DIGITAL TWIN COMPUTING

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CONTENTS

INTRODUCTION

**Surrounded by high levels of advanced technologies,
our rich modern society has been achieved through
continued cooperation among many people
specializing in a diversity of fields.
Information and Communication Technology (ICT),
which connects distant strangers all over the world
and enables the transmission of various digitized data,
has greatly expanded the world and made it possible
for many people to cooperate with each other.
In recent years, the use of ICT for collecting vast amounts
of data on people and objects and quickly reflecting
the results of analysis of this data in the real world
has not only made human behaviors and social systems
more efficient, but has also led us into an era where
human capabilities themselves can be expanded
using artificial intelligence and biotechnology.
This paper sets down the "Digital Twin Computing Vision"
- a vision that entails the use of high precision
digital representations of humans and objects called
"digital twins" to create diverse worlds in cyberspace
that will exceed the limitations of the real-world.
In this vision, the value obtained through advanced computations
and communications using these digital twins in cyberspace
reflected back into the real world and enables collaboration
among humans with expanded capabilities in cyberspace
to achieve new digital societies.**

The Digital Twin Computing Concept

The first part of this chapter briefly describes the current state of, and issues with existing digital twins. This chapter then presents the features and architecture of the digital twin computing (DTC) set out in this paper through comparison with existing digital twins.

Existing Digital Twins ("Reproductions") and Issues

Digital twins that link the real world with cyberspace have been brought about with advancements in ICT, and are gaining attention. A digital twin is an accurate cyberspace representation of the shape, state and function of a real-world object such as a production machine in a factory, aircraft engine or automobile. Digital twins enable analysis of current states, future predictions and simulations of possibilities of objects in cyberspace. Based on the computation results and by leveraging the versatility of ICT in cyberspace, digital twins also enables feedback to the real-world to enable intelligent control of real world objects for instance. As well as objects, human medical imaging data such as MRI and CT images used in the medical field are also considered as forms of existing digital twins. Currently, the digital twin concept is focused on reproducing real-world objects for specific purposes. Examples of digital twin usage with objects include digital twins of production machines for monitoring operational conditions, or digital twins of aircraft engines for predicting malfunctions and maintenance, etc. Examples of digital twin usage with humans include billing services based on personal usage data or healthcare services such as illness prediction using personal health data. Each digital twin represents a real-world object with the accuracy and range required for its use within an application. Computations and operations such as analyses and simulations are performed in cyberspace with methods aligned with the purpose of the digital twins. Going forward, advances to digital twins of various real-world objects will lead to higher demands for large-scale simulations entailing the interaction and combination of different types of digital twins across various industries. For example, entire supply chains including production lines or entire factories and logistics could be reproduced starting with individual production machines, or entire cities could be reproduced by combining buildings, roads, cars and citizens. However, since current digital twins are created and used for specific purposes, it is difficult to combine various digital twins and get them to interact.
In addition, currently human digital twins mainly involve anatomical and physiological data for medical and health purposes, and are only reproductions of humans as objects. This also makes it difficult to achieve domains in which reproduction even of human internalities is required, such as communications or high-precision simulations of social life.

CHARACTERISTICS

Digital Twin Computing Characteristics

Until now, the digital twin framework has entailed mapping real-world objects into cyberspace to perform analysis and predictions, with the results of those analyses and predictions used after reverse mapping them back into the real world. The concept of “Digital Twin Computing (DTC)” we are aiming for is a significant advancement on the existing concept of digital twins - it is a new computing paradigm that will enable previously impossible new, large-scale, high-precision real-world reproductions by performing various operations to freely combine various digital twins, and will enable new interactions in cyberspace, including the interaction of human internalities, which will go beyond physical reproductions of the real world. Through digital twin operations, which will be described later, we aim to create simulations in cyberspace that will surpass the “reproductions” of the real world, and that could even have conditions that are different from the real world, and then use them in the real space. A feature of DTC, “digital twin operations” executed on digital twins, are described below.

Digital twin operations will offer standardized methods for large-scale and complex interactions between digital twins to enable the creation of virtual societies by freely combining various digital twins and using them for analysis and prediction.

By duplicating digital twins of an instance in the real world and placing them in cyberspace, or exchanging or fusing some components between different digital twins, digital twin operations enable the creation of never-before-seen human/object digital twins and allow direct interaction beyond physical laws. Differing from reproduction that originates in the real world, this is the creation of virtual societies in cyberspace that transcend the real world.

Another challenge is that of reproducing human internalities, which will be a major feature of DTC.

We believe that expressing the internalities of humans such as consciousness and thinking in addition to their outward appearance will enable sophisticated interactions with social aspects such as human behaviors and communications. Also, expressing the individuality of each human will enable interactions based on diverse individual characteristics rather than interactions between characterless entities statistically rounded off as averages.

These characteristics will make it possible to create virtual societies in which various humans and objects can engage in high-level interactions that go beyond the limitations of the real world. Developing opportunities for human activity even in virtual societies in cyberspace will expand human potential and enable the creation of innovative and never-before-seen services for decision-making and social design to solve various social issues such as sustainable development goals (SDGs) (Figure 1).

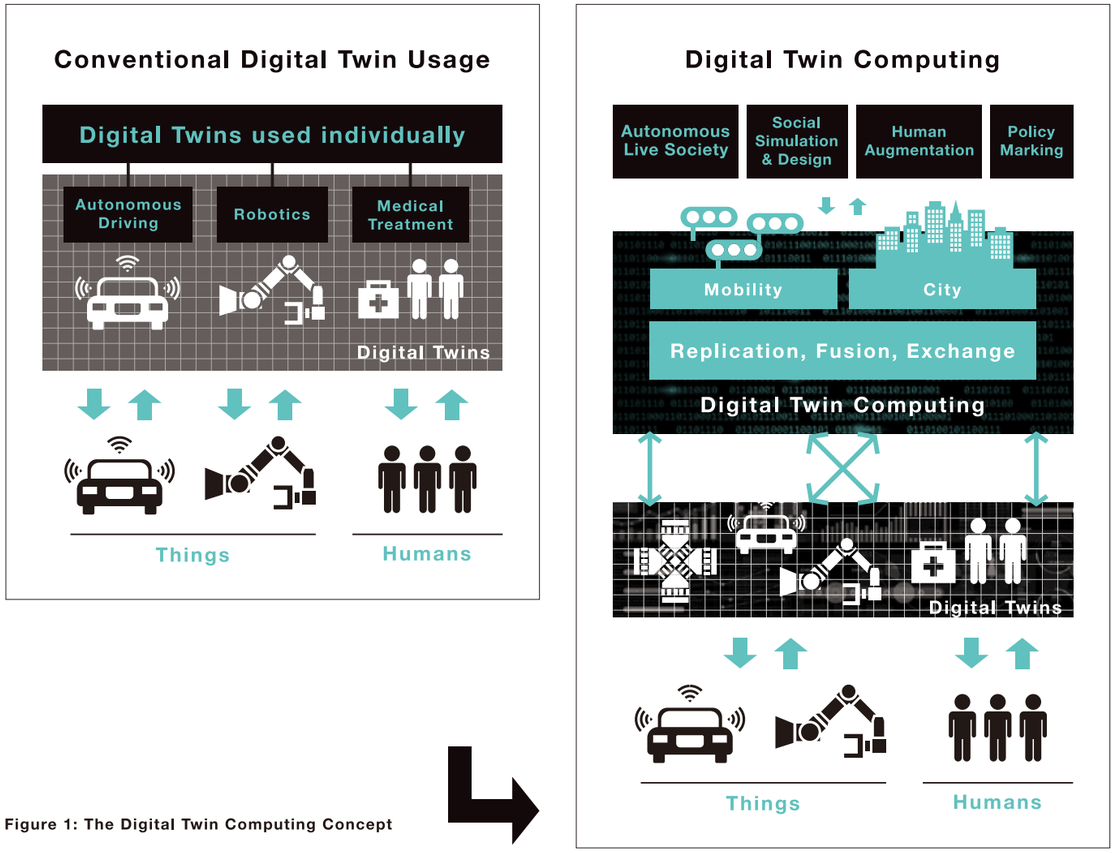


Figure 1: The Digital Twin Computing Concept

CREATION

Creation of Virtual Societies

DTC does not use digital twins for limited purposes, but creates a whole world by positioning a wide range of digital twins in cyberspace. Hence, we define digital twins that can be expressed in a unified format that transcends the differences between types of people, objects or industries. This will make it possible to operate digital twins that are interacting with various other types of digital twins that previously could not be easily used in combination, which will enable the creation of complex virtual societies.

The purpose of DTC is not only to digitize reality unaltered with conventional digital twins, but also to create worlds that do not exist. For this reason, in DTC, virtual societies with environmental conditions set for a purpose can be created, and various digital twins, including those that do not exist in the real world, can be positioned in such virtual societies to enable trials and controls in nonexistent worlds. For example, a vast conference room could be created in a virtual society for a large and physically unthinkable number of people to hold discussions, or virtual worlds with physical properties such as the gravity of the moon or the buoyancy of the sea could be created and cities designed therein. This will enable digital twins of humans and objects to operate under various environmental conditions so that their behavior can be understood.

DERIVED

Derivative Digital Twins Created by Operations (Exchange, Fusion, Replication)

With DTC, it will be possible to create digital twins that have properties and performance capabilities that do not exist in the real world, by performing operations on components between digital twins. These digital twins are called “derivative digital twins”.
Data and models are the types of digital twin components that can be subjected to computational operations. Data may include values for the shapes or conditions of objects or humans obtained by observation or estimation. For example, the data could include angles between parts, rpm, human body temperature, images being observed, and emotions and memory. A model is information needed for reproducing functions of objects or humans. For example, this information could include whether mechanical parts can be opened or closed, vehicle driving conditions or human personal values and capabilities. New digital twins can be created by performing operations on these components. There are three types of component operations between the digital twins - “exchange”, “fusion” and “replication” (Figure 2).

Exchange:

between digital twins. For example, a digital twin could be given a communication capability beyond reality by changing its foreign language conversation models and vocabulary data.

Fusion:

Combining and updating some or all data and models between digital twins to create derivative digital twins of objects or humans. This will enable the creation of derivative digital twins fused from digital twins from different times and spaces, or enable expanded capabilities by superimposing different humans and objects.

Replication:

Copying a digital twin itself. Replication makes it possible to increase the number of instances of a digital twin so the same digital twin can be used in different virtual societies. Combining these derivative digital twins to create virtual societies will realize interactions of humans and objects beyond the real world.

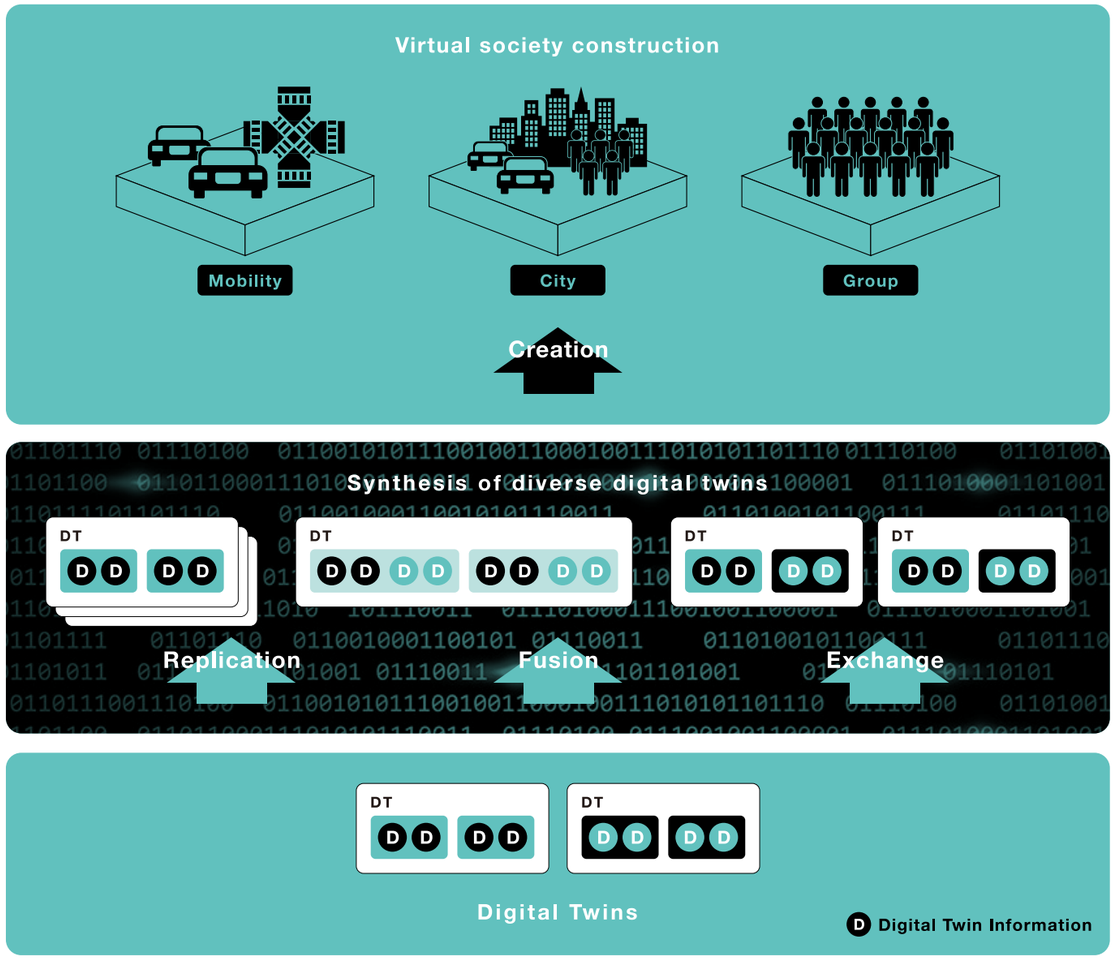


Figure 2: Digital twin operations

EXCHANGE, FUSION, DUPLICATION

HUMAN

Human Digital Twins

Human digital twins in DTC make it possible to expand the scope of human activity from the real world to cyberspace. You could interact with all kinds of digital twins in cyberspace through your own digital twin, and results of those interaction could also be fed back to yourself in the real world to acquire the experiences gained from cyberspace activities in the same way as acquiring experiences in the real world (Figure 3).

Human digital twins in DTC are not only digital representations of the outward appearance of humans such as physical and physiological characteristics, but are also representations of human internalities. A human digital twin consists of data that represents real-world and cyberspace human conditions and behaviors (e.g., physiological information such as pulse, psychological behavior information such as speech, attitude and emotions, physical movement information such as bodily movements and actions, information about the environment surrounding people such as about places and situations, clothing worn, and social information such as addresses, occupations and relationships with other humans), and models to reproduce the character and personality of the human (e.g., character and thought models that model the person's tendencies, personality and values, and models of the person's capabilities such as their perception, knowledge, language skills and physical abilities). The model prescribes the behavior of the digital twin and responds to the actions of other digital twins in cyberspace as if it were the actual person. By giving the digital twin autonomy in the virtual society, it enables the digital twin to attempt to influence other digital twins.

There are two aspects to human digital twins in DTC. First, a human digital twin is an interface that enables your real-world self to interact with various digital twins in cyberspace. An interface to convey such cyberspace experiences to your real-world self could be enabled through virtual reality (VR), augmented reality (AR), mixed reality (MR) or brain-machine interface (BMI) devices. As well as experiencing cyberspace in a form adapted to your own perceptual characteristics, you could also expand yourself as a derivative digital twin by incorporating the capabilities of others through the DTC characteristic operations of exchange and fusion to further your capabilities (for example language skills), which you could then demonstrate in the real world through various devices.

Second, the DTC characteristic operation of replication could be used to copy yourself to create a derivative digital twin which could also be given activity and experience. Human digital twins contain not only data that represent conditions and behaviors, but also models to express human individuality such as judgment and behavioral tendencies, which will enable interaction with other digital twins and autonomous activity in virtual societies, as if you were engaging in them yourself. Realizing interactions based on social aspects and diversity will enable precise analysis and prediction with consideration given to include even the individuality of the human. Also, as shown in the use case in Chapter 3, you could create a powerful personal agent by making a copy of yourself work on your behalf. Furthermore, your derivative digital twin could become independent of your real-world self and feedback the activities it performs in virtual society and the experiences it gains so that these activities and experiences become your own (Figure 4).

Human digital twins that represent even the individuality of humans will enable self-understanding and discovery through dialogue with past and future selves, or use of the knowledge and experience gained through interactions with humans that don't actually exist such as the deceased. Digital twin computing will also enable advanced human-to-human interactions never-before-realized such as deep communications or knowledge and experience sharing so that you could allow another party to more directly experience your own experiences, consensus building in groups that consider the value of group members based on diversity and commonalities, or negotiations based on multifaceted options for consensus building between groups. Since these interactions can be high-speed, large-scale and asynchronous and leverage the advantages of digital technology, the value of these interactions is certainly set to increase (Figure 5).

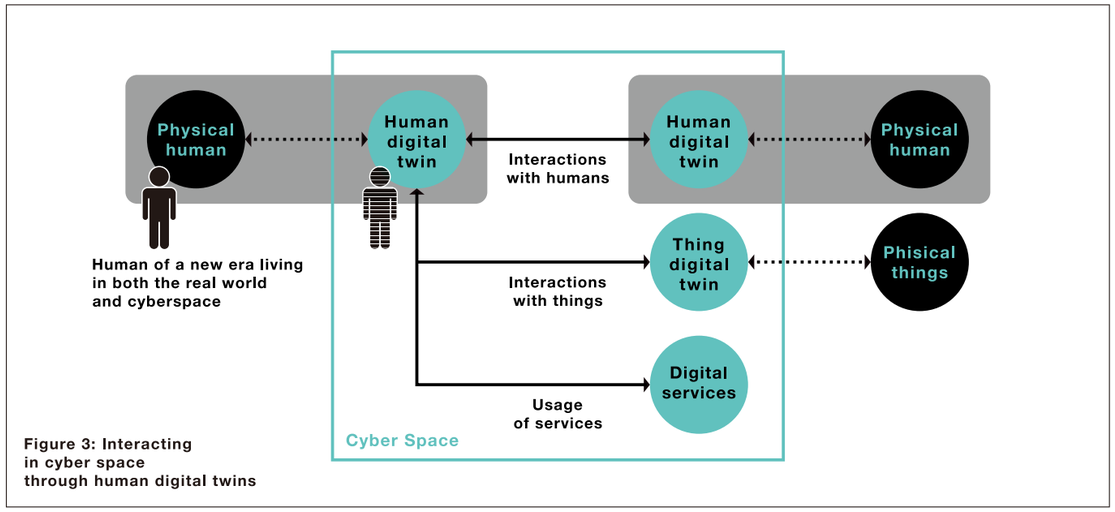


Figure 3: Interacting in cyber space through human digital twins

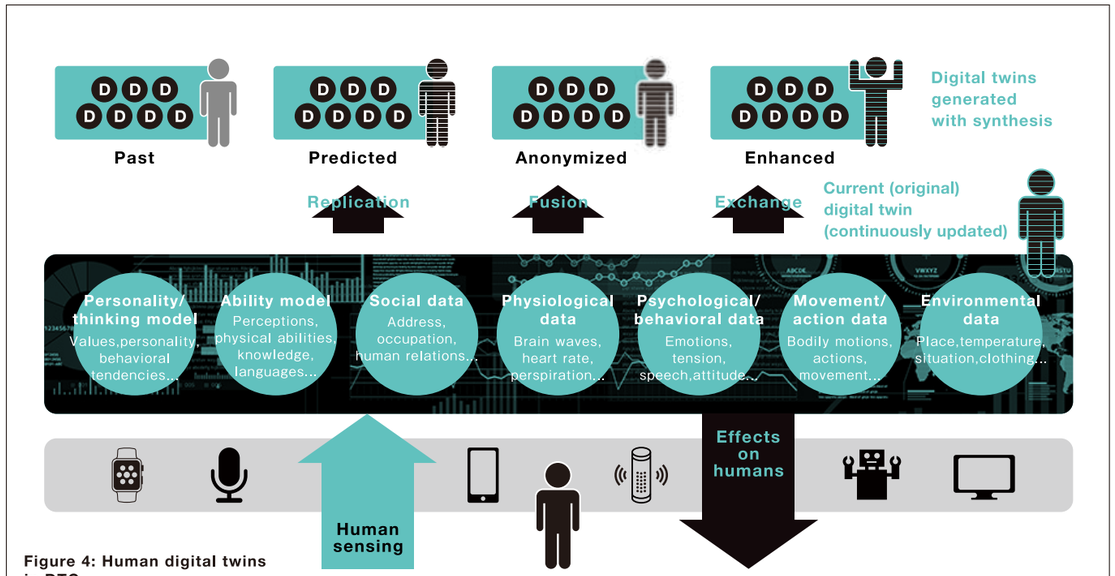


Figure 4: Human digital twins in DTC

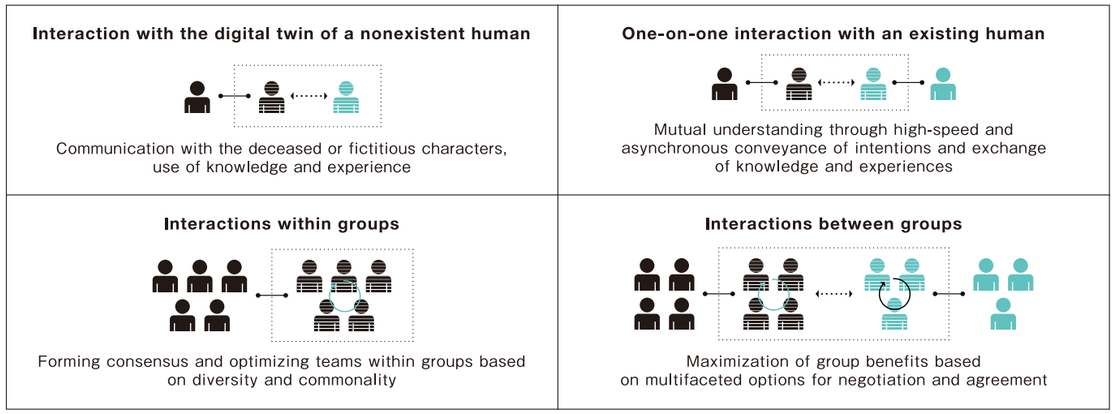


Figure 5: Various interaction patterns between humans through digital twins

ARCHITECTURE

The Architecture of Digital Twin Computing

DTC will generate digital twins by sensing humans and objects in the real world, create derivative digital twins by computing between digital twins, create virtual societies by combining them, and provide feedback to the real world. We assume the DTC architecture will consist of the layers shown in Figure 6.

[Cyber／Physical Interaction Layer]

This layer provides functions to collect data required to generate digital twins through sensing of real-world humans and objects, and functions to provide feedback to the real world of the results of trials and controls in virtual society.

[Digital World Presentation Layer]

Derivative digital twins will be created in this layer through operations (replication, fusion, exchange) on digital twins stored in the digital twin layer. These derivatives digital twins can also be combined to build virtual societies.

[Digital Twin Layer]

Collected data and models will be stored in this layer. They then can be used to create and store digital twins.

[Application Layer]

This layer enables implementation and execution of applications using the digital world presentation layer.

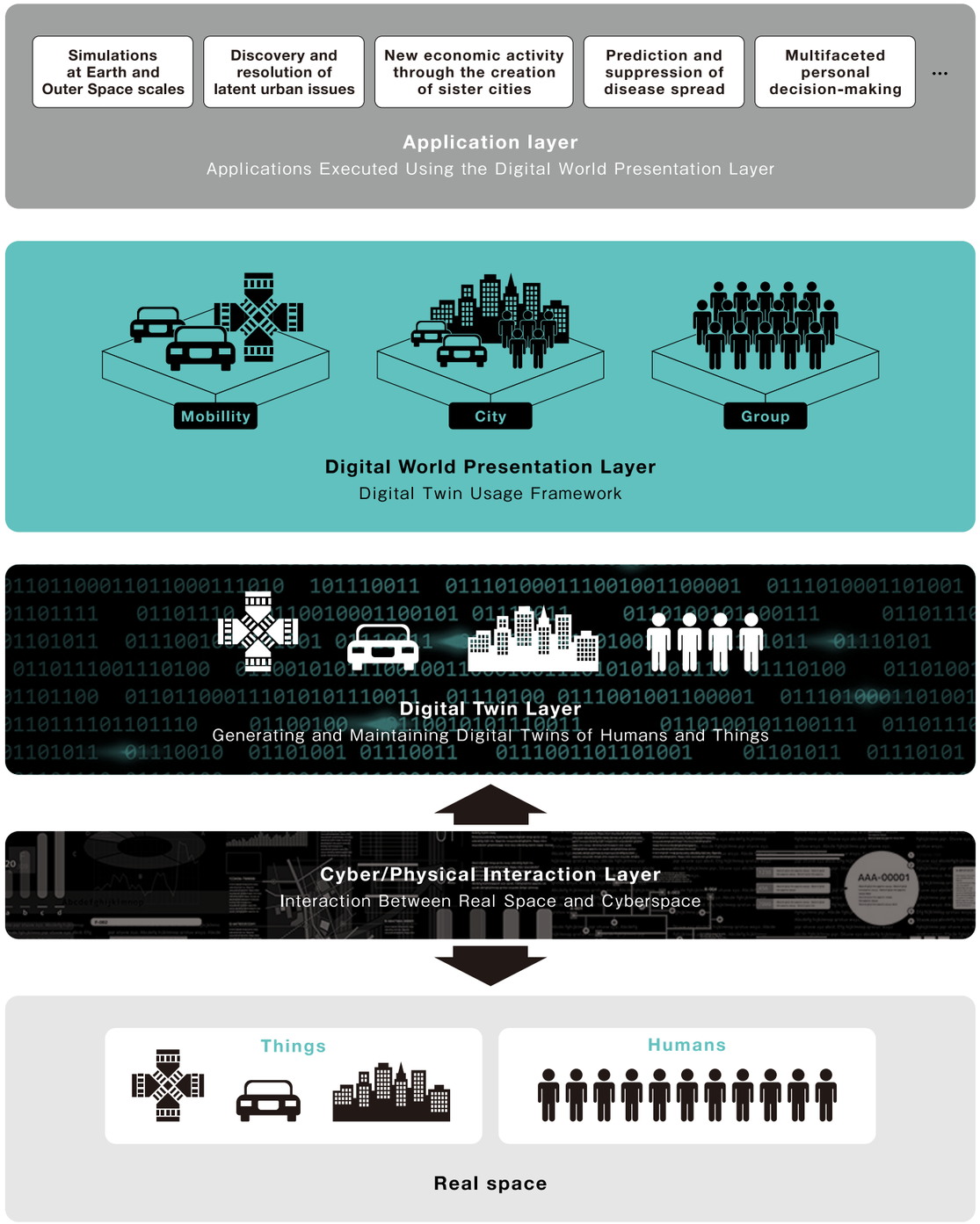


Figure 6: The Digital Twin Computing architecture

Digital Twin Computing Use Cases

This chapter provides example use cases of digital twin computing.

Use Cases with Human Digital Twins

[Future predictions]

Thinking, decision-making and behavior processes are modeled with individuality and contained in human digital twins in DTC. Therefore, gathering multiple digital twins to create a virtual society will make it possible to simulate people's lives in the virtual society and predict various future possibilities. Unlike simulations that model humans uniformly with statistics, more accurate simulations can be realized by reflecting various human thoughts and behaviors. As well as using simulation results for entire virtual societies for decision making in organizations or societies, results of simulations for individual humans at the micro level can also be used to decide their own actions. It will be interesting to use derivative digital twins that have been given new knowledge and abilities through fusion and exchange to develop yourself and society by predicting other future possibilities, such as what would happen if you gained new knowledge.

[Consensus building]

Human digital twins contain a record of the knowledge and experiences of an individual. Because they are able to think and make judgments the same as the actual person, it will be possible to engage them in various tasks in place of the actual person in the real world. Particularly in DTC, realizing the same communication between digital twins as their counterparts in the real world will enable execution of both work done alone and advanced tasks that require communications among many people. A representative example of this is consensus building in a meeting. Consensus building with DTC will differ from classical solution searching in which optimal solutions are found on a predetermined scale within given conditions. The same as meetings in the real world, conferencing among digital twins will involve information exchange, bargaining and persuasion, restrictions could be relaxed, and agreements that might not have been anticipated in advance could be reached. In addition, “duplication" of digital twins in DTC will allow digital twins to exist in multiple virtual societies at the same time, regardless of real-world conditions. This means they could engage in multiple conferences at super high-speed without being restrained in a particular place or time, which will surely provide value that goes beyond that gained from real-world meetings.

[Sharing impressions and excitement]

Human beings have long shared various impressions and excitement through methods such as books and paintings in olden times, and more recently with videos. The popularity of social network services in recent years can also be perceived as one method of sharing impressions and excitement of which anybody can be a publisher.
DTC will also enable sensing of human emotions, and allow them to be recorded, reproduced and propagated. In other words, not only will it be possible to reproduce and share ways of seeing things from the perspective of the person having an inspiring experience, but also to realistically reproduce emotions as they overflow and share them with others. DTC aims for sensing, recording and propagation of the five senses, focus, perceived time distortion and even the consciousness of the experiencer without being constrained by conventional technologies for sensing, recording and propagation such as “correct reproduction of space" or the “grasping and expressing of rough emotions that have been quantized".
For example, by exchanging your current digital twin with your past digital twin, you could revisit the feelings of when you held your child for the first time. Or, by fusion of an actual athlete's digital twin with your own digital twin, you could even have feelings based on experiences that could only be previously imagined. In this way, we believe sharing impressions and excitement with DTC will go beyond mere sharing of photography or video recording or physical viewpoints, and convey human feelings in that moment that are inexpressible with words, which will become a new communications form that transcends the conventional framework of text, pictures and video.


Future predictions

Consensus building

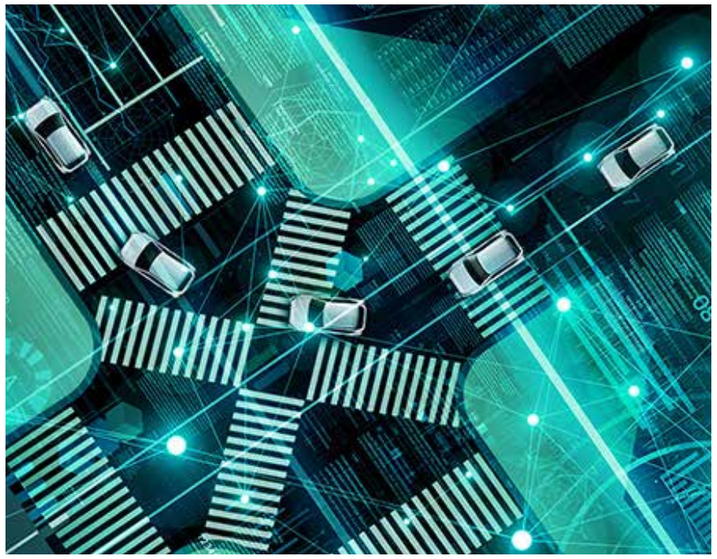

Sharing impressions and excitement

USE CASES 1

Use Cases with Digital Twins of Objects

[Future urban design]

DTC will enable urban design that currently doesn't exist. To create a new city for example, a virtual society with local conditions and climate could be built, and objects synthesized by fusing digital twins of infrastructure from existing cities such as residences, buildings and electricity supplies could be positioned therein, which would enable a city's optimal composition of infrastructure and urban area to be simulated in advance. In addition, residents could also be placed as digital twins to simulate the interaction between people and cities while accounting for their lifestyles and culture to even reproduce live social activities in the city.

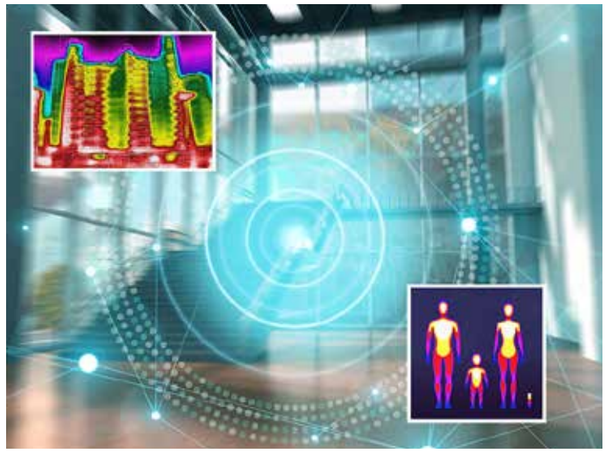


[Optimized traffic control]

DTC could also be used to design traffic flows for entire towns. Constructing an entire town's transport system including roads and railways in a virtual society will make it possible to test outcomes when such transportation methods are changed. For example, based on the changing values of individuals, the impacts on traffic flow when private car digital twins are exchanged for car share digital twins can be evaluated, or transitions in the transport systems used due to changes in individual needs or preferences when resident digital twins are exchanged for older digital twins can be analyzed. This will demonstrate the effectiveness of the flexibility of DTC for predicting the multiple complex future patterns that might accompany such changes through time.

[Controlling living environments]

DTC will enable realistic simulations of living environments. It will be possible to precisely reproduce not only the temperature and humidity, but also the interactions between occupants and the furniture and fixtures in places such as stadiums or even in relatively small environments such as living spaces or offices so that living comfort and ease-of-use can be evaluated from the perspective of the occupant. Also, fusing human digital twins will enable prediction of the effects of environmental changes or degradation of objects by reproducing cases such as future occupant increases or people crowding into a stadium.



USE CASES 2

The Future Outlook

The new value created by the realization of DTC will spread widely through society on discovery of solutions to the following issues and the implementation of DTC in society. However, such problem-solving and social implementation cannot be achieved by players involved with ICT technologies alone. Collaboration among experts across a wide range of academic and specialist fields and players in various industries will be required.

Example issues facing the realization of DTC:

Human understanding:

Interdisciplinary study of human understanding needs to be deepened for insight into the externalities and internalities of humans, humans as groups, the design of human digital twins and methods of simulating societies based on these.

Privacy:

Appropriate creation, protection and management of human digital twins created from data originating from individuals are essential, and policy must be considered from the perspectives of systems, technologies and benefits for individuals and societies.

We will also examine the social impacts of the spread of DTC in view of the above issues, and seek social consensus so that society as a whole can enjoy the benefits of DTC.

Example issues related to social impacts:

Digital ethics:

Diversity, transparency and fairness will be required for future predictions and judgments made with DTC and applied to social issues - more than ever before. Expanding human capabilities will enable societies in which all people can work and fulfill their dreams through virtual societies. Therefore, it will be necessary to consider the ethical aspects of how much people and society should depend on digital technology.

Values of the digital society:

With accelerated fusion of the real world and cyberspace, resources and capital can be expanded to cyberspace and easily cross the various boundaries existing in the real world. As a result, it is possible that existing real-world values such as money, nations and ideologies will change and new values will be created. Such possibilities and the scope of their impacts must be considered.

We believe that we need to work with a wide range of interdisciplinary partners, such as those listed below, to further identify and deeply examine problems and issues, and to find solutions and make agreements that will make DTC truly useful.

- **Social sciences (sociology, social psychology, pedagogy, economics)**
- **Humanities (human sciences, psychology, philosophy, ethics, cultural anthropology)**
- **Natural sciences (biology, bio-genomics, physics, earth sciences)**
- **Applied sciences (system science, AI, media engineering, HMI (Human-Machine Interface), computer science, networks, urban engineering, medicine)**
- **Interdisciplinary fields (behavioral sciences, cognitive sciences, communications sciences), etc.**

OUTLOOK

Collaboration among players in various industries will be crucial for this concept to be implemented in society. Since the advantage of DTC is that it can be used across various services, we would like to infuse the new value it offers widely in society.

DIGITAL TWIN COMPUTING

The “DTC Innovation Forum" invites partners to come together to build DTC. We look forward to joining forces to innovate together to materialize this concept and advance society with new value!

INNOVATION FORUM

About the DTC Innovation Forum

The DTC Innovation Forum is a collaboration framework for jointly advancing initiatives towards the realization of DTC, such as refining the DTC concept, realizing methods for its achievement, studying analysis and solutions of various issues, and R&D and field trials to drive implementation in society.
Those in favor of the DTC concept and interested in contributing to its creation please inquire as follows:

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CONTACT