A Comprehensive Review of Simulation Technology: Development, Methods, Applications, Challenges and Future Trends

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Abstract—**Simulation technology is a comprehensive method for predicting possible outcomes or evaluating decision-making effects by establishing computer models of complex systems and simulating their behavior and evolution processes. This paper systematically reviews the development history, main methods, application fields, challenges, and future trends of simulation technology. Firstly, the article defines the connotation of simulation technology and expounds its important value in military, business, public policy, and other fields. Secondly, the article traces the development of simulation technology from its origins in World War II to the present, summarizing key milestones such as modeling languages, graphical interfaces, distributed interaction, and cloud computing. Thirdly, the article introduces the main modeling paradigms, such as system dynamics, discrete events, and agents, as well as compound modeling methods like continuous-discrete hybrid and multi-agent-macro hybrid. Meanwhile, the article also demonstrates typical applications of simulation in defense, business, government, engineering, healthcare, and other fields, using case studies in military operations, consumer markets, macroeconomics, traffic management, and disease spread. Based on an analysis of existing technical challenges, practical dilemmas, and methodological controversies, the article finally outlines the development prospects of simulation technology in the directions of large-scale high-performance computing, data-driven modeling, human-computer hybrid, cognitive-behavioral simulation, and cross-domain coupling. The article points out that simulation is accelerating its integration with artificial intelligence, big data, digital twins, and other technologies, evolving towards more intelligent, real-time, and immersive directions, and will become an indispensable enabling technology in the digital era. Strengthening theoretical innovation and application expansion of simulation is of great significance for enhancing national scientific and technological strength and comprehensive competitiveness.**

Index Terms—**Simulation technology, Modeling and simulation, Artificial intelligence, Digital twin, Hybrid modeling**

I. Introduction

Simulation technology is a method of predicting future results by simulating real-world systems, processes or events. It has wide applications in military, business, public policy and other fields, and is an important tool for decision support and risk assessment. This paper will comprehensively review the development history, main methods, application examples, challenges and future trends of simulation technology.

II. Definition of Simulation Technology

Simulation technology refers to the use of computer models and simulation tools to simulate the behavior and evolution of complex systems by setting initial conditions, parameters and rules, so as to predict possible results or evaluate the effects of different decision-making schemes [1]. It is a comprehensive method that combines qualitative analysis with quantitative calculation, and integrates expert knowledge with data-driven approaches [2]. The core of simulation technology is to establish a model that can reflect the key characteristics of the real system. By adjusting the parameters and variables of the model, simulation data under different scenarios are generated to analyze the response of the system to changes in internal and external factors, assess risks and uncertainties, and provide decision makers with visualized and interpretable predictions and decision support [3]. Simulation technology plays an indispensable role in many fields. In the military domain, simulation technology is widely used for weapon equipment demonstration, combat plan evaluation, force deployment planning, etc., and is the core means of military strategy and command [4]. In the business domain, simulation technology can help enterprises forecast market demand, assess investment risks, optimize supply chain and production processes, and improve operational efficiency and economic benefits [5]. In the field of public policy, simulation technology provides a scientific basis for policy formulation and evaluation, such as population forecasting, transportation planning, environmental impact assessment, and health emergency decision-making [6]. In addition, simulation technology has extensive and in-depth applications in financial risk management, engineering design verification, artificial intelligence algorithm testing, social science research and other fields [7]. With the rapid development of computer technology and data science, simulation technology is becoming an increasingly powerful and universal analysis tool.

III. The Importance and Application Fields of Simulation Technology

Simulation technology plays an indispensable role in many fields. In the military field, simulation technology is widely used in weapon equipment demonstration, combat plan evaluation, force deployment planning, etc., and is a core component of military operations research [4]. In the business field, simulation technology can help enterprises forecast market demand, assess investment risks, optimize supply chain and production processes, and improve operational efficiency and

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As shown in Figure 1, the main application fields and examples of simulation technology are presented.

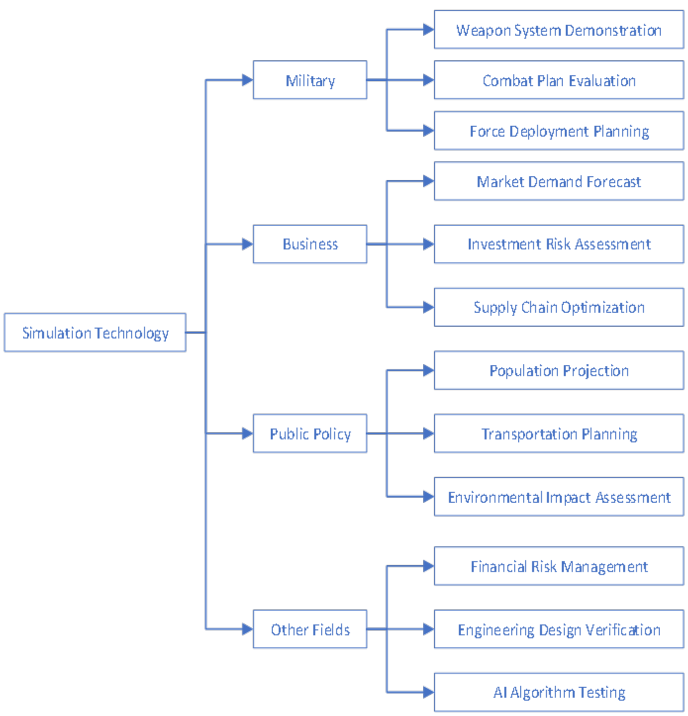

Fig. 1. Main application fields and examples of simulation technology

IV. Historical Development of Simulation Technology

A. Early Methods and Theoretical Foundations

The early ideas of modern simulation technology can be traced back to the application of operations research in World War II. With the development of computers in the 1950s, researchers began to use Monte Carlo simulation to establish military models [8]. The "Linear Programming-400 Project" of the U.S. Air Force in 1957 marked the beginning of computer-aided force analysis [9]. In the 1960s, theories such as game theory, queuing theory, and inventory theory were introduced into military simulation [10]. Meanwhile, in the business field, IBM's Geofrey Gordon developed the first general-purpose discrete event simulation language GPSS in 1961 [11]. With the creation of system dynamics, agent-based modeling, and object-oriented simulation languages, simulation applications in various industries continued to deepen [12].

B. Recent Advances and Milestone Events

Since 2014, simulation technology has entered a stage of rapid development driven by new-generation information technologies. Table I summarizes the milestone events in this period. These milestone events reflect the accelerated integration of simulation with emerging technologies such as big data, AI, IoT, and blockchain since 2014, giving birth to new applications like digital twins and metaverse, and making simulation a key enabler of the digital transformation.

TABLE I
Important Milestones in the Development of Simulation Technology

Year	Milestone Events
2014	US DARPA launched the DDDAS project, promoting the fusion of simulation and big data [20].
2015	Alibaba's "Tao" digital twin warehouse simulation system launched, a benchmark for industrial simulation [21].
2016	AlphaGo defeated top human Go players, showing the potential of deep reinforcement learning in complex simulations [16].
2017	Gartner listed digital twin as a top ten strategic technology trend, indicating the convergence of IoT, big data and simulation [22].
2018	AWS launched the SageMaker RL cloud platform, reducing the threshold for developing and deploying reinforcement learning applications [23].
2019	IEEE approved the P2807 digital twin system framework standard project, accelerating the standardization process [24].
2020	The COVID-19 pandemic promoted large-scale application of computational epidemiology models in public health decisions [25].
2021	MITRE proposed the ASGS (Actionable Simulation Guidance System) framework, enhancing the interpretability and trustworthiness of simulation [26].
2022	Shanghai launched a city-level digital twin CIM platform, integrating simulation, monitoring and intelligent applications [27].
2023	NVIDIA released the Omniverse platform, providing a foundation for the industrial metaverse based on physically-accurate simulation and AI [28].

V. Main Methods and Models of Simulation Technology

A. Traditional Simulation Methods

Traditional simulation methods are mainly based on mathematical models and analytical methods, such as differential equations, stochastic processes, queuing theory, inventory theory, etc. These methods focus on quantitatively describing and analyzing the macro behavior of the system, and generally require appropriate simplification and assumptions about the system [?]. For example, in the military field, Lanchester equations are widely used to describe the dynamic process of attrition of combat forces on both sides [?]. In operational research, optimization methods such as linear programming and dynamic programming are commonly used for optimal selection of weapons and equipment and optimal deployment of troops [?]. The advantages of traditional simulation methods are relatively simple modeling, high computational efficiency, and analytical form of results, which are easy to understand.

However, they are often difficult to finely describe the complex interactions within the system, and have limited descriptive power for systems involving intelligent behavioral subjects [?].

B. Modern Simulation Technology

Modern simulation technology mainly refers to a series of methods based on computers and integrating cutting-edge achievements in fields such as artificial intelligence and complexity science. Among them, the individual modeling and simulation method represented by agent-based modeling (ABM) has injected new vitality into simulation. ABM generates the emergent behavior of the system from the micro-interactions of a large number of heterogeneous intelligent agents, and can model complex adaptive systems that traditional methods are difficult to describe [?]. For example, in financial market simulation, ABM can simulate the game of investors with different trading strategies and its impact on market stability [48]. In traffic flow simulation, ABM can study the self-organizing behavior of vehicles and pedestrians in road networks [29]. Artificial intelligence technology is another important driving force for modern simulation. Various machine learning algorithms are used for behavioral modeling, environment perception and decision-making of simulation agents, making simulation more intelligent [?]. Reinforcement learning allows agents to learn optimal strategies through continuous trial and error [33]. Deep learning enables agents to handle high-dimensional perception data, such as learning to understand battlefield images [47]. Knowledge graphs and causal reasoning allow agents to make reasonable decisions based on domain knowledge [39]. In addition, evolutionary computation, swarm intelligence and other methods have also been applied in military and socio-economic system modeling [34].

$$\frac{dx}{dt} = ky(t) - \alpha x(t) \ \frac{dy}{dt} = kx(t) - \beta y(t) \tag{1}$$

Equation 1: Lanchester's square law equations, describing the attrition rate of combat forces $x(t)$ and $y(t)$ on both sides

C. Hybrid Simulation Methods

Hybrid simulation methods refer to integrating multiple heterogeneous modeling and simulation paradigms within a unified framework, leveraging their respective strengths to describe complex systems at multiple levels and dimensions. Typical hybrid simulation methods include:
(1) Continuous-discrete hybrid simulation, that is, a model contains both continuous processes and discrete events, such as the coexistence of continuous material flow and discrete events such as equipment failures on a production line [40];
(2) System dynamics-discrete event hybrid simulation, the former depicts the overall structure and feedback loops of the system, while the latter describes local processes, such as the macroscopic operation of the supply chain and the microscopic simulation of order processing [?];
(3) ABM-macro modeling hybrid simulation, such as in disease transmission models, ABM depicts individual contact behavior, while macro differential equations describe the susceptible-infected-recovered transition of the population [36].
Simulation systems with hybrid paradigms have high modeling flexibility and fine-grained multi-scale mapping, but the complexity and computational cost of modeling increase accordingly. Constructing a reasonable conceptual framework to coordinate the semantic interoperability of heterogeneous models is a challenging problem faced by hybrid modeling [54].

VI. Application Examples of Simulation Technology

A. Military and Strategic Planning

The military is the earliest, widest and most in-depth application field of simulation. The DMSO (Defense Modeling & Simulation Office) under the U.S. Department of Defense is specifically responsible for military simulation construction, and has developed a series of large-scale simulation systems and key technologies [?]. In recent years, the application of simulation systems has expanded from campaigns and tactics to military system demonstration, equipment development demonstration, situation assessment, command information systems, etc. Figure 2 shows the Gantt chart of the Peninsula War simulation project plan.

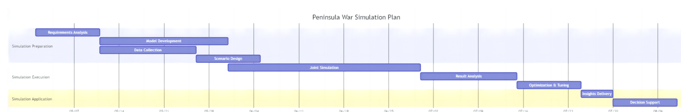

Fig. 2. The Peninsula War simulation is a typical case of the U.S. military conducting joint combat simulation analysis [?]. The simulation integrates high-resolution models of multiple services such as land, sea, air, and space, constructs a refined battlefield environment of the Korean Peninsula and its surroundings, and sets up multiple confrontation plans for Red and Blue. Through more than 100,000 simulations, the effect evaluation of different military action combinations was analyzed, the force deployment and resource allocation were optimized, and potential tactical insights were studied, providing strong support for the planning and decision-making of theater commanders.

B. Business and Market Forecasting

In the business field, simulation technology is widely used in supply chain management, production scheduling, market forecasting and other aspects. Agent-based modeling is particularly suitable for simulating the complex interactions and adaptive behaviors among the many participants in the market. Procter & Gamble (P&G) has developed an agent-based consumer market simulation system [29]. The system builds an artificial market space, and creates virtual consumers, retailers, competitors and other agents. Each consumer agent has its own demographic attributes, psychological preferences, social networks and behavioral rules. They perceive product information, exchange experiences, and make purchase decisions in the market environment. By adjusting product, price, channel and promotion strategies, P&G simulated the market response, forecasted demand, optimized marketing mix, and supported new product development decisions. The accuracy of the simulation prediction once reached 90%.

C. Public Policy and Social Sciences

In the field of public management, simulation is an important means to assist policy formulation and evaluation. In recent years, social computing, a new interdisciplinary field integrating social science and computer science, has emerged, aiming to understand and tackle complex social problems with the help of computational simulation methods [30]. The European Union has funded the EURACE (European Agent-based Computational Economics) project to develop an agent-based model of the European economy [31]. The model includes millions of autonomous agents such as households, companies, banks, and governments, as well as various markets such as labor market, product market, credit market, etc., to simulate the complex interactions and dynamic evolution of the economic system. By setting different policy scenarios such as fiscal, monetary, and regulatory policies, EURACE evaluated the effects of policies on economic growth, employment, inflation, and income distribution, providing a "policy wind tunnel" for EU decision makers. During the European debt crisis, EURACE provided valuable policy insights.

D. Other Application Areas

In addition to the above typical areas, simulation technology has been widely used in many other fields in recent years. In the field of engineering design, simulation is used to verify the function, performance, safety, reliability and other indicators of complex systems. For example, in the development of aircraft, finite element simulation is used to analyze the structural strength, computational fluid dynamics simulation is used to study the aerodynamic characteristics, and multi-disciplinary simulation is used to evaluate the overall performance, greatly reducing the cost and cycle of physical tests [32]. In the field of artificial intelligence, simulation provides an important means for the development and testing of various intelligent algorithms. For example, in the development of autonomous driving technology, simulation scenarios are constructed to train and validate the perception,decision-making and control modules of driverless cars. Waymo, Baidu Apollo and other leading companies have developed advanced simulation platforms, which can generate massive scenes, and support the testing of algorithms in complex road conditions, extreme weather and fault scenarios [33]. In the field of social science research, simulation provides a "computational experimental platform". Sociologists construct artificial societies in computers, exploring the emergence of norms, the evolution of cultures, the spread of public opinion, group behaviors and other issues [34]. For example, Epstein's civil violence model simulated the interaction between rebels and law enforcers, revealing the effects of factors such as hardship, legitimacy and repression on the scale of insurgency [35]. The Mentat project at the University of Zurich aims to simulate the entire life cycle of the ancient Roman society, from the rise to the fall of the empire, to reveal the key driving forces of historical evolution [36].

VII. Challenges and Limitations

A. Technical Challenges

Simulation technology faces many challenges in terms of technical implementation. One is the "curse of dimensionality". As the scale and complexity of the simulation system increase, the state space will explode exponentially. How to rationally characterize the system, control the model scale, and ensure the computational efficiency is a dilemma [37]. The second is the validation of the simulation model. Whether the model can reflect the essence of the real system, whether the structure and parameters are properly set, and whether the simulation results are reliable, all need to be strictly validated, but the workload is huge [38]. In addition, simulation models often involve a large amount of uncertain information. How to express and process various types of uncertainty and evaluate its impact is also a technical difficulty [39].

B. Practical Application Challenges

In practical application scenarios, simulation also faces many challenges. One is the acceptance of decision makers. Simulation is a "black box" process for many managers. They often doubt the reliability of simulation results and are unwilling to use them as a basis for decision making [40]. The second is data availability. High-quality data is the cornerstone of simulation, but in many areas, data is scarce, isolated, or difficult to access, making it difficult to support simulation [38]. In addition, the application of simulation also faces challenges such as high cost, long cycle, professional barriers, and integration with business processes [37].

C. Methodological Controversies

Simulation, as an emerging technology, still has many controversies in methodology and epistemology. One view is that simulation is only an auxiliary tool and cannot replace the traditional scientific methods such as theoretical analysis and experimental verification [41]. Another view is that simulation has created a "new scientific paradigm" that is parallel to theory and experiment [42]. At the same time, some scholars question the explanatory power of simulation. They believe that simulation models, especially agent-based simulation, are difficult to reveal the causal mechanism, and often stay at the level of correlation and phenomenon reappearance [43].

VIII. Future Trends and Prospects

A. Technological Innovation

The development of a new generation of information technology will further promote the innovation of simulation technology. The new generation of AI represented by deep learning and reinforcement learning will give simulation systems stronger autonomous learning and complex decision-making capabilities [44]. Digital twin, CIM engineering and other technologies will make simulation models more real-time and consistent with physical entities [45]. VR/AR and other emerging interaction technologies will also bring more immersive simulation experience. In addition, the development of cloud computing, big data, blockchain and other new infrastructure will provide strong computing, data and credible support for the implementation of simulation applications [46].

B. Application Field Expansion

In the future, simulation technology will be more widely used in more fields. In the military field, with the development of intelligent warfare, simulation will penetrate into the whole chain of military activities such as strategy, weapon development, tactical deduction, and actual combat [47]. In the economic field, central banks and financial institutions are digital economic systems" to assist macro-control and financial supervision [48]. In the field of smart cities, city simulators" will become an important tool for urban planning, operation management and emergency response [49]. In addition, simulation will also have great application potential in the fields of smart healthcare, education and training, entertainment and media.

C. Research Directions

In the future, the research and innovation of simulation technology will focus on the following directions:
(1) Large-scale, high-performance simulation method. Research on parallel, distributed, and cloud-based simulation frameworks to improve computing efficiency [50].
(2) Data-driven modeling and simulation. Use machine learning, data assimilation and other methods to directly mine simulation models from data and combine knowledge-driven with data-driven [51].
(3) Human-machine hybrid simulation. Integrate human experts into the simulation loop, leveraging human experience and machine capabilities to achieve human-machine collaboration [52].
(4) Cognitive and behavioral modeling. From the modeling of simple behaviors to the simulation of advanced cognition such as emotion, learning and creativity [53].
(5) Cross-domain composite simulation. Break down disciplinary barriers and couple multi-disciplinary, multi-domain and multi-level simulation models [54].

IX. Conclusion

This paper comprehensively reviews the development course, main methods, typical applications, existing challenges and future trends of simulation technology. As an important means of understanding the world and assisting decision-making, simulation technology has developed vigorously in both military and civilian fields, and has produced huge economic and social benefits. At present, simulation technology is ushering in a new round of revolution under the background of a new generation of information technology. Simulation is integrating with emerging technologies such as artificial intelligence, big data, and digital twins, and is evolving towards a more intelligent, real-time, and immersive direction. It is foreseeable that in the future, simulation technology will be more widely used in various economic and social fields, and will become an indispensable tool for humanity's ability to understand and shape the world around us. Therefore, strengthening the research on the theory and methods of simulation technology, promoting the development and application of simulation technology, is of great significance for enhancing the country's scientific and technological innovation capability and comprehensive national strength.

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