# Data-centric Middleware based Digital Twin Platform for Dependable Cyber-Physical Systems

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***Abstract* - the concept of digital twin, a kind of virtual things with the precise states of the corresponding physical systems, is suggested by industrial domains to accurately estimate the status and predict the operation of machines. Digital twin can be used for development of critical systems, such as self-driving cars and auto-production factories. There, however, will be so different digital twins in terms of resolution, complexity, modelling languages and formats. It is required to cooperate heterogeneous digital twins in standardized ways. Since a centralized digital twin system uses too big resources and energies, it is preferable to make large-scale digital twin system geographically and logically distributed over the Internet. In addition, efficient interworking functions between digital twins and the physical systems are required also. In this paper, we propose a novel architecture of large-scale digital twin platform including distributed digital twin cooperation framework, flexible data-centric communication middleware, and the platform based digital twin application to develop a reliable advanced driver assistance system.**

***Keywords—Communication Middleware; Digital twin; CPS; Modeling&Simulation; ADAS***

## I. Introduction

In the last decade, CPSs (Cyber-Physical Systems) have been introduced to physical fields, such as manufacturing, agriculture, homecare, automotive, traffic control, military, etc. As widely believed, CPS is a kind of a dependable system in which it supports reliability, real-time, robustness, stability, safety and security, etc. Since in many cases CPS components or sub-systems are distributed and inter-connected over networks, deep monitoring the sub-systems is necessary to orchestrate the CPS as an entire system in a well-designed way. It is the reason why CPS is called as "a system of systems". CPS has many heterogeneous aspects and features in terms of applied key technologies for the CPS [1]. For instance, design approach has many modeling architectures, simulator & simulation engines, tools and programming frameworks and V&V (Verification & Validation) methods. Of course, there are lots of CPS-based applications guaranteeing QoS, reliability and security. In other words, it is very clear that the integration of heterogeneous CPSs will be extremely difficult, complex and troublesome work. The more IoT connectivity extends, the larger the demands of CPS integration are. That is to say, IoT accelerates the speed of CPS evolution to a large-scale system [2]. Especially, a large-scale CPS suffer from interworking issues, time synchronization between cyber part and physical part, data transparency problems and QoS guaranteeing, etc.

Recently, a brand new terminology of CPS, named digital twin, was made and deployed in manufacturing domain [3]. Since digital twin is a perfect digital entity of a physical system, it accurately reflects the status of the corresponding physical machine. We can tightly control the system through digital twin, that is, cyber model of the machine. In addition, we can get the prediction of a physical machine operation by means of precise simulations of the digital twin. Digital twin concept is very useful in safety critical systems such as ADAS (Advanced driving assistant system) and mission critical system such as manufacturing control system. Therefore, effective interworking functions between digital twins and physical systems is required to develop and validate systems based on digital twin [4]. And co-simulation functionalities between heterogeneous digital twin models are necessary to enhance the scalability of digital twin. As you know, there are so many modeling languages and simulation architectures for CPSs. If we try to extend digital twin space, co-simulation between different models or between a digital twin and its physical system will be required. In this regard, some communication capabilities are required to support the functions in various network environments. For example, the functions include reliable transmission between multiple entities, mixed format data transfer, dynamic object discovery, and so on.

In this paper, we propose a digital twin platform for safety critical CPS, such as a self-driving electric vehicle with ADAS. The platform-based approach, generally speaking, has scalable and flexible services to various applications. However, a localized platform has limitations in terms of acceptance and distribution in industrial domains. We decide to adopt international standards for our digital twin platform, named uDiT (universal Digital Twin platform), which has many functions: a data centric communication middleware based on OMG (Object Management Group) DDS (Data Distribution Service), middleware and digital twin runtime engine interface, co-simulation functions based on FMI (Functional Mockup Interface), gateway functions for media and protocol conversion. The paper is organized as follows. Section 2 gives the legacy design approaches for CPSs and the background knowledge about the legacy communication middlewares for digital twin. Section 3 presents the overview of uDiT architecture, data centric communication middleware of uDiT, co-simulation interfaces and a case study of reliable ADAS development. In the last section, we conclude this paper and describe our future work.

## II. Related Works

### A. Design of Cyber-Physical Systems

The cyber-physical system refers to the integration of embedded computers and networks with physical processes. CPS, which monitors and controls in the network through feedback on various physical processes, can provide many applications such as manufacturing and smart structures, defense systems, traffic control and safety, and networked autonomous vehicles [5]. These diverse CPS applications increase complexity by building large-scale service systems. Synchronization of parameters in the virtualization space and physical processes is also required for real-time performance. Due to these characteristics, a method has been proposed to abstract the system and separate control tasks into action primitives. Separate action primitives can reduce the CPS suitability of large systems. In order to eliminate the difference between the abstracted system and the actual operation, P. Martin and M. Egersedt constructed an intermediate process to inline the physical details that affect the execution [6]. PESSOA 2.0 proposes an integrated controller that automatically synthesizes the cyber-physical system modeled by the equation of differential equations and automata. It provides a controller that can properly control heterogeneous systems by using abstraction parameters as inputs [7]. It is also proposed to provide synchronization of the physical model with continuous system simulation by automatic code mapping. Y. Zhu et al. Analyze physical phenomena analytically. They proposed automatic mapping from analysis models to simulation code. By modeling the complex functions of a real system and automating the mapping of models and continuous system simulations to code, the gap between models and simulations can be eliminated [8].

### B. Communication Middleware for Digital Twin

Each component of the Digital Twin system could have a heterogeneous systems, however information exchange between heterogeneous systems with interoperability is required. Communication middleware technology is applied to provide a flat communication environment for exchanging information between these heterogeneous systems. In CPS domain, various communication middleware is used such as DDS, HLA/RTI, MQTT, RT-CORBA. The functional comparison between representative communication middleware is shown in Table1.

In the real world, the state of physical assets of the system changes in real time, therefore real-time interworked with the cyber model is required for forming a digital twin. To do so the communication middleware should provide a real-time communication environment. The digital twin systems scale from one product to the factory and the city. Which scales are composed a lots of digital twins. So communication middleware should support high scalability and reliability and real-time services.

### C. Interworking functions for heterogeneous cyber model

For intelligent monitoring and prediction using digital twin, it is necessary to interwork of components in heterogeneous environments. And M&S based on distributed computing required for efficient system development. In this background, Functional Mock-Up Interface (FMI) has been proposed as a result of a Modelisar project for interworking between heterogeneous simulation environments [13]. FMI is a tool independent standard for exchanging of dynamic models and co-simulation. FMI consists of two modes, which are FMI for model exchange and FMI for co-simulation. FMI for model exchange, which exchanges only the simulation model, and FMI for Co-Simulation, which supports interworking simulation [14]. Dynamic simulation model is interpreted to the Functional Mock-Up Unit(FMU) for using FMI. And The FMU is loaded to simulator, which support FMI, and simulated even though simulation environments are different. Because of these strengths FMI technology can use in various CPS development. In the process of CPS development, rapid prototyping is possible by a model based simulation applying FMI [15]. FMI co-simulation applied to HLA/RTI which support distributed

Table 1. Functional Comparisons of Communication Middleware

| | **Communication Middleware** | | | |
|---|---|---|---|---|
| | **DDS [9]** | **HLA/RTI [10]** | **MQTT [11]** | **RT-CORBA [12]** |
| Data transmission | Pub/Sub | RTI controlled | Broker Pub/Sub | Broker |
| Communication architecture | Distributed | Centralized | Centralized | Centralized |
| QoS | 22 policies | Reliable, Ordering | 3 policies | Real time |
| Real-time | Soft Real Time | Non Real Time | Non Real Time | Hard Real Time |
| Scalability | Middle | Low | Low | Low |
| Dynamic participate | Support | Not support | Support | Support |
| Support scale | Middle scale | Small scale | Small scale | Middle scale |

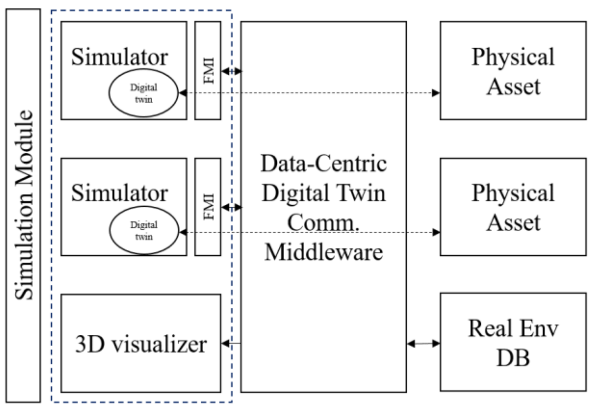


**Figure 1. Architecture of uDiT Platform**

simulation interworking technology to support distributed co-simulation [16].

## III. The Overview Of uDiT Platform

In this section, we design the architecture of digital twin based reliable physical system development platform. we propose DDS based data-centric communication middleware for Digital twin platform. Finally, we suggest a scenario of ADAS development & validation process using uDiT.

### *A. Design of uDiT Platform*

#### *1) Architecture of uDiT Platform*

Figure 1 shows the structure of the uDiT platform for physical system development. It provides interlocking with physical asset and cyber model as a digital twin by a communication middleware. For context-matched simulation of these digital twin in heterogeneous simulators, FMI technology is applied. Distributed co-simulation between these simulators is performed through the data-centric communication middleware for reliable simulation. Also, received data from the Real Env DB, which store data about the environment data around the physical asset, applies to the simulation process to enable more accurate simulation. Finally, visualization based on the simulation results in the 3D visualization helps the simulation verification of the physical asset.

#### *2) Development Process using uDiT*

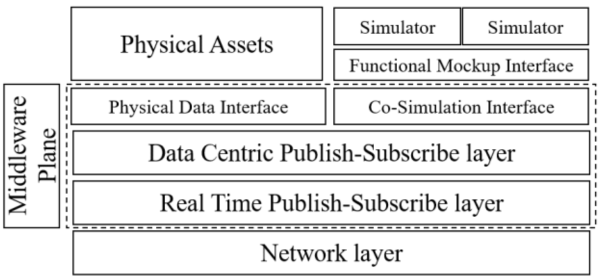


**Figure 2. uDiT platform with Middleware.**

Data of target system that are needed to test is reflected in digital twin model. Based on data onto the Digital Twin model, the simulation is performed and the simulation results are presented to the user. Simulated system is verified with the 3D visualization and feed data back into the simulation module and, if necessary, reset the target system and repeat above process. This development process can reduce the risk and cost of testing and validation.

### *B. uDiT based on communication middleware*

uDiT platform supports interworking of reliable physical assets and digital twins and co-simulation between simulators of simulation modules. Figure 2 shows the middleware architecture.

#### *1) Requirements of Data-Centric Middleware for uDiT*

Since digital twin is a kind of CPS that has a real-time interworking with physical assets and cyber models, these digital twin nodes interconnect with each other. Thus, a digital twin system requires real-time data distribution. The specific

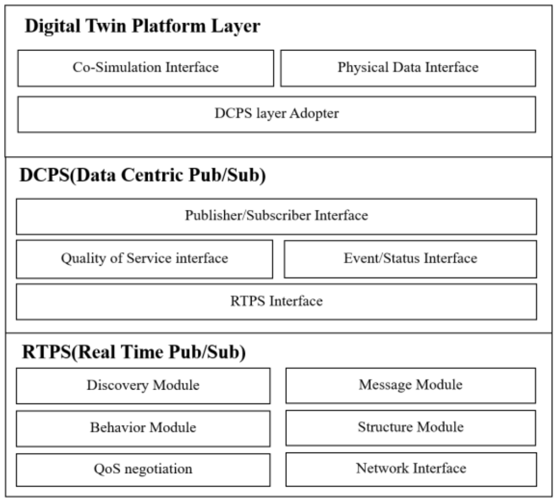


**Figure 3. uDiT Communication Middleware**

QoS requirements are also necessary for digital twin interworking. During simulation step, communication middleware provides simulation data interface to each simulator for co-simulation communications. These co-simulation communications should consider time synchronization between simulators. On the other hands, digital twin middleware also considers about interconnection with a physical asset. In physical side, the data format is not a formal type but a complex type. The digital twin model is a 'twin' that accurately reflects the complex data of physical asset. Therefore, it is necessary to manage and transport multimedia data.

In order to satisfy the requirements, digital twin communication middleware should offer real-time interworking environments. It provides accurate reflection to cyber model about physical asset and time synchronization between each simulator that is necessary for accurate simulation. Therefore, the real time connection is an important element of communication middleware. However, only one middleware cannot provide the all functions. First of all these requirements, reliable interworking should procedure for satisfying the others. Therefore, we propose an additional layer to formal data-centric middleware for providing the reliable digital twin interworking environment. The most important thing is to support accurate reflection of physical asset to cyber model. It helps co-simulation by applying simulation context matching technology.

#### *2) uDiT Communication Middleware*

As depicted in Figure 3, the proposed DDS-based data centric communication middleware has three layers. The DDS includes two layers. The one is Data-Centric Publish-Subscribe (DCPS) and the other is Real-Time Publish-Subscribe (RTPS). We implement the DCPS layer for DDS-based publish/subscribe. DCPS layer includes connectivity with application service to the publisher/subscriber, and provides interface to set QoS policy required application layer. An interface to exchange events and states from other participants of the DDS is also

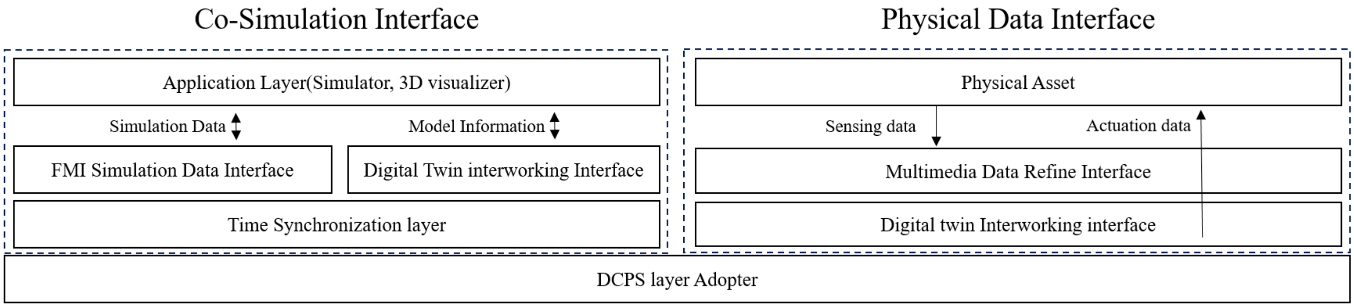


**Figure 4. Detail of digital twin platform layer**

provided. Then DCPS is served by RTPS for actual communication through physical networks. The RTPS layer includes a discovery module for finding other objects requiring communication and a module for defining the structure and the contents of a message to be exchanged. In addition, a module that reflects the requirements of the QoS of the application received through the DCPS layer to satisfy the required QoS, such as real-time performance, is also included. In order to construct DDS based digital twin communication middleware, we propose the addition of digital twin platform layer as an upper layer from DCPS layer. As described above, the digital twin requires real-time interworking of the physical side and the cyber side, and an interface should be made as well. The proposed digital twin platform layer consists of two modules. Co-simulation Interface to provide a communication environment of cyber model and co-simulation of models, and Physical Data Interface to collect data from the physical side asset. The detail structure of uDiT platform is shown in Figure 4.

*a) Co –Simulation Interface*

Co-simulation interface consists of functions for supporting co-simulation and exchanging data with digital twin. In order to help co-simulation between FMI-supported heterogeneous simulators, an interface to exchange FMI-based simulation data is provided. The interface not only helps to send and receive simulation parameters and data between each simulator during the co-simulation process, but also provides the control function of the entire simulation. For reliable simulation, digital twin model is required to be precisely interworked. The digital twin interworking interface is included as an interface to support this. It provides a connection the sensing data of the physical asset received the parameter value of the digital twin model through the DCPS layer and the RTPS layer. In order to reflect reliable simulation and accurate model information, time synchronization of each element is also required. To add time synchronization layer under each interface layer, time information is exchanged in the communication process and the simulation step is shared.

*b) Physical Data Interface*

Physical Data Interface is provided for accurate interworking of Digital twin with Physical Asset. As described in the above requirements, a complex form of data collection and transmission is required for an accurate reflection of the digital twin. So, in order to transfer the collected complex multimedia data, an interface for refining the data in a form suitable for transmission is provided. The digital twin interworking interface for the ability to transmit refined data in a form suitable for interfacing with the digitally matched digital twin is also included in the physical side connection. And the actuation data from cyber model are provided by this layer.

### *C. Multimedia Data on uDiT*

In digital twin system, data of the real world should be collected multimedia data (e.g. image, audio etc.) as well as simple sensing data. These collected multimedia data should handle for using simulation and validation. The collected raw data are formed as a DDS topic and sent to other components through uDiT. Especially, these data which stored in Real Env DB are used for simulation and validation of Digital twin. In simulation step, multimedia data could be an input for digital twin model and affect to whole system validation.

### *D. uDiT application for reliable ADAS developments*

ADAS is an intelligent vehicle driving support technology and is considered one of the key technologies for autonomous vehicle. Reliable ADAS requires complex verification procedures for accurate supporting. This subsection introduces ADAS development process as one application of uDiT.

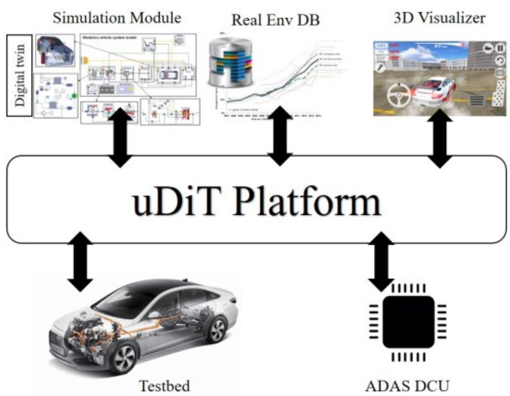


**Figure 5. Structure of uDiT application for ADAS development**

*1) Structure of uDiT application for ADAS development*

In order to develop reliable ADAS, we should do repetitive testing and verification processes. As you know, the test processes, however, take a lot of time and cost. In this paper, we apply the uDiT to the process. The structure of application using uDiT is shown figure 5. ADAS supports the driver through the process of receiving video data. The overall reliability of the ADAS system in this process is strongly influenced by the ADAS DCU. The proposed architecture adopts the uDiT as an environment for ADAS DCU verification.

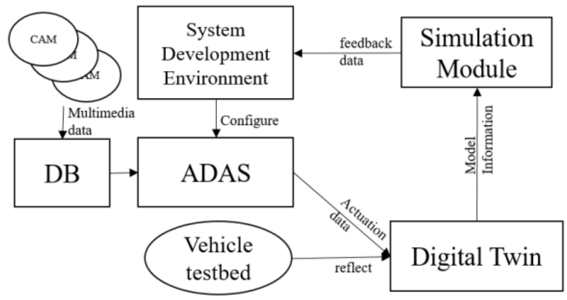


**Figure 6. uDiT Development flow of ADAS**

*2) ADAS Verification & Validation*

Video camera data added with time and GPS are collected and stored together into Real Env DB. We captured the video data during the runtime of a test vehicle. On verification process, we use the stored video data with the additional environment data. The simulation module as a master simulator in this situation commands Real Env DB to inject the stored data into ADAS DCU which in turn makes decision to control the digital twin of the self-driving electric vehicle. In addition, we develop a digital twin model on a FMU getting the whole characteristics of the target electric vehicle. All testing and verification processes are designed to perform on uDiT platform as shown in figure 6.

## IV. Conclusion and Future Works

We identified the key requirements of a digital twin platform for develop a dependable cyber-physical systems. As mentioned above, digital twins come to be large-scale, distributed and heterogeneous in terms of resolution, complexity, modelling languages and formats. It is very important to make transparency against the issues. Many CPS vendors will provide vendor dependent digital twins and the interconnection between them is essential to make large-scale digital twin space. In this paper, we proposed a novel digital twin platform which can overcome the problems by means of extending international standard middleware, OMG DDS. Our digital twin platform, uDiT, is designed to support dynamic simulation environment which has various simulator/ simulation engines and physical machines. OMG DDS is topic-based data centric middleware with that any entities can easily share data in any formats. Moreover, it has 22 QoS policies to satisfy any requests from various applications like digital twins. OMG DDS supports interworking functions for a large number of digital twins and physical systems. In addition, uDiT extends OMG DDS to have transparency to heterogeneity of digital twins by adopting FMI standard. In order to perform co-simulation between them, uDiT adopts FMI over DDS architecture. We already developed FMI over HLA/RTI and finished some tests for co-simulations. Now, we try to verify the functionalities and performance of uDiT platform by a well-designed application of electric vehicle in digital twin space and ADAS in physical world.

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