A Six-Layer Architecture for Digital Twins with Aggregation

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Abstract. Digital twins, the cyberspace counterparts of physical systems, play an important role in cyber-physical production systems (CPPS), within the context of Industry 4.0 and the Internet of Things (IoT). In complex manufacturing systems with many digital twins, information must be aggregated, which leads to the requirement for digital twins to interact. Reference architectures for digital twins are required when digital twins from different vendors have to interact. This paper extends the Six-Layer Architecture for Digital Twins (SLADT) to a reference architecture with aggregation (SLADTA). The architecture makes maximum use of vendor-neutral off-the-shelf software, as well as secure and open protocols for twin-to-twin communication. SLADTA is illustrated through an application in a manufacturing cell scenario.

Keywords: Industry 4.0 · Cyber physical systems (CPS) · Internet of Things (IoT) · Digital twin · OPC

1 Introduction

The fourth industrial revolution or Industry 4.0 is the current trend in manufacturing automation and data exchange. The rise of Industry 4.0 is characterized by the introduction of the Internet of Things (IoT) and Services (IoS) into manufacturing facilities. Industry 4.0 is expected to exceed the first three revolutions in terms of flexibility, advanced connectivity, optimized decision-making and resource productivity and efficiency [1].

A cyber-physical system (CPS) can be defined as an embedded physical device, object or equipment, that interacts with the virtual world through a communication network [2, 3]. The vision of Industry 4.0 is to converge physical and digital entities, in the form of CPSs, to integrate the physical with the digital information world [1]. The integration of CPSs into a manufacturing environment contributes to shaping cyber-physical production systems (CPPS) [4–7].

A major contribution towards the Industry 4.0 initiative is the concept of a *digital twin*, which is the counterpart of a physical entity. The *digital twin* is an emerging technology and a key consideration for interaction between the cyber and physical worlds [8]. The concept of a digital twin, as defined by [9], is a digital information construct about a physical system that is created as an entity of its own. The digital

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information therefore forms the *twin* of the physical system and is linked to the physical system over its whole lifespan [9].

A digital twin, according to [10], is a *live* model and can be implemented in various ways, such as a digital twin of a specific asset, an entire facility or of an individual product or component. They also mention major advantages of digital twins in manufacturing, that is visualization, collaboration, and that *"Human learning and decision-making is enhanced through visualization"* [10].

The establishment of practical reference architectures is considered a major contribution towards the success of Industry 4.0. This aspect includes the need to develop real-time enabled infrastructures [1].

In this paper, the six-layer architecture for the digital twin (SLADT) [11] is extended to accommodate a multi-system environment through digital twin to digital twin communication. The idea of a *digital twin of twins* through the aggregation of digital twins is therefore considered in this paper.

In Sect. 2, an overview of the SLADT is presented followed by a discussion of digital twin aggregation in Sect. 3. In Sect. 4, the SLADT is expanded to accommodate the aggregation of digital twins. In Sect. 5, a manufacturing cell scenario is presented to illustrate digital twin aggregation using the extended SLADT. The paper draws conclusions in Sect. 6.

2 Six-Layer Architecture for the Digital Twin

Figure 1 illustrates the SLADT proposed for a manufacturing cell [11], with some minor modifications. This architecture facilitates bi-directional flow of data/information between the layers to connect a physical twin to its corresponding digital twin.

Layers 1 and 2 constitute the physical twin and consist of various devices and data sources. Layer 3 in the architecture consists of local data repositories. Here, technologies such as the Open Platform Communication Unified Architecture (OPC UA) serve as a vendor-neutral tool for collecting data from the data source layer (Layer 2) and sending it to the IoT gateway (Layer 4). The IoT gateway is a custom developed software application that acts as a data-to-information conversion layer. It receives data from Layer 2, adds context if necessary and sends the information to the cloud repository (Layer 5). Layer 5 stores historical information about the physical and digital twins. Layer 6 contains simulation and emulation tools, as well as user interfaces. As indicated in Fig. 1, Layer 6 can connect to multiple layers in the SLADT and, therefore, creates a suitable layer to provide human interaction with the digital twin. In Layer 6, the user can obtain a near real-time emulation through remote monitoring and also historical information from the cloud repository.

The layers in the architecture are not vendor dependent and provide a clear separation of roles, yet with flexibility, so that it can be implemented with new and existing manufacturing systems. The SLADT was formulated to make the maximum use of off-the-shelf software applications, without the restriction of using a particular vendor's software. Only the IoT gateway layer has to be custom-developed, although some custom development in Layer 6 may be necessary too.

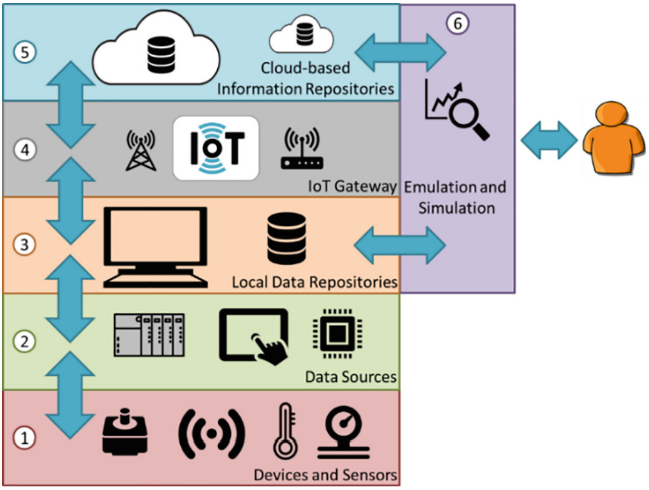

Fig. 1. Connection architecture for a digital twin (adapted from [11])

This architecture was demonstrated for a small, but typical, manufacturing component [11]. In Layer 2, a Siemens S7-1200 PLC that controlled Layer 1 was used as the data source. A KEPServerEX from Kepware Technologies was used as the OPC UA server layer (Layer 3) to obtain data from various tags in the data source layer (Layer 2). A custom C# application was used as the IoT gateway in Layer 4. Google Cloud Platform (Layer 5) was used to store historical information in the cloud. Tecnomatix Plant Simulation was used as the simulation and emulation tool for Layer 6.

The SLADT proved to be a useful architecture for representing a physical twin in cyberspace through its corresponding digital twin. However, this architecture was only demonstrated by [11] for a single physical twin.

3 Digital Twin Aggregation

Grieves and Vickers [9] distinguish between digital twin *instances* and *aggregates*. A digital twin *instance* (DTI) describes the physical twin that corresponds and remains attached to the physical twin during its entire lifespan. A digital twin *aggregate* (DTA) is the aggregation of some of the DTIs and other DTAs. While the DTI can be an independent structure, a DTA cannot. DTIs can thus be interrogated by a DTA for their current system state [9].

Kitain [10] mentions that *"The amount of data collected from monitoring a smart factory is enormous, but if that data isn't aggregated and organized in a way that can support the decision-making process, then it's of no use."*

From the above-mentioned in [9] and [10], it is clear that there is a need for aggregation, leading to the idea of a *digital twin of twins* for a manufacturing cell, which can be described as a digital twin that is aggregated from multiple digital twins. For example, an entire manufacturing cell can be represented in cyberspace by layers of digital twins through the aggregation of information from lower-level digital twins. Through the concept of a *digital twin of twins* (aggregation of digital twins), users of digital twins can make better informed decisions by interfacing with various layers of digital twins.

The remainder of this paper will investigate the expansion of the SLADT, described in the previous section to form an aggregation of digital twins.

4 Six-Layer Architecture for the Digital Twin with Aggregation

In this section, an extension of the SLADT to accommodate multiple digital twins is considered. Other possible extensions of the SLADT for digital twin aggregates will be considered in future research. The extension considered here is illustrated in Fig. 2. For brevity, the "Six-Layer Architecture for the Digital Twin with Aggregation" will be abbreviated as SLADTA.

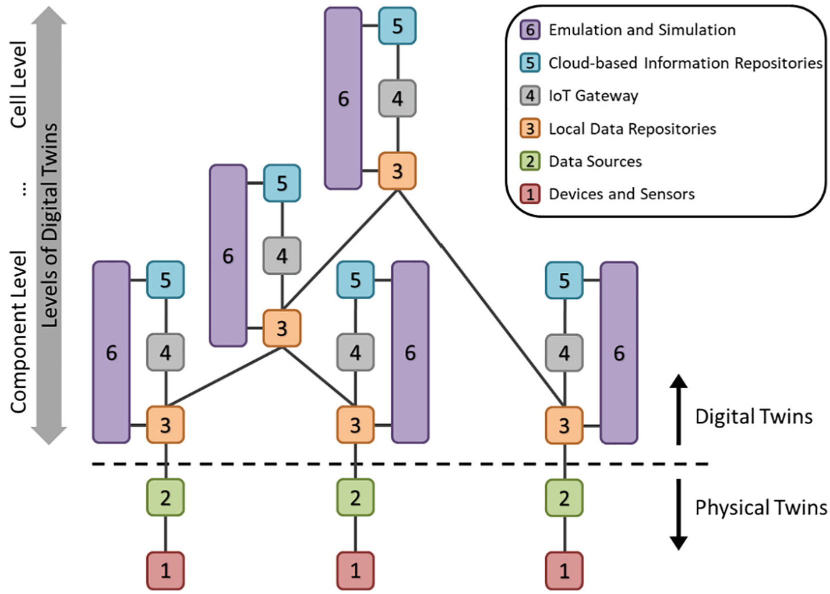

Fig. 2. Connection architecture for the SLADTA

In terms of DTIs and DTAs (Sect. 3), the lower-level digital twins in Fig. 2 can be characterized as DTIs, while the top two levels can be characterized as DTAs. This architecture can also be thought of as that of a digital twin of twins whereby, for example, the digital twin of a production plant can be broken into smaller entities or digital twins.

The connection between layers, as well as the data and information flow between digital twins, are presented in the next subsection, followed by a method of configuration. Thereafter, the rationale behind the architecture and the decision-making capabilities are discussed.

4.1 Data and Information Flow

Figure 2 presents the interaction between the higher and the lower digital twins using the SLADTA for a situation with three physical twins and three layers of aggregated digital twins. As indicated by the legend in the top-right of Fig. 2, the colours in this figure are used to identify the layers. The colours and layer types correspond to that in Fig. 1. The main aspects of this architecture are as follows:

- Every physical component with its sensors connected to a data source can be connected to its own SLADT (with all six layers).
- Higher level digital twins contain only the layers of the SLADT that are relevant, i.e. Layers 3 to 6.
- The connections between digital twins are through Layer 3, i.e. the local data repositories. In this paper, it is assumed that each Layer 3 contains at least one OPC UA server, which is used for the connections to other digital twins.
- The IoT gateway (Layer 4) manages the interaction with a higher or lower level digital twin.

Figure 3 illustrates the data and information flows between digital twins. In the SLADTA, as in the SLADT, the IoT gateway (Layer 4) converts data to information and is the main (or only) custom-developed software.

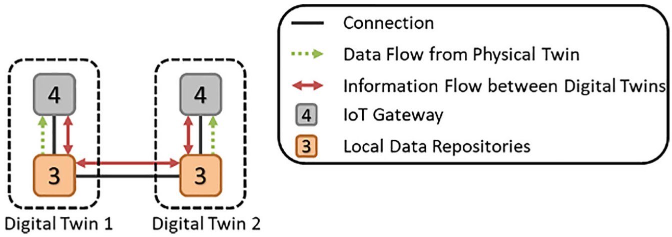

Fig. 3. Data and information flow between digital twins

Layer 4 is therefore the logical layer to manage the interaction with a higher or lower level digital twin, but the information from one digital twin's IoT gateway is passed through an OPC UA server on Layer 3 to an OPC UA server in the other digital twin's Layer 3 and then to its Layer 4.

4.2 Flexible and Reconfigurable Configuration

Large hierarchical structures can be difficult and expensive to design, maintain and modify [12]. Therefore, this section considers implementing modularity and reconfigurability: Each digital twin can be configured using the IoT gateway connection to the cloud server in Layer 5, through a record of its configuration in Layer 5. After the information is obtained from the cloud, the IoT gateway can then, for example, subscribe to the relevant OPC UA tags through a connection to the OPC UA server on Layer 3.

The IoT gateway configuration can efficiently be recorded as an Extensible Markup Language (XML) document, which facilitates adding context to data. Depending on the configuration, the XML document can include aggregation of information, along with the other data-to-information conversion configuration information required for its other roles. In the XML example, the *System Name* corresponds to the name of the system or subsystems of interest. The *Attribute* represents the type of tag such as – geometry, sensors, control tags, etc. Under the *Attribute* tab, each tag consists of a *Name*, *OPCID*, *DataType*, *Value* and *ScaleFactor*. Presented below is a short example of such an XML configuration:

```
-<Systems>
    -<System Name>
          -<Attribute>
                <Name>” “</Name>
                <OPCID>” “</OPCID>
                <DataType>” “</DataType>
                <Value>” “</Value>
                <ScaleFactor>” “</ScaleFactor>
          -<Attribute>
    -<System Name>
-<Systems>
```

Since the configuration record on Layer 5 may contain confidential information, the record should be accessible to only its own digital twin. This arrangement also simplifies changes to the record, since only one digital twin has access to it. However, similar configuration information may need to be exchanged between digital twins in the aggregation. To facilitate this exchange, the IoT gateway of each digital twin can create a similar XML document, convert it to a string format and send the string to its OPC UA server as a string data type. The cloud-based configuration record will also contain all the OPC UA connections that a digital twin must establish with other digital twins, as well as the tag of the configuration string on each OPC UA server. When the configuration string is changed, that OPC UA server will send a notification of the change to all the OPC UA clients that subscribed to the tag, thereby communicating the configuration (or an update thereof) to other connected digital twins. Once the higher-level digital twin has received the configuration from a lower level one, and decoded the XML document, it can selectively subscribe to tags in the lower level digital twin's OPC UA server.

The value of configuring the digital twin from the cloud and communicating related configuration information between digital twins as described above can be summarized as:

- Increases modularity and flexibility;
- Simplifies data aggregation;
- Minimizes the IoT gateway application development (avoiding reprogramming);
- Adds reconfigurability to the physical and digital twin setup – when a physical twin and its digital twin is added or removed from the manufacturing cell, only the configuration records of the other digital twins affected by the change, needs to be updated;
- By updating the cloud database table, the IoT gateway will reconfigure the digital twin (e.g. by adding/removing sensor or control tags).

4.3 Rationale

As shown in Fig. 2, in the SLADTA the interconnections between digital twins are restricted to interconnections between their respective local data repositories (Layers 3). The advantage of this restriction is that the aggregation can be done using off-the-shelf software with good cybersecurity mechanisms, such as OPC UA. The IEC 62541 standard OPC UA has been recommended by the Reference Architecture Model for Industry 4.0 (RAMI 4.0) for implementing the communication layer [13]. Cybersecurity is a major challenge in the era of Industry 4.0 and hackers are continually attempting to gain access to system information by infiltrating weak points in system connections [14]. OPC UA is claimed to be able to provide Industry 4.0 related requirements such as real-time performance and reliability, data security and integrity, integration and interoperability between production, non-production, business and IT systems [15]. OPC UA is therefore able to assist in secure communication between digital twins. The confidentiality of data and information exchange is secured through OPC UA connections as the exchange of messages are encrypted [16].

From a hierarchical perspective, the SLADTA makes use of master/slave relationships. Information flows upwards from the lower to the higher levels of digital twins and, potentially, requests or instructions can flow from higher levels to lower levels. The type of software typically used in Layer 3 is not suited to managing these flows. Therefore, the flows are managed by the custom developed IoT gateway application in Layer 4. As illustrated in Fig. 3, the IoT gateway receives data from its own physical twin (if it is connected to a physical twin) and generates the information that is made available to other digital twins.

The SLADTA provides for the aggregation of information from various digital twins, and also allows for segmentation of the information. This segmentation can be especially beneficial where components from different companies or original equipment manufacturers (OEMs) are interacting in the same station, cell or system. The various stakeholders can retain ownership over some data/information from their components, while providing selective access to information to other digital twins. Each digital twin can then have access to component information without breaching data confidentiality. This motivates the major reason for maintaining Layers 5 and 6 for each digital twin. For simplicity, and to indicate the separation of information of the various digital twins, Layers 5 and 6 were separated in Fig. 2, but the entire production facility can also be connected to one cloud instance (Layer 5) and simulation and emulation tool (Layer 6).

The higher-level digital twin is an aggregation (compilation) of lower-level digital twins. This architecture therefore exhibits the *fractal* characteristic, where a digital twin can comprise of multiple digital twins. Aggregating the information, through communication between multiple digital twins, reduces complexity by encapsulating the functionality of related information for each digital twin. This is also known as the concept of *separation of concerns* by reducing complexity and breaking a large digital twin into smaller digital twins of encapsulated functionality. Each digital twin is then flexible, intelligent and able to make decisions. The higher-level digital twin only obtains the relevant information that is required from the lower-level digital twin. Less information is then processed through a single IoT gateway of a digital twin.

Two alternative connection architectures will briefly be considered here; the first is with Transmission Control Protocol/Internet Protocol (TCP/IP) communication directly between IoT gateways. This alternative was not chosen here for security and stability reasons. The IoT gateway is typically a custom developed software application and would often be developed by a party such as a manufacturing system integrator, who may not be well versed in cybersecurity issues. Therefore, connections between IoT gateways can create weak entry points for cyber-attacks. Also, maintaining reliable TCP/IP connections between applications developed by different companies require mutually agreed protocols and specific development expertise. Restricting connections between digital twins to their Layers 3, avoids both these complications.

The alternative connection architecture is the interconnection through the cloud-based repositories (Layer 5). The strengths and weaknesses of such architecture should be explored in future research, but for the work presented here, the longer communication latencies that can be expected in this architecture were unacceptable.

4.4 Decision-Making Capabilities

The roles of digital twins can include making decisions based on the information in the digital twin and external inputs from users. This section considers in which layers of the SLADTA decisions should be made.

In the SLADT (Fig. 1), Layer 6 connects directly to Layers 3 and 5, as well as with the user. Layer 6 is thus provided with the current status information and also historical information and is, in that respect, well placed to make decisions. The user interfacing with the digital twin through Layer 6 can also make informed decisions. To aid in the decision making and informing the user, Layer 6 is typically equipped with simulation and emulation capabilities, such as Tecnomatix Plant Simulation. This layer can further use the growing range of available cloud-based apps to exploit the information stored in the cloud-based repositories on Layer 5. The extended architecture in Fig. 2 preserves these advantages of allocating decision making to Layer 6. However, in both the SLADT and the SLADTA, decision making in Layer 6 may be hampered by latencies, with latencies lengthening as information is drawn from higher levels of the SLADT.

The IoT gateway (Layer 4) is custom developed software and could also potentially contribute to decision making. However, in the SLADT, the functionality of the custom developed IoT gateway application (Layer 4) has been restricted to converting data to and from information. Restricting the decision making in Layer 4 to what is required for such conversions helps to keep this custom developed layer small and robust. In the SLADTA, the IoT gateways are allocated additional responsibilities, in particular to interpret information received from other digital twins, taking into account its own context. The IoT gateway must also resolve conflicting information received from multiple sources (e.g. the cloud-based repository vs. another digital twin). The IoT gateways further are responsible for setting up the aggregation connections as described in Sect. 4.2.

In manufacturing scenarios, the data sources on Layer 2 often correspond to controllers such as PLCs. Time-critical and safety-related decisions should preferably be made in this layer, because these decisions are closest to the equipment (fewer connections need to be maintained) and latencies are at a minimum. On the other hand, implementing complex algorithms in these controllers is often not productive and better handled in Layer 6.

In the SLADTA shown in Fig. 2, the digital twin of a single physical twin has access to the information from its own physical twin (Layer 2), its own cloud-based data repository (Layer 5), its own Layer 6 and higher level digital twins (communicated through its Layer 3). Such a lowest level digital twin can therefore make decisions based on its internal context, and also with selected information from its broader context. An aggregated digital twin's situation is similar, except that, from the aggregated digital twin's perspective, its lower level digital twins fulfil roles similar to Layer 2 and the aggregated digital twin can make decisions that involve multiple physical twins or processes.

5 Application in a Manufacturing Cell Scenario

In this section, an application of SLADTA for a typical manufacturing cell scenario is presented, as shown in Fig. 4. This case study example presents a manufacturing cell which consists of several stations for a typical pick-and-place process. A more complete evaluation of the SLADTA and the various implementation strategies used in the case study is beyond the scope of this paper (due to length restrictions) and therefore only an example case study implementation is covered briefly in this section.

It must be acknowledged that the case study is relatively simple since a connected architecture of multiple digital twins can involve many complexities and variations. One of these complexities, which should be considered in future research, is subsystem interdependence, where subsystems are collaboratively interdependent, i.e. processes in one subsystem depend on the processes of other subsystems. An example of this is when the end effector of a robot and the robot has each its own digital twin. Another complexity is where the interconnections between digital twins change during operation, such as when a robot's end effector is changed from time to time. Such changes will not only affect the digital twin of the components, but also the aggregated digital twins.

In this case study (Fig. 4), the pick-and-place cell consists of four physical twins: a robot without an end effector (PT-A), an intelligent gripper (PT-B), a robot with a gripper fully controlled by the robot's controller (PT-C) and a conveyor with part sources and destinations (PT-D). Each of the physical twins, which all contain a data source, has its corresponding digital twin (DT-A, DT-B, DT-C and DT-D). DT-AB presents an aggregation of DT-A and DT-B. The cell-level digital twin (DT-ABCD) forms an aggregation of digital twins DT-AB, DT-C and DT-D.

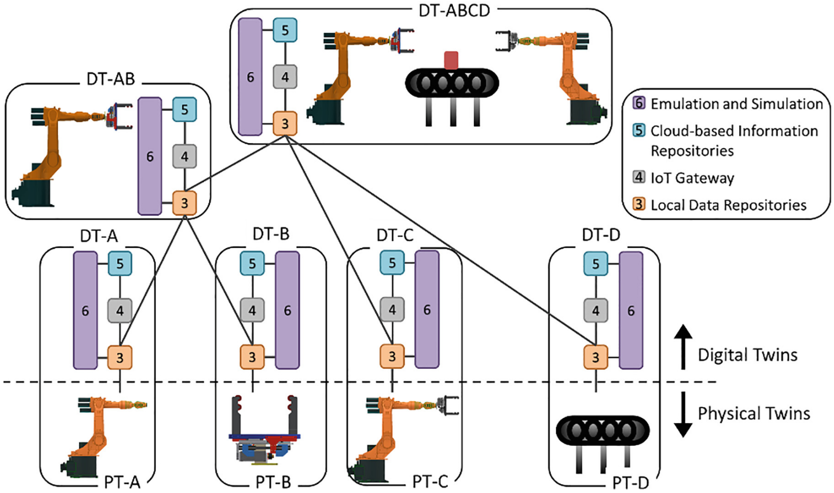

Fig. 4. Layered digital twins for a manufacturing scenario

As shown in Fig. 4, if a physical twin is connected to a data source (often a controller), then the OPC UA server (Layer 3) is able to obtain the status of the physical twin. It is therefore presented in this figure that, even though PT-A and PT-B forms part of the whole, they can each have their own digital twin. It is also further shown in Fig. 4 that the information of each physical twin is encapsulated by its corresponding digital twin (i.e. DT-A has access to all the information available from PT-A).

In some cases, PT-A and PT-B can be manufactured by different companies. These companies might want to maintain confidentiality over some of the data/information that is obtained from each physical twin. The OPC UA servers of DT-A and DT-B can be set up so that DT-AB will only have access to the information that is made available to it by DT-A and DT-B, thereby maintaining data confidentiality.

As an example, consider the data and information flows in the case study scenario (as presented in Fig. 4) where the aggregated digital twin (DT-AB) obtains the information about both physical twins PT-A and PT-B, through subscribing to the relevant registers in the OPC UA servers on Layer 3 of DT-A and DT-B. The information from both physical twins can then be combined by DT-AB and stored in the OPC UA server in its Layer 3, to which DT-ABCD can subscribe. The flows are visualized in Fig. 5. In this simple example, the power consumption of each component is aggregated to a higher-level digital twin. The raw power consumption data of the robot (P_R) and the gripper (P_G) is obtained from the data sources (Layer 2) of the physical twins through Layer 3. The IoT gateways of DT-A and DT-B obtain this data from Layer 3 and calculate the average power of the robot (P_{RA}) and gripper (P_{GA}). The aggregated digital twin (DT-AB) can then calculate the average power consumption of the robot-gripper combination (P_{RGA}) using the IoT gateway (Layer 4).

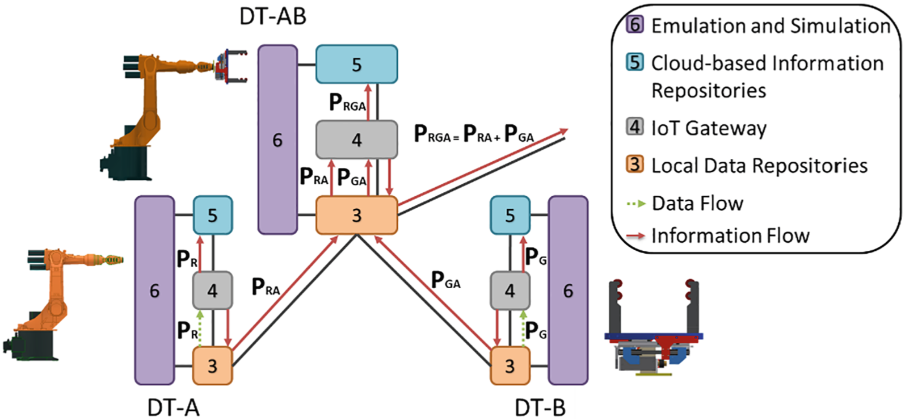

Fig. 5. Connection architecture for the SLADTA

6 Conclusions

The paper presents the SLADTA, an extension of the SLADT to accommodate the aggregation of multiple digital twins. In SLADTA each physical system component connected to a data source can have its own digital twin according to the SLADT. The information from each physical twin, through the lowest level digital twins, can then be aggregated to higher-level digital twins. The digital twin aggregates do not have Layers 1 and 2 of the SLADT, but their local data repositories (Layer 3) are connected to other digital twins in a hierarchical arrangement. OPC UA offers numerous advantages for implementing such connections on Layer 3. Although the interconnections are on Layer 3, the flow of information between digital twins is controlled by each digital twin's custom developed IoT gateway (Layer 4). The IoT gateway is also able to configure the digital twin, including its interconnections with other digital twins, using a configuration record from the online cloud repository (Layer 5).

The SLADTA therefore exhibits the desirable characteristics of modularity, flexibility and reconfigurable aggregation. The architecture further makes provision for controlling access to information, thereby preventing access by one digital twin to confidential information in another, and for each level of digital twin to implement safeguards when instructions are received from higher level digital twins. Through the separation of concerns, the decision-making is encapsulated to the information that is available for each digital twin.

A manufacturing cell scenario is also presented in this paper to illustrate the layers of digital twins for a realistic manufacturing environment. The scenario comprises of various components (physical twins) that are each connected to their corresponding digital twins. In future work, the SLADTA will be demonstrated as a proof of concept for a realistic and complex manufacturing environment.

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