Digital twin of earth: A novel information framework for managing a sustainable earth

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As the progress of human society rapidly enters a new stage, sustainable development has become an essential target. It is necessary to have an effective approach to managing the resources and ecosystems of Earth, with the target of promoting sustainable development while meeting the needs and requirements of both present and future generations. Digital twin technology provides a fresh perspective on sustainable management with a better understanding of the interconnectedness of Earth's systems and accurate simulation and prediction of future changes. By integrating various types of data and models, including climate models, geophysical models, and social media data, a digital twin of Earth can simulate and analyze various aspects of the planet. The digital twin of Earth leverages real-time multi-source data integration through advanced IoT and wireless sensor networks, feeding into a data lake architecture that supports the seamless integration and processing of heterogeneous data. The integrated data then informs dynamic models, combining numerical simulation models with intelligent algorithms for enhanced prediction and analysis. This approach emphasizes the integration of environmental, social, and economic considerations into decision-making that balances economic growth, social well-being, and environmental protection to achieve sustainable development. This paper introduces the definition and information framework of the new concept of a digital twin of Earth to promote the current research on Earth management based on digital transformation techniques.

Earth has suffered a surge in global issues, such as population growth, resource scarcity, environmental degradation, ecological imbalance, water pollution, and pandemic outbreaks. In an attempt to defend against potential hazards and promote Earth system balance in development, the United Nations promulgated the "2030 Agenda for Sustainable Development" during a 2015 summit. This agenda contained 17 sustainable development goals (SDGs) that defined targets toward ending poverty, hunger, and inequality; improving health, education, and cities; and protecting the climate, land, and water environments. The SDGs can be used to statistically summarize the status of the entire Earth system from different perspectives. To quantitatively optimize the SDGs, explicit actions are urgently needed to support and help in leading Earth evolution.[1]

High-efficiency data integration, effective data analysis and mining, and conclusions based on accurate knowledge to manage decisions are the primary components of sustainable management.[2] In embracing observation technique enhancement, a large amount of Earth "big data" (termed "big Earth data") is obtained to constitute sufficient information of the Earth system at a specific point in time. Big Earth data in time series describe the characteristics of a target on Earth and illustrate its changing status for that period of time.[3] This information leads digital Earth research into a new phase and provide seemingly unlimited possibilities for sustainable management. Nevertheless, the large volume of big Earth data makes manually processing an impractical solution, and the multisource and heterogeneous nature of big data presents a serious obstacle to comprehensive machine automation analysis and processing. Furthermore, translating data patterns and knowledge into precise management strategies is another significant barrier to achieving sustainable management. Specific technique paradigms are needed to support big Earth data integration and inferences from sustainable management actions.

With the rapid development of the Internet of Things and wireless sensor network techniques, multi-source big Earth data can be utilized to monitor the stability of the Earth system. To further digitalize an object or system and attempt to estimate the evolutional tendencies of its status, a novel technique paradigm, the digital twin, has been defined as a holistic management methodology.[4] A digital twin is a theoretical framework that maps a real physical space to a virtual digital space and provides feedback to guide understanding of the physical world. The digital twin concept has been widely applied in specific fields, such as aerospace and the military industry, since it was first theoretically proposed, and it is now widely used in daily life applications, such as urban transportation, electrical systems, and workshop assembly line production.[5] This theoretical model has demonstrated outstanding capabilities in processing real-time big data, system monitoring, process simulation, and decision support.

The digital twin of Earth (DTE) is derived from the industrial scope of Earth science-related research.[6] The Earth system is translated into a digital model such that the DTE shares the same characteristics and life cycle. The twinned Earth in virtual space can not only describe the status of the Earth system in every detail for monitoring and analysis but also provide a perfect environment for the support of sustainable management. The twinned Earth is recognized as a sandbox to pre-view the effects of Earth management actions. The evolution of the Earth system caused by a management action can be presented in the DTE to provide a visualized illustration and help support the choice of sustainable Earth strategies. Moreover, taking advantage of the complete synchronization of the digital and physical spaces, sustainable Earth management with the DTE enhances the ability of continuous decision-making to accomplish long-term sustainable development.

DIGITAL TWIN OF EARTH

With the rapid development of Earth observation data, the European Space Agency (ESA), National Aeronautics and Space Administration (NASA), and National Oceanic and Atmospheric Administration (NOAA) have all noticed the significance of developing a digital twin of the Earth.[7] However, there has not been an agreed-upon, clear definition of the DTE. An explicit definition is proposed as follows:

DTE refers to an interoperable, scalable, expandable, and fidelity virtual representation or model of the Earth's systems, including its physical, biological, and social components. It integrates diverse data sources, advanced modeling techniques, and simulation technologies to provide a comprehensive and dynamic understanding of the Earth's complex interactions, processes, and dynamics in near real-time.

Through real-time synchronization with the physical Earth, the DTE aims to facilitate monitoring, analysis, and predictive capabilities to support informed decision-making and sustainable management. Universal sensing and Earth management are the essential bonds between the physical and digital space.

Digital space: Ubiquitous perception

The Earth system can be described by four subsystems: the atmosphere, biosphere, hydrosphere, and geosphere.[8] The large gaps between different aspects of these subsystems place a high requirement on elaborate monitoring techniques. Ubiquitous perception refers to the ability of a system to have continuous and pervasive awareness of the environment through various sensors and data sources. The ubiquitous perception in observation of the Earth system is provided with a bottom-up view through the integration of sensors, such as meteorological, biological, oceanographical, and geological sensors. In embracing a satellite network, round-the-clock air-to-ground monitoring becomes a reality. Apart from traditional observation techniques,

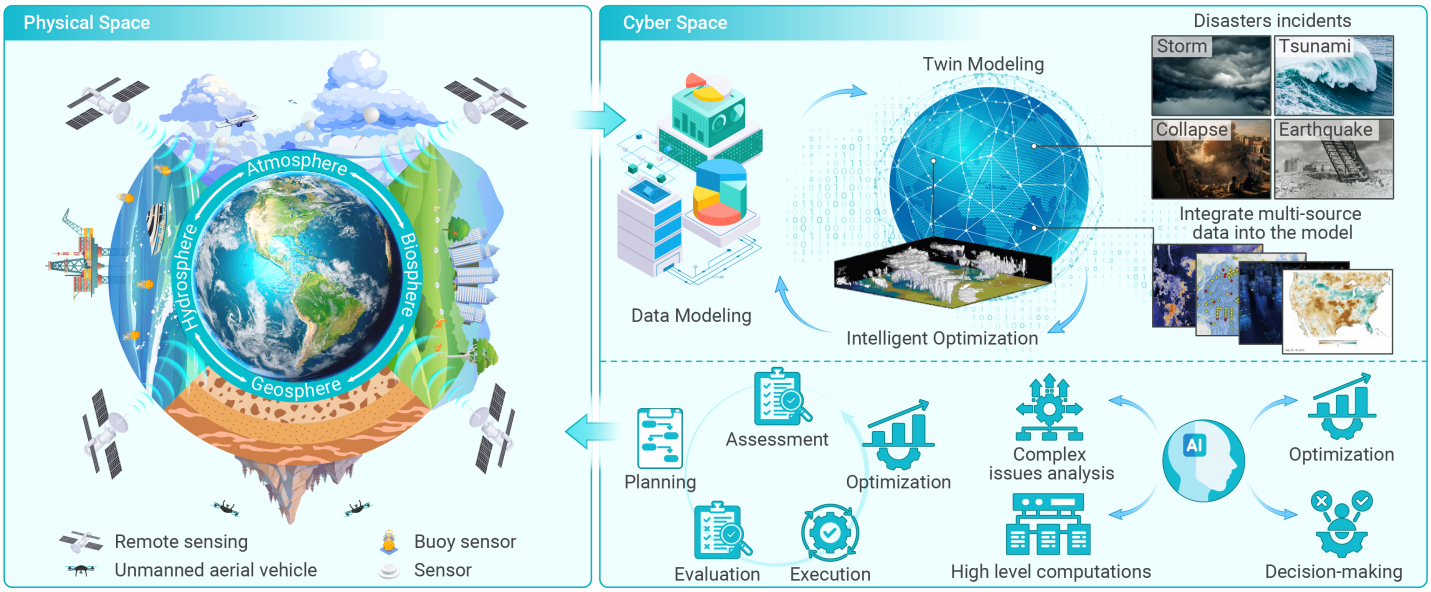

Figure 1. An Information Framework of DTE to support sustainable Earth management.

multimodal data from social media can also be a significant information source. A continuous stream of data offers a holistic, real-time view of the environment, enabling better insights and understanding of complex systems and interactions.

Physical space: Earth management

Throughout history, research on Earth management has increasingly recognized the interconnectedness of the environmental, social, and economic dimensions, leading to the development of more holistic and integrated approaches to sustainability. This ongoing research continues to inform policy-making, promote sustainable practices, and support efforts toward a balanced and resilient Earth management system. The definition of sustainable Earth management is as follows:

Sustainable Earth management refers to the responsible and management of the planet's resources to ensure their availability for future generations. It involves balancing economic, social, and environmental factors to achieve long-term Earth evolution.

The concept of Earth management encompasses a wide range of practices, including sustainable agriculture, biodiversity conservation, climate change mitigation and adaptation, ecosystem restoration, waste management, and sustainable urban planning. Using the DTE technique, it is possible to draw inferences about the effectiveness of sustainable management strategies from the digital space. In this case, a management strategy can be a policy for future development, a scheme for the workflow of an institution, or even a concrete plan regarding a specific incident or event. With quantified management calculus, strategies that have higher credibility in their support of sustainable development in the physical space can be found.

THREE ELIMENTS IN THE DIGITAL TWIN OF EARTH

Data, model, and knowledge

In terms of scope, the basic elements of the DTE can be divided into the physical space, digital space, and linking information, as shown in Figure 1. From a processing perspective, the essential elements in the DTE are the data, model, and knowledge. Data and knowledge are the connections that link physical objects and their counterparts in the digital twin, which are reproduced as objects by modeling techniques.

In the physical space, information collection consists of two types. The first type is data collected manually, such as design rules and budget standards. The second type is collected by sensors, for instance, drone radar sensors, wearable devices, etc. After completing information collection in the physical space, a high-performance data management technique, data lake, is required for streaming the data storage. For real-time data, the value of the data is assessed, and valuable information is selected for storage. During the storage process, the information undergoes data cleansing and fusion before being stored on the high-performance computing platform.

Subsequently, in the virtual space, real-time information usually goes through two rounds of processing: digital modeling and data analysis. In the digital modeling stage, a twin body identical to the physical entity is constructed based on real-time data. The twin body is modified constantly to reflect the corresponding state. In the data analysis, data mining methods are used to analyze change patterns from the information, determine the current state of the physical entity, and analyze abnormal conditions in the current state and the state in the next phase.

Knowledge in the form of feedback information to the physical space typically falls into two categories. The first category is warning information, which indicates any abnormal conditions that have occurred in the current state of the physical entity. The second category is advisory information, which highlights potential dangers and corresponding solutions based on the current state's inertia. From real-time information input to storage, synchronization, analysis and prediction in the virtual space and finally to feedback to the physical space, the information undergoes multiple rounds of processing. It is transformed from metadata into recommendations and knowledge that guide physical space decision-making. This process provides digital twin users with a real-time understanding of the state of physical entities while positively promoting system development.

The essence of DTE lies in its ability to integrate diverse data sources into a coherent framework, enhancing the accuracy and detail of our environmental understanding. By leveraging advanced modeling capabilities, DTE can simulate the complex interactions within Earth's subsystems—like atmosphere, land, and ocean circulations—thereby enabling a deeper comprehension of global processes and mechanisms. Furthermore, through sophisticated computational analytics, DTE excels in quantitatively characterizing these interactions, facilitating the simulation and prediction of Earth's future states under various scenarios. By setting specific goal constraints, DTE efficiently navigates through complex data and model outputs to identify effective solutions. This approach provides robust technical support and tools, essential for devising scientifically sound pathways towards addressing the multifaceted challenges facing our planet.

NUMERIC SIMULATION, MECHANISM TECHNIQUE, AND ARTIFICIAL INTELLIGENCE

Earth contains multiple subsystems involving a diversity of processes.[9,10] Three concepts (numeric simulation, mechanism, and artificial Intelligence) are coupled in the DTE for the digitalized complex Earth system.

Numerical simulation technology maps physical spatial objects to the digital space and helps in building a 1:1 standard-model in the digital space for simulating and predicting the state of the physical spatial objects. These simulations bring in a cognition of the object's evolution process and future changes.

Mechanisms aim to uncover the step-by-step sequences of events and the factors that influence the behavior of the system. Mechanism techniques attempt to understand the underlying processes, interactions, and causal relationships that lead to the observed outcomes. A phenomenon, for instance, a physical process, chemical reaction, biological pathway, social behavior, or any other system of interest, is organized and defined based on a mechanism concept. Numerical simulations are organized based on a conceptual model. Different subsystems with multiphysics processes must be holistically integrated in the DTE.

Artificial intelligence techniques are applied to improve the fidelity of the twin model and to generate sustainable management strategy decisions. Data-driven artificial intelligence works as an optimizer to rectify potential uncertainty inside the entire DTE model. Furthermore, artificial intelligence can also serve as a decision-maker and has already found mature applications in areas such as energy management, crop sales, and resource management. Based on a current twin model, an artificial intelligence method can iteratively train and promote decision-making ability.

Integrating methodologies including numeric simulation, mechanism technique, and artificial intelligence, the digital twin of Earth offers a multifaceted tool for understanding and managing complex Earth systems. This holistic approach underpins the digital twin's application across various sectors, demonstrating its broad utility and value. Policymakers leverage it for informed decision-making on climate action, urban development, and disaster preparedness, benefiting from its predictive capabilities and scenario simulations. Researchers utilize the digital twin to deepen scientific knowledge of environmental processes, climate dynamics, and ecosystem health, exploiting its comprehensive data analysis and modeling strengths. Environmentalists can harness the digital twin's predictive capabilities to enhance conservation measurements, assess the impact of human activities on biodiversity, and mobilize public support for sustainability efforts. Meanwhile, urban planners and resource managers apply the digital twin in optimizing sustainable practices in development, energy use, and natural resource management, guided by its detailed environmental and urban simulations. These varied applications underscore the digital twin of Earth's significant role in facilitating a more sustainable, informed, and proactive approach to global environmental management, directly benefiting from its advanced integration of numerical simulations, mechanistic insights, and artificial intelligence-driven analytics.

CONCLUSION

Sustainable Earth management is deemed essential for mitigating environmental challenges, promoting economic stability, fostering social equity, and securing a sustainable future for both humanity and the planet. In this research, the DTE is introduced as an innovative information framework that bridges the gap between the physical and digital realms. By integrating ubiquitous perception technologies, numerical simulations, mechanistic techniques, and artificial intelligence, it is established that the DTE significantly enhances the understanding of complex environmental dynamics and improves decision-making capacity. Through its automated training and inference capabilities, the DTE is shown to support the development of effective, data-driven strategies that are crucial for advancing sustainable management practices. Consequently, this system is highlighted as a pivotal advancement in the ability to monitor, analyze, and respond to environmental changes promptly and effectively, thereby contributing to a more sustainable, equitable, and resilient future.

REFERENCES

1. Hai, C. (2020). Future Earth and sustainable developments. The Innovation 1: 100055. DOI: 10.1016/j.xinn.2020.100055.
2. Peng G., Huadong G., Bin C., et al. (2023). iEarth: An interdisciplinary framework in the era of big data and AI for sustainable development. Natl. Sci. Rev. 10: nwad178. DOI: 10.1093/nsr/nwad178.
3. Guo, H., Nativi, S., Liang, D., et al. (2020). Big earth data science: An information framework for a sustainable planet. Int. J. Digit. Earth 13: 743–767. DOI: 10.1080/17538947.2020.1743785.
4. Grieves, M. and John V. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior. Franz-Josef, K., Shannon, F., Anabela, A. (ed). Transdisciplinary perspectives on complex systems: New findings and approaches. (Springer), pp: 85–113. DOI: 10.1007/978-3-319-38756-7_4.
5. Caldarelli, G., Arcaute, E., Barthelemy, M., et al. (2023). The role of complexity for digital twins of cities. Nat. Comput. Sci. 3: 374–381. DOI: 10.1038/s43588-023-00431-4.
6. Bauer, P., Stevens, B., and Hazeleger, W. A. (2021). A Digital twin of Earth for the green transition. Nat. Clim. Change 11: 80–83. DOI: 10.1038/s41558-021-00986-y.
7. Frolov, S., Rousseaux, C. S., Auligne, T., et al. (2023). Road map for the next decade of earth system reanalysis in the United States. Bull. Am. Meteorol. Soc. 104: E706–E714. DOI: 10.1175/BAMS-D-23-0011.1.
8. Capone, D. G., Popa, R., Flood, B., et al. (2006). Follow the nitrogen. Science 312: 708–709. DOI: 10.1126/science.1111863.
9. Yang, W., Wang, F., Ma, L., et al. (2023). An international journal of Earth science. The Innovation Geoscience 1: 100001. DOI: 10.59717/j.xinn-geo.2023.100001.
10. Popescu, D. C. and Dumitrache, I. (2021). Relational modeling framework for complex systems. U.P.B. Sci. Bull., Series C 83: 16-28. https://www.scientificbulletin.upb.ro/rev_docs_arhiva/rez3a6_719008.pdf.

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AUTHOR CONTRIBUTIONS

Y. Wang conceptualized the study, drafted the manuscript, and led the overall direction and planning of the paper. L. Wang contributed to the development of the theoretical framework and provided critical revisions of the manuscript. W. Han assisted in the literature review and contributed significantly to the writing and editing process. J. Yan participated in the interpretation of the results and offered significant insights during the revision process. All authors reviewed and approved the final version of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.