Computation-enabled Digital Twin in the Built Environment

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ABSTRACT

This study makes an original attempt to equip a digital twin (DT) for an information construct with computational capabilities to achieve an information-computation construct in the built environment. This attempt is achieved by developing a DT methodology for a university campus environment, enabling a twin representation of real-world construction with spatiotemporal analysis in multiple scales, integrating computation, information, and machine learning models into a cyber-physical-social system (buildings, infrastructure, and affected community) for seamless decision-making from design through construction to operation phases, and evaluating structural behaviors under extreme loads. Potential value of the campus-scale DT includes the understanding of student aggregation, traffic flow, structural stability, building constructability, damage/cost scenario of existing and new buildings, and community impacts in the wake of a postulated earthquake event.

INTRODUCTION

Infrastructure assets have been traditionally managed using a database and recently with the aid of Building Information Modeling (BIM) for value engineering and as-built information. To enable spatiotemporal analysis and societal impact study, a DT is required as demonstrated by the 2007 Minneapolis Interstate 35W Bridge Collapse that killed 13 people and injured 145. This incident was due not only to the overlooked design information, which can be extracted from a BIM, but also to the insufficient capacity of bridge members, which cannot be evaluated from the BIM. The need for such an action becomes increasingly important as our nation's infrastructure is aging and thus requires more frequent condition assessment and maintenance, particularly under accelerating climate changes and increasing natural disasters. The cybersecurity risk of infrastructure also increases as demonstrated from the Colonial Pipeline ransomware ($4.4 million) attack on May 7, 2021. Therefore, an open-source DT with computation capabilities and security measures are in dire needs.

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The idea of digital twins (DTs) under the name of “Mirror Worlds” was first envisioned in the 1991 book *Mirror Worlds* by David Gelernter [1]. The model of a DT was introduced in 2002 under the name of the virtual twin by Michael Grieves as a concept of Product Lifecycle Management (PLM) [2]. The model was finally referred to as a DT by John Vickers in the 2010 National Aeronautics and Space Administration (NASA) Roadmap Report [3]. The early development of DTs and their applications in PLM and aerospace engineering [4] mainly for monitoring purposes was extended to the areas of design and production engineering [5] and architecture, engineering, construction, and facility management [6]. In these extended areas, DTs began to be connected to societies and built environments [7].

In 2017, the United Kingdom (UK) National Infrastructure Commission launched a national DT initiative in their report *Data for the Public Good* [8]. During the evolution of their DT initiative, the UK construction industry alone saved $1.1 billion in 2014 just by sharing information. Ever since then, the concept and development of DTs has been significantly advanced worldwide as demonstrated by an increase of publications (mentioned “digital twin” in their titles) to more than 1,200 since 2018 [9]. The value delivery of digital twins for smart cities was summarized in the first book *Digital Twin Technologies and Smart Cities* [10]. A holistic view of DTs from an asset level to a city level was provided in the second book *Digital Twins in the Built Environment: Fundamentals, Principles, and Applications* [9], including four chapters on implementation case studies.

This paper is organized into six sections: Introduction, Goal and Objectives, Methodology and Framework, Foundational Platforms, Case Study, and Conclusions.

GOAL AND OBJECTIVES OF THIS STUDY

The goal of this study is to transform currently disparate design, construction, and operation phases of buildings and infrastructure into an open-source, cloud-based application featuring modulated DTs of physical infrastructures overlaid with cyber infrastructure. Such a digital infrastructure initiative enables grand-scale fundamental and convergence research on the integrated design-build-operation process of infrastructure and buildings, examining their environmental implications, life-cycle cost assessments, and socio-economic impacts on community resilience in the case of catastrophic events.

Depending on the value-based use cases of interest, a DT can be developed and presented in different facets and phases of a physical twin. This study aims to

1. Develop a rapidly implementable DT methodology and framework for a Missouri University of Science and Technology (Missouri S&T) campus-like environment, buildings and infrastructure, and community services,
2. Enable a twin representation of real-world construction of partially erected buildings with spatiotemporal analysis in multiple scales,
3. Integrate computation, information, and machine learning models into a cyber-physical-social (CPS) system for seamless decision-making from design through construction to operation phases, and
4. Evaluate structural behaviors of the campus-scale DT under a postulated earthquake, which are intertwined with the engineering values of damaged buildings and aging infrastructure.

METHODOLOGY AND FRAMEWORK IN THE BUILT ENVIRONMENT

PLM vs. Asset Lifecycle Management (ALM)

The DT concept originated from the modeling of PLM that handles a good as it moves through the stages of its product life. The life cycle of a product starts when a product is introduced to consumers into the market and ends when it is removed from the shelves. Due to the availability of commercial products in large quantity and short term at relatively low costs, the integration of multiple products into a new system product can easily be viewed as an intended physical prototype. The DT of the system is used to ensure all component products fit together before investing a new system product line in a physical factory. This is a valuable design attribute of DTs in the era of digital manufacturing in addition to real-time monitoring as envisioned originally.

On the other hand, ALM for large-scale buildings and infrastructure works differently. A set of strategies (e.g., maintenance, rehabilitation, and replacement) is organized and implemented with the intent of preserving and extending the service life of public infrastructure assets, such as roads, utility grids, bridges, and railways. Unlike commercial products, infrastructure assets are often unique for both esthetical and functional purposes and require capital investment over a long time. As such, the attractive attribute of DTs for product assembly in manufacturing may have no equivalence in infrastructure asset management. For buildings and infrastructure management, computational mechanics modeling is desirable as their physical and functional conditions affect the decision-making of asset management strategies. In addition, using sensing data alone to assess their conditions is costly due to their large scale or even impossible for hidden damage. Model updating with limited sensor data is one of the effective ways to provide the needed condition assessment capability.

The above difference between PLM and ALM determines the way in which DTs are applied effectively in the built environment. To start with, the definition of DTs must be modified from those targeted at applications in manufacturing. In the past decade, 29 definitions of DTs were used by academia, industry, government, and software sources [11]. In the built environment, the term DT has been used mainly in three ways [12]: (1) modifying the original DT definition to reflect a realistic digital representation of assets, processes, or systems; (2) extending BIM to enable real-world data capture and feedback or completely replacing BIM; and (3) formulating a closed-loop digital-physical system for built asset delivery and operation. In general, DT differs from BIM in two distinctive ways: (1) two-way digital threads between DT and its represented physical asset, and (2) focus on operation and maintenance instead of the entire lifecycle of an asset as BIM encompasses with an emphasis on design and construction. The BIM implementation for operation is also different from DT's. While the DT supports the operation of built assets, BIM for facility management focuses compiling information of the delivered built asset to support inventory and space management, general upkeep, and building services maintenance, which does not result in an accurate replica of the condition and performance of the asset.

Most, if not all, of the current DT research has been focused on an information construct [13]. In the built environment, however, damage assessment of existing infrastructure and design options of new infrastructure are important in the lifecycle management of regional assets. In addition to the production application strategy in manufacturing, a creation strategy is thus needed for buildings and infrastructure.

DT Definition in ALM

In this study, the three ways of using the DT term in the literature are combined into a comprehensive definition. A DT is defined as a synergetic, multifunctional, value-added, effectively indistinguishable digital representation of an intended or actual real-world asset, system, or process - a physical twin in the built environment. Presented in the form of simulation, integration, testing, monitoring, and maintenance, the DT is intertwined and corroborated through two-way digital threads with a lifecycle of its represented physical infrastructure from planning through engineering and operating to decommissioning. In a physical-to-digital thread, the sensing data and information obtained from a physical twin can be used to update and improve its digital representation. In a digital-to-physical thread, the practice and optimization of intervening strategies on a digital twin enable scenario studies to understand the outcomes of multi-faceted decision-making.

Connections, Hierarchy, and Architecture of Modulated DTs

The DT for the CPS infrastructure system will consider three systems: cyber, physical, and social. The cyber system provides services to promote economic development and improve the quality of life and human wellbeing. The physical system includes an engineering-to-operation process to ensure safety, functionality, and resiliency. The social system describes common traditions, habits, patterns, and beliefs present in a population group. The main component, key function, and performance evaluation criteria of the three systems are detailed in Table I.

TABLE I. CHARACTERISTICS OF THE THREE SYSTEMS IN THE BUILT ENVIRONMENT

System	Main Component	Key Function	Performance Evaluation Criteria
Cyber	Internet of Things	Enable people to exchange data via wireless communication and store data in cloud	Integration tool, security management, endpoint management
	Software	Provide computational modeling and intelligence	User interaction and support services
	Virtual reality	Create the virtual representation of a real world integrated with high fidelity models	Latency, cybersickness, sense of presence, and technological advancements
Physical	Load bearing components	Support service and extreme loads to provide living/working spaces or various functions	Vulnerability under loads, design consistency and optimization of various elements
	Non-load bearing components	Provide utility facilities and communication infrastructure including computers	Function and security of working spaces, interdependency with load bearing components
Social	Economics	Estimate cost-benefit ratio of major projects	Maintenance costs, strategy development, and profitability
	Social work	Alleviate conditions of people in need of help or welfare	Social and emotional needs, an environment of respect and rapport

The evaluation criteria considered in Table I are limited to those used during the technology development stage. In a general sense, computers (e.g., CPU, GPU, smart phones, and augmented reality devices) serve as an interface between the cyber system and another system. The interface between the physical and social systems is from utility facilities, linking buildings to human functions. Overall, the non-bearing components highlighted in Table I play a critical role in the overlapping space of the CPS twin system. However, their operation under service and extreme loads largely depends on the serviceability, safety, and resiliency of load bearing components in additional to mechanical and electrical part failures in such components as air conditioners, water heaters, and pipes. The twin system allows the modeling and impact study of its surrounding environment to address community sustainability through surveillance cameras and other sensors.

The DTs of an autonomous region are organized from the region level to asset and system levels in a hierarchical structure as shown in Fig. 1. The overall structure is divided into two parts: (1) open-sourced for public buildings and regular infrastructure and (2) secured for information-sensitive buildings and critical infrastructure. In doing so, public sectors can support the development of the open-sourced framework while private sectors will invest application-specific components that are set up with data security and privacy policies in place. The application components can be plugged into the open-sourced framework to run the overall model at the region level to understand potential impacts of new development on surrounding communities. Multitask learning is combined with a secure platform to limit the use of sensitive information and models to authorized users only. The platform sets specific roles and missions of the users while the learning engine identifies users before availing sensitive information and models by encrypting them with users-specific keys. In addition, the hierarchic asset and system structure will evolve in the process from planning through design, construction to operation phases as schematically illustrated in Fig. 1.

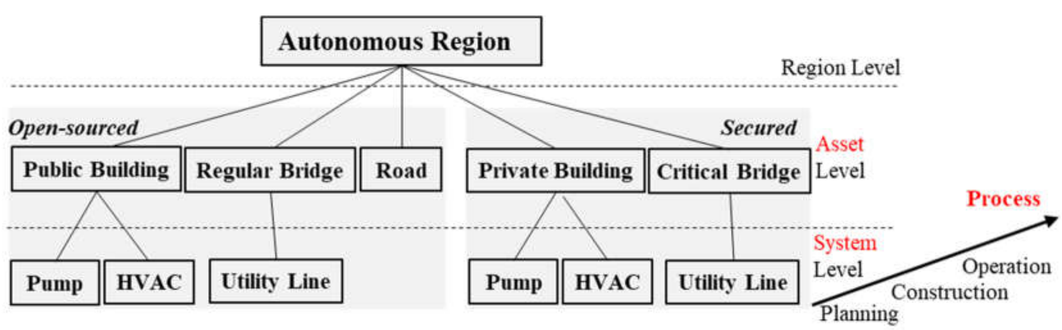

Fig. 1 Temporal and spatial connections and hierarchy of modulated DTs

When applied to similar assets, such as highway bridges with same configurations along an interstate highway, an application strategy is proposed to modify Fig. 3 of [12] and include both prognosis and diagnosis to meet the needs for both information and computation modeling. Analogous to the DT paradigm updated by Grieves in 2019 [13], including three manifestations: Prototype, Instance, and Aggregates for PLM, the new strategy for ALM consists of Creation, Option, and Evaluation. The DT Creation is the design and construction twin version with all its variants in similar infrastructure assets. The DT Option is the twin of each individual built infrastructure such as an actual concrete-girder, steel-girder, prestressed-girder, or box-girder bridge.

It will provide insights through diagnosis and prognosis for the inspection, preventive maintenance, and rehabilitation of existing infrastructure as illustrated in the process dimension in Fig. 1. The DT Evaluation is the composite of all the DT Options for both temporal and spatial representations of behavior through interrogation, prediction, and learning.

For unique assets, such as river-crossing bridges and iconic buildings, the design, construction, maintenance, and rehabilitation phases can be done directly in an integrated system. The system architecture of each DT at the region scale consists of five layers: data acquisition, wireless transmission, digital modeling, feature mapping, and user interface. First, multimodal data are acquired from in-situ sensors, aerial nondestructive testing and evaluation, and remote sensing. Then, the collected data are transmitted to decentralized data curation and storage facilities in the region. Next, the received data are analyzed using information, computation, and learning models to extract features of interest in asset management and regional planning, which are visualized and presented in mapping formats to end users. Finally, the processed features are communicated with end users to assist in informed decision-making.

FOUNDATIONAL COMPUTATION PLATFORMS

While computational modeling of structural components (e.g., load-bearing steel frames in a building) is critical to address structural safety, BIM of the structural components and non-structural components (e.g., utility lines) is key to understanding the functions of a building system. Damage in the structural components will impact the functions of non-structural components. As such, computational and informational modeling cannot be separated for an efficient and effective management of building and infrastructure assets. Therefore, two foundational computation platforms will be established to enable the implementation of DTs, as briefly described below:

1. *Spatial connection of structural and non-structural components*. Current computational and informational modeling tasks are done by two completely isolated technical communities using different approaches. For the development of DTs, the two modeling techniques are transformed into one simple yet effective computational and informational engine to meet the multiple needs in performance evaluation as summarized in Table I.
2. *Temporal connection between a built facility/environment and a new facility/environment to be built in part or entity*. This platform plays a critical role in bridging planning, engineering, and operation of a physical building and infrastructure system.

Coupled Computational and Informational Modeling

The structural components (related to engineering) and nonstructural components (related to operation) are represented by computation and information models that are integrated in a seamless platform of fiber elements to address both mechanical (stress and strain at material levels) and functional (integrity and cost at component or system levels) fields. To maintain simplicity and efficiency, macro-scale models are introduced for various nonstructural components and meso-scale models are used for structural components. The model and analysis methods to enable the coupled computational and informational modeling will be reported in a subsequent paper.

Hybrid Instrumented and Computational Modeling

Buildings are traditionally instrumented with accelerometers to monitor structural behavior. This approach has two drawbacks. First, acceleration measurements must be processed extensively to derive structural behavior-related data, such as crack width and steel mass loss. This mathematically daunting process often impedes the adoption of sensing technologies. Second, this deployment depends upon the configuration of a complete structure, which is not adaptable to a partially erected structure or a completely new structure during a regional planning phase.

In practice, all stories of a building are typically built with the same materials using the same erection process of prefabricated components during construction. The first story, resting on a rigid base, is often subjected to a larger drift than the second and above. Thus, this study proposes a novel strategy of monitoring the load-displacement response of the first story and evaluating the responses of above stories using real-time computational simulation. This hybrid experimental and computational treatment is compatible with the sequence of construction of a new building. For a four-story, two-bay steel building structure, it proved at least 25% more accurate than those simulations even from a post-earthquake calibrated model [14].

CAMPUS-SCALE DIGITAL TWIN – A CASE STUDY

Missouri S&T campus owns more than 300 acres of land. The main campus spans ten streets in the north-south direction and ten in the east-west. The campus has both existing buildings and new buildings under construction as well as one pedestrian concrete bridge. Its surrounding area has one steel-girder highway bridge and one steel truss bridge over the I-44 highway.

The DT development team collects campus data biweekly using RGB, infrared, and hyperspectral cameras as well as a Light Detection And Ranging (LiDAR) scanner. The RGB image gives general features of the campus. The thermal image shows the temperature distribution around various buildings that are related to energy use and efficiency in different buildings. The LiDAR image with three-dimensional (3D) coordinate and light reflection information allows a 3D construction of building elevation models as a base DT for the visualization and presentation of features of interest. The hyperspectral image sheds light on the health condition of campus landscapes and the types of construction materials. Informational, computational, and multitasking machine learning models of buildings and bridges are developed toward realizing the potential value of the campus-scale DT in understanding of student aggregation, traffic flow, structural stability, constructability of partly erected buildings, damage assessment, cost analysis, and community impact in the wake of a postulated earthquake event.

CONCLUDING REMARKS

This paper extended the concept of DTs to enable information, computation, and machine learning modeling of buildings and infrastructure so that their condition assessment and impact on surrounding communities can be studied during normal operations and emergency responses in the wake of a catastrophic event. The two foundational computation platforms coupled information and computation modeling and hybridized instrumentation and computational simulation. They addressed both spatial and temporal connections within existing infrastructure or between existing and new infrastructure. The extended DTs can be applied to a wide spectrum of tasks in a lifecycle of assets from designing through constructing, operating to preserving buildings and infrastructure.

The concept and model of DTs are still evolving. They warrant more discussion at special forums during professional meetings to realize their full potential in the built environment and develop standards and guidelines. More and closer collaborations among academia, industry, government, and software sources are required to identify societal needs, synergistic functions, and thus value for adoption in practice. For any capital DT projects, clear outcomes and end users must be identified to develop and sustain needed infrastructure and workforce both administratively and financially.

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