types across various programming languages [25]. ROS 2 keeps a centralized registry of IDL data types that can be expanded and utilized by any module created within the ROS ecosystem [24]. ROS 2 also has facilities for communicating IDL-type instances as messages between modules [24]. The combination of vendor support, the extensible data representation offered by IDL, and the capability to send IDL as messages positioned ROS 2 with IDL as a practical framework for the common data model in this use case.

After defining the data requirements for all parts of the system and the common data model, the next step in designing the composed digital twin using the integrated DTC process is to specify the relationships between the physical systems (i.e., OMEs), each digital twin, and any additional functions. ISO 23247-2 provides a reference architecture for representing the structure of a digital twin [26]. The format has four sections: OMEs, device communication entities, digital twin entities, and user entities [26].

Figure 3 shows the digital twin architecture for this use case mapping to the ISO 23247 reference architecture. Each individual digital twin is connected to the centralized controller through ROS 2 to report its state and receive commands. The commands are sent to the OMEs via Real - Time Data Exchange (RTDE), a communication protocol that enables direct communication with the UR5e and its attached gripper [28]. Universal Robots supports ROS by providing IDL data types that represent RTDE messages, along with ROS modules to

facilitate sending those messages to the robot. Converting raw data to the IDL data types is trivial because IDL types are usable in Python and C++ programs when registered with ROS [24]. The digital twins communicate through IDL messages defined in the common data model. The centralized controller contains additional functions to support the control and analysis of the composed digital twin. Among the extra functions is the “pose monitor”, which monitors for violations of the positional or angular tolerances between the OMEs and their digital twins. The user interface displays relevant information about the system to a human operator. The implementation of this digital twin architecture fulfills the system’s purpose and

requirements: the centralized controller has sufficient information to coordinate pick-and-place operations, the path planner avoids collisions, the pose monitor verifies accuracy, and the UI can issue warnings to the human operator when an issue arises.

The common data model for this system is a collection of data types defined in IDL that can represent all necessary data to communicate with the physical robots, their digital twins, and any additional functions. The data required to control and observe each OME and digital twin is shown in Figure 4.

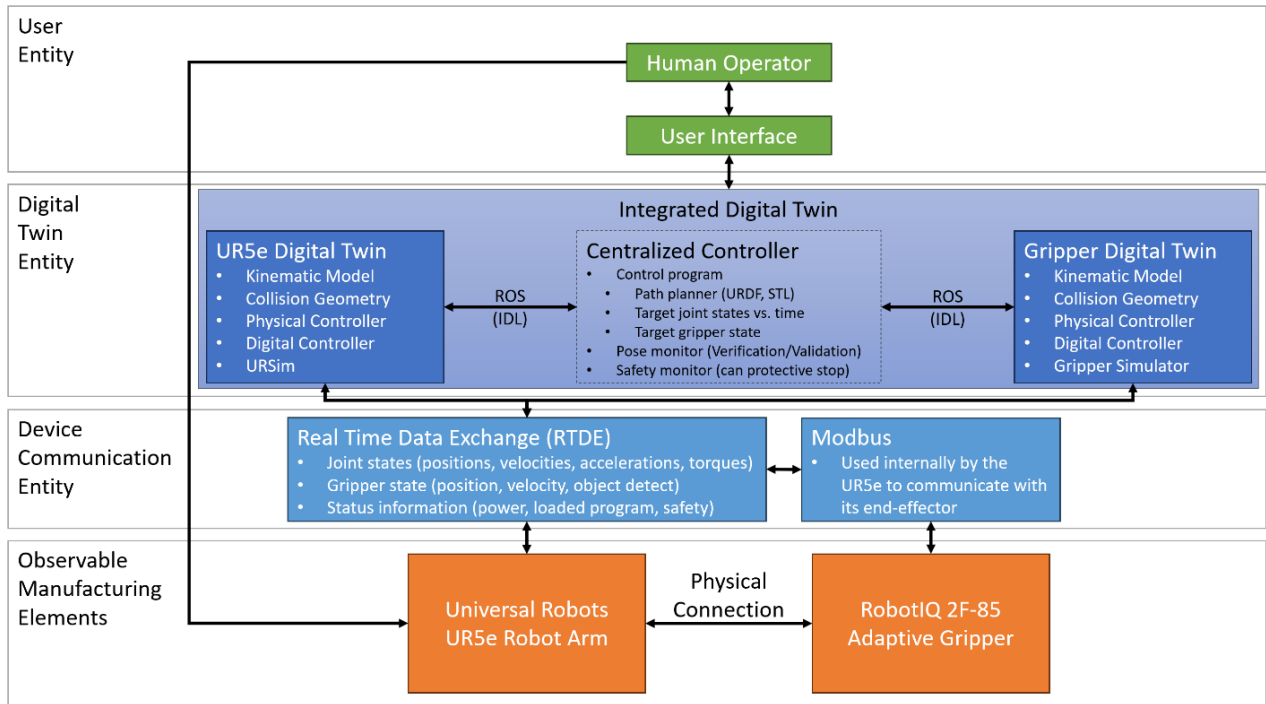


FIGURE 3. ROBOT ARM AND GRIPPER DTC BLOCK DIAGRAM.

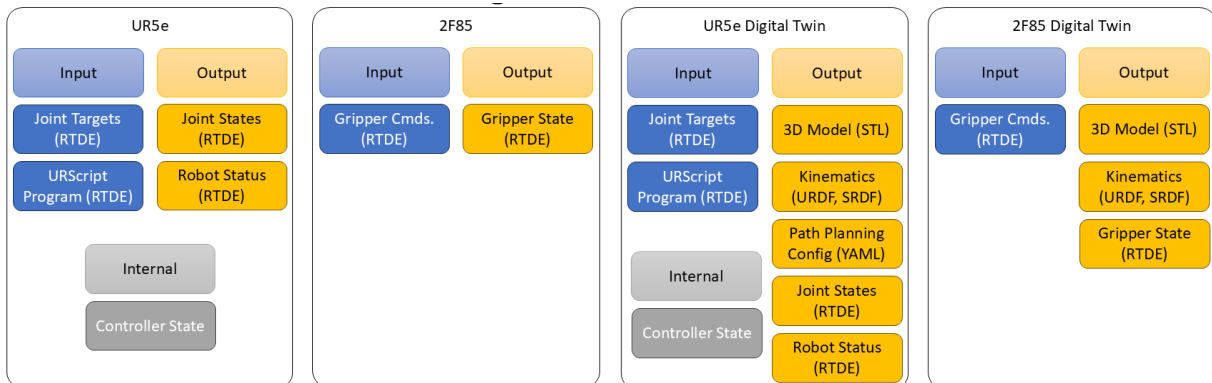


FIGURE 4. DATA REQUIREMENTS FOR OMEs AND THEIR DIGITAL TWINS.

Each OME has a type that represents the commands it accepts for control, such as “Joint Targets” and “Gripper Commands,” along with outputs that represent its physical state, including “Joint States,” “Robot Status,” or “Gripper State.” The remaining data types represent configuration data, specifically kinematics and 3D models, which are utilized for additional functions, such as path planning or UI.

The additional functions also contribute to the common data model. Figure 5 shows the data types required for each. Some of the inputs to these functions are output from the OMEs or their digital twins, i.e., kinematics information. Some outputs are directly communicated to the OMEs and digital twins, such as joint targets, URScript programs, or gripper commands. The remaining data is communicated between the functions. The path planner outputs a joint trajectory to reach a desired target, which is a sequence of joint targets to be sent to the robot arm. The centralized controller receives input targets of various forms for the robot arm and the gripper, utilizes a path planner to generate commands for the robot arm, and sends these commands to both physical and digital entities to reach the targets. Lastly, the pose monitor computes the pose, that is, the position and orientation, of the gripper based on the joint angles of the robot arm. The pose monitor also calculates the difference between the OME and digital twin poses, referred to as the “pose error.” To summarize, Table 2 lists the component digital twins (i.e., UR5e Robot Arm twin and RobotIQ 2F85 Gripper twin), required exchange data, interfaces and protocols, and added translation integration layers.

4.3 Development

In this phase, the composed digital twin is developed based on the design and often requires multiple iterations of modifications to the assumptions and system structure to achieve optimal results. Much of the development of this system involved creating models for ROS to facilitate communication between the digital twins and their OMEs, as well as implementing additional functions. The development phase also includes developing a user interface for the composed digital twin, which may reuse whole or parts of the component digital twins’ interfaces. In this case, the user interface for the UR5e included the teach pendant for the physical robot and the URSim UI. The gripper digital twin UI displayed its current state: position, velocity, and force. The composed digital twin UI included a plot for the path planner, a 3D visualization of the entire robot in space, and a graph tracking the pose error between the physical and digital grippers. Figure 5 shows the physical robot arm with an end effector, individual component digital twins (i.e., for both the robot arm and the end effector), as well as the composed digital twin of the robot arm (aka integrated digital win).

Preliminary verification and validation are performed to ensure that the system meets its requirements. For this system, both the functional requirement of moving the robot arm and the gripper for pick-and-place operations, as well as the position

and orientation tolerances of 1 mm and 1 degree, were evaluated by executing a sequence of motions and gripper commands. After initial testing, the pick-and-place operation was successful; however, a positional error of approximately 2 mm was measured when the robot arm was stationary. After reviewing the configurations for the path planner and robot arm controllers, it was found that the tolerances for each were set to 1 mm, which compounded the measured 2 mm error. After these tolerances were reduced so that their sum was less than 1 mm, the measured positional error was within tolerance. This completed the preliminary verification and validation for the DTC process and the composed digital twin.

TABLE 2. SUMMARY OF COMPONENT TWINS, EXCHANGED DATA, INTERFACES PROTOCOLS, AND ADDED TRANSLATION LAYERS.

Component Twin / Module	Exchanged Data	Primary Interfaces / Protocols	Added Translation / Integration Layers
UR5e Robot Arm Digital Twin (URSim)	Joint targets, joint states, robot status, kinematics, trajectories	RTDE, ROS 2, IDL	ROS 2 IDL mapping for RTDE messages
RobotIQ 2F85 Gripper Digital Twin	Gripper commands, gripper state, position, velocity, force	RTDE, ROS 2	Custom RTDE-to-ROS translation
Centralized Controller	Commands, trajectories, pose error, coordination logic	ROS 2, IDL messaging	Common data model orchestration
Path Planner	Joint trajectories, target poses, kinematics	ROS 2 / IDL	Shared IDL data representation
Pose Monitor	Pose, orientation, pose error, tolerance violations	ROS 2 / IDL	Pose comparison and monitoring logic
User Interface	System state, warnings, visualization, logs	ROS 2 / UI modules	Visualization and monitoring integration
Common Data Model	Joint states, commands, kinematics, 3D models, status data	ROS 2 IDL registry	Semantic/data normalization

4.4 Operation

The operation phase involves maintaining the composed digital twin, which entails tracking, preserving, and enhancing the system’s performance and integrity throughout its remaining life cycle [4]. This was implemented using the logging system built into ROS 2 to log any pose tolerance violations, along with displaying a warning on the UI and a timestamp. Any future tolerance violations can be investigated by human operators to determine if hardware deterioration or software bugs are resent.

5. DISCUSSION

Digital Twin Composition (DTC) is the transition from a monolithic model to a modular ecosystem, which allows the building/acquiring of individual digital twins and then composed them as needed. DTC influences the modeling, design, and implementation of a digital twin: (1) Without composition, engineers need to try building a "one-size-fits-all" digital twin model. DTC forces a shift toward granular modeling. For example, there is no need to model a whole "Robotic Workcell" digital twin. Instead, a "Gripper" and a "Robot Arm" twins can be developed independently and then integrated together. This allows for multi-fidelity modeling, where the gripper might require high-fidelity Finite Element Analysis (FEA) for contact physics, while the robot arm only requires a low-fidelity kinematic model. Interface modeling is needed to define "ports" or "connectors." (2) Designs can be transitioned from static to reconfigurable architecture, where designers may use approaches such as AAS to "wrap" models in standardized envelopes so they can be swapped. If a new gripper is designed, it should be able to "plug and play" into the existing robot arm digital twin. Standards such as ISO 10303 STEP or DTDL can be used to ensure the digital twins can "talk" to each other once composed. (3) Implementations may use distributed execution instead of strictly local synchronization or Edge-Cloud Orchestration. For example, the gripper's digital twin might run on an edge gateway (for low latency), while the robot arm's global path planner digital twin runs in the cloud. With DTC, organizations avoid models that are so specific and rigid that they cannot be updated or integrated when the physical factory floor changes.

The challenge of DTC has evolved from "how to connect data" to "how to manage a complex system-of-systems." While

individual digital twins for a robot arm or a gripper might work perfectly in isolation, composing them could create significant friction across several layers.

- The "Virtual-to-Real" gap in DTC: Each component (e.g., the robot arm, the gripper, the sensor) has its own mathematical model and boundary conditions. When composed, there might be error accumulation, e.g., small positional errors in the robot arm digital twin (0.1 mm) combine with gripper deviations (0.2 mm), leading to a composite error that can cause the physical robot to crash while the digital twin looks a "success."
- Semantic and information silos: Even with standards like ISO 23247, achieving "Semantic Interoperability" remains a top-tier hurdle. For example, a KUKA robot arm might define "velocity" using one set of parameters, while a Schunk gripper's controller uses another. Without a Translator or Mediator, the digital twins cannot exchange high-context information.
- Synchronization and latency: Keeping multiple digital twins synchronized with their physical counterparts simultaneously is difficult. For example, if the robot arm digital twin updates at 10 ms intervals but the gripper twin updates at 50 ms due to network latency, the composed digital twin would become desynchronized. There is a lack of standardized orchestrators that can manage the many-to-many synchronization of multiple digital twins while preventing collisions in the virtual space.

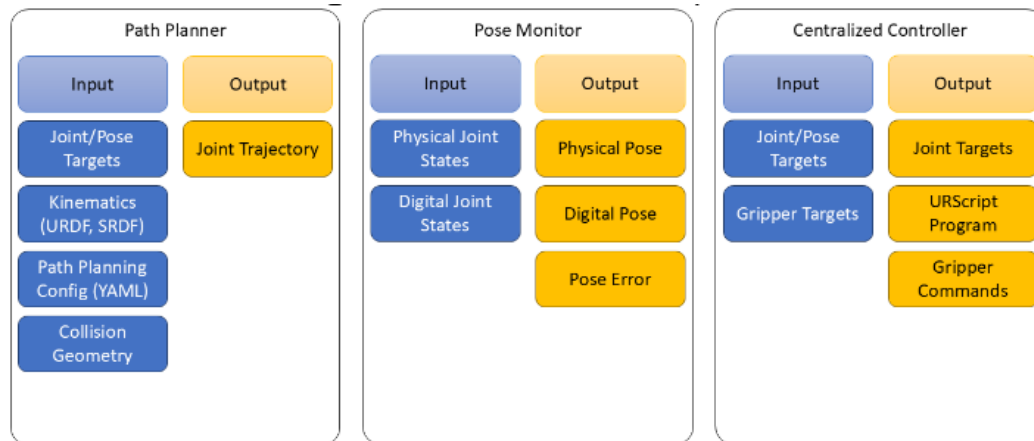


FIGURE 5. DATA TYPES FOR ADDITIONAL FUNCTIONALITY.

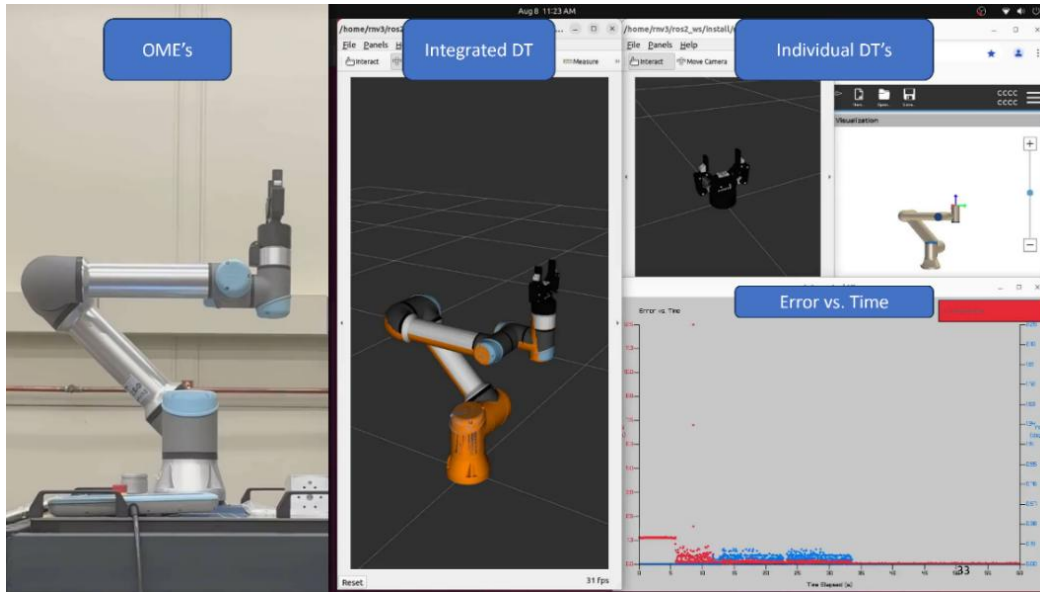


FIGURE 6. PHYSICAL ROBOT ARM, COMPOSED DIGITAL TWIN, AND COMPONENT DIGITAL TWINS.

ISO 23247-6 provides a standardized framework for DTC, specifically addressing the technical and architectural hurdles of linking multiple independent digital twins into a larger, functional system. Even though it does not provide full solutions for all the challenges discussed above, it does provide fundamental concepts, definitions, principles, methodologies, development procedures for three types of DTCs, and use case examples for digital twin composition in manufacturing. Specifically here are the benefits using this standard.

1. Eliminates architectural guesswork: One of the biggest challenges is deciding how digital twins should talk to each other. ISO 23247-6 defines three distinct patterns, Integrated, Unified, and Federated, giving engineers a clear roadmap to ensure the right approach can be taken.
2. Solves the interoperability deadlock: In multi-vendor environments, data formats rarely match. The standard addresses this by providing guidelines for various cases, e.g., a common data model for Integrated DTC and a interoperability layer for Unified DTC. Standardized protocols are required to support these.
3. Provides a lifecycle roadmap: Composition often fails because it's treated as a one-time setup rather than a continuous process. The standard formalizes a four-stage lifecycle to ensure the process is valid and stay valid.
4. Manages scalability and consistency: The standard explicitly identifies the trade-offs in different approaches. For example, it warns that while Integrated DTCs provide the best consistency, they are hard to scale when more components are added.

This use case implementation successfully showcased that DTC is an effective approach for creating larger digital twins by combining existing digital twins. Because of its relevancy,

this use case of composing a robot arm with a gripper is incorporated into ISO 23247-6 standard to illustrate the implementation of an integrated digital twin approach [4]. It provides a practical example of implementing DTC by following the standards. Therefore, this use case has a significant impact on the audience of the standards.

To answer the research questions listed in Section 2, the case study shows that, even though high-level, the development procedures in the standards provides very clear step-by-step guidelines to be followed when creating the integrated DTC for the robot arm and gripper digital twins. Composing existing digital twins can significantly reduce development time. The resources provided by Universal Robots and RobotIQ help shorten the DTC development time, increase quality, and lower costs. Third-party digital twins have a significant impact on the structure of a composed digital twin through their interface and data requirements. These requirements often vary, and design decisions made by third parties can impact the speed and difficulty of development. The integration of third-party digital twins is a critical challenge especially if multi-vendor digital manufacturing environments are involved.

- Interface mismatches, including differences in data models, APIs, communication protocols, semantic representations, and synchronization mechanisms across heterogeneous digital twin platforms.
- Data transformation and interoperability requirements, such as schema mapping, semantic alignment, unit conversion, temporal synchronization, and mediation between proprietary and standardized interfaces.
- Development and integration effort, including middleware adaptation, custom connector implementation,

orchestration logic, testing complexity, and lifecycle maintenance considerations.

These challenges impact scalability, synchronization fidelity, latency, maintainability, and overall system interoperability in digital twin compositions. The role of standardized information models and interoperability frameworks will help in reducing integration complexity and improving portability across vendors help both practitioners implementing multi-vendor digital twin systems and researchers investigating composable and interoperable digital twin architectures. In the case of the UR robot arm, Universal Robots already had support for the ROS ecosystem, which made incorporating the UR robot and URSim into the integrated DTC straightforward. However, RobotIQ did not have the same level of support, so a translation layer between RTDE and ROS had to be developed for the gripper. This highlights the remaining development costs associated with using third-party digital twins due to the need for data conversions. The common data model can make this cost manageable as scale increases. Third party-provided digital twins help reduce development time and cost, but digital twins designed to interoperate are necessary to fully realize this potential.

The primary benefit of saving development time by composing digital twins derives from the composability and compatibility of models and software. The common data model implemented with IDL in ROS enabled communication between modules, which is a critical function for software composability. Another important feature of IDL in ROS is that the central registry of types can be extended. The extensibility of IDL enables it to be flexible for new use cases and for changes to the composed digital twin. However, there are constraints when using a common data model. The requirement to represent all necessary types of data implies that the set of data types within the model may change as new digital twins are added. When these changes occur, they can incur a significant development effort if many systems depend on them. Determining data requirements before usage in dependent models helps avoid extra development effort when using a common data model.

6. CONCLUDING REMARKS

Digital twin composition is an important approach to modularizing the development of digital twins. DTC can help lower the costs by eliminating duplicated development efforts if existing digital twins are reused and designed to be composed of others. With this, DTC can help accelerate the adoption of digital twins in manufacturing. The recent extension to the ISO 23247 series, Part 6: Digital Twin Composition, represents a significant step toward creating interoperable, scalable, and reconfigurable digital twin ecosystems. By establishing principles for enabling the modular composition of digital twins, the standards provide a foundation for more integrated and dynamic smart manufacturing environments.

Looking ahead, several new aspects will enhance the standards adoption:

- Continued effort is needed to develop a new part of the standard focused on Verification, Validation, and Uncertainty Quantification (VVUQ). This will provide an essential framework for guiding VVUQ implementations that ensure accuracy, consistency, trustworthy, and reliability of digital twins.
- Demonstrating the value of various types of digital twin composition through real-world manufacturing testbeds will be critical for encouraging both industrial and research adoption of the standards.
- Clear pathways are needed to help companies integrate the new standards into their existing workflows and digital platforms, with a focus on cost-effectiveness, scalability, and workforce readiness.

The ISO 23247 framework provides a foundation for building trustworthy AI/ML models and agents that can help enhance trustworthy predictive and prescriptive decision-making. In alignment with NIST's mission, the new additions also support the development of digital twins for measurement equipment and systems, enabling new advancements in metrology. Ultimately, the success of these standards depends on broad collaboration. Stakeholders from industry, academia, standards bodies, and government are encouraged to engage in joint efforts to harmonize approaches, contribute to testbeds, and accelerate adoption. Only through such collective action can the potential of digital twin composition be fully realized to transform manufacturing.

DISCLAIMER

Certain commercial systems are identified in this paper. Such identification does not imply recommendation or endorsement by NIST. Nor does it imply that the products identified are necessarily the best available for the purpose.

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