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Parallel Live Performance Simulation Based on a Multidimensional Hierarchy and Application

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Abstract: *A parallel simulation method* is proposed for modern live performance. *By decomposing the live performance process from the top down, this method assists creators in delivering stage design and control with time and space constraints, which is unattainable for traditional live performances. A multi-layer constraint hierarchy is constructed to apply parallel simulation to art performances.* The live performance procedure is continuously optimized by leveraging the circulation of data between virtual and physical stages. The parallel simulation method for stage space has been applied to a digital TV stage for ten years. The experiments show that parallel live performance simulation based on a multidimensional hierarchy can effectively assist with the whole live performance process and promote live performance efficiency.

Keywords: parallel simulation; modern live performance; multi-layer constraint hierarchy; whole process

基于多维层级的表演平行仿真及应用

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摘要：提出了一种面向现代化表演的平行仿真方法。*该方法通过自顶向下分解表演过程，在时空限制下辅助创意者实现传统表演中难以实现的舞台设计和控制。通过构建多层级约束结构，将平行仿真应用于表演领域。利用虚拟舞台和物理舞台之间的数据循环，不断优化表演流程。*将舞台空间平行仿真方法连续应用于某数字电视舞台10年。实验表明：基于多维层级的表演平行仿真可以有效地辅助表演全流程，提高表演效率。

关键词：平行仿真；现代化表演；多层级约束结构；全流程

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Introduction

Due to the difficulties in visual evaluation, multi-process cooperation, and real-time monitoring, traditional live performance often fails to fully implement the creators' ideas. As modern live performance diversifies, many kinds of components, such as visual, sound, and behavioral ones, are included. Given the large numbers of pieces of equipment and performers, live performance management and control have become extremely difficult. Focusing on live stage performance, this paper proposes a parallel simulation method for live performance to overcome the challenges facing live

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stage performance. In this system, a virtual stage is generated to simulate the physical one. Through the data interaction between the two stages, live performances achieve a better constantly iterative process.

This paper offers two main contributions:

(1) The proposal of a parallel simulation method;

(2) The establishment of a multi-layer constraint hierarchy for live performance.

The proposed multi-layer parallel simulation method has been applied to a theater for ten years.

1 Related Work

Since computer simulation was first proposed, parallel systems and digital twins have been developed in many areas.

Parallel systems originated from the research of intelligent systems in 1994 when Wang proposed an embedded collaborative method called the shadow system[1]. Since then, the concepts and methods of parallel systems have been further studied and applied in military, traffic, emergency, and other fields[2-3]. Subsequently, parallel simulation was proposed as a new mechanism for parallel control and management. To solve the problem of artificial phenomena in the field of complex systems, Wang proposed parallel system methods[4] and an artificial systems, computational experiments, and parallel execution (ACP) approach[2]. Wang et al. presented the concept and basic framework of parallel vision based on the ACP approach[3].

Grieves took the lead in proposing the concept of the digital twin[5], although it was mainly used in the military industry and aerospace[5-7]. Since then, many models and systems of digital twins have been proposed. Grieves proposed a digital twin implementation model[8]. Schroeder et al. explored the concept of a cyber-physical system (CPS) model in the virtual part of industrial devices[9]. Tao investigated the application methods and frameworks of digital twin-driven product design, manufacturing, and service[10]. He also proposed an emerging technology to achieve the physical-virtual convergence for prognostics and health management (PHM)[11]. Alam presented a digital twin architecture reference model for the cloud-based CPS and C2PS[12]. Tavares proposed a solution available for representing any industrial work cell[13]. Graessler presented an approach for assuming communication and coordination tasks[14]. He et al. presented Pavatar, a real-world Internet of things (IoT) system for ultra-high-voltage converter stations (UHVCSs) [15]. With the evolution of digital twin technology, its application gradually extended from the military industry and aerospace[6,16] to the industrial field[9,14,17-19], as well as logistics[20], medical engineering[21], power control management[15,22], driving assistance[23], and material science[24]. Digital twin solved the interaction gap between virtual and physical systems.

In the field of live art performances, Yan developed a simulation system to trigger the adaptive performance cues according to electroencephalographs (EEGs) [25] and proposed an EEG-based engagement level to detect the engagement status of the audience[26]. This research was the first to relate audience response with live art performances in the area of simulation.

2 Methodology

2.1 Parallel simulation method for stage space

Fig. 1 shows the two processes in traditional

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live performance generation. The first one is embodying the creators' idea in the live performance, while the second one is converting the live performance scenes to the sight of the audience. Through the two processes, the live performance is converted from a virtual form to a physical one and then to another virtual form. According to the concept of simulation, the live performance is equivalent to a medium linking creators to the audience. The stage is an important component of a live art performance. In this paper, a parallel simulation method is applied to the above two processes. The physical stage is guided and assisted by the information generated by the virtual stage.

The structure of the parallel stage simulation is shown in Fig. 2. This simulation involves resources such as the creators' live performance schemes, live performance elements, live performance equipment, and virtual reality (VR) interactions. Live, virtual, constructive (LVC) simulation resources are fully utilized. Directors guide real actors and actresses in practice in a virtual environment for live simulation. Creators generate virtual live performances in the virtual environment to achieve virtual simulation. A live performance is constructed with the resources for constructive simulation. LVC simulation resources are applied to achieve generalization, service, and integration of the simulation system, thereby achieving reusable, scalable, composable, and interoperable simulation.

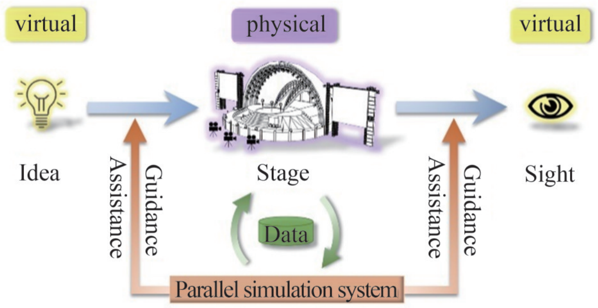

Fig. 1 Transformation process of virtual and physical forms of live performance by parallel simulation

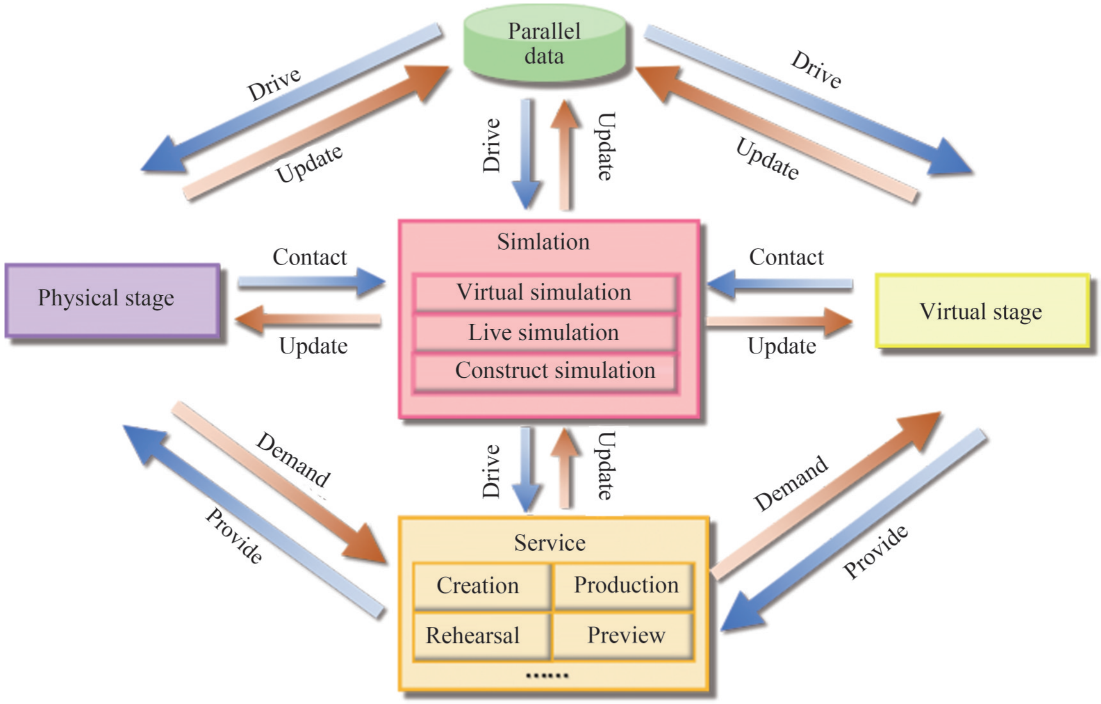

Fig. 2 Structure of parallel stage simulation

Many components are used in live performances, such as props, screens, lighting, and stereos. The parallel simulation system for live performances involves the states of all the components of the physical and virtual stages. The system state S_t at time t is expressed as

$$S_t = \bigcup_{i=1}^{n} \{ s_{i,t}^R, s_{i,t}^V \} \tag{1}$$

where $s_{i,t}^R$ is the state information on the i^{th} live performance component of the physical stage at time t and $s_{i,t}^V$ is the state information on the i^{th} live performance component of the virtual stage at time t. In the parallel stage simulation system, the information on the virtual stage is updated by state data interaction and then used to predict the state of the physical stage.

2.2 Multi-layer constraint hierarchy for live performance stages

This paper also presents a multi-layer constraint hierarchy for live performance stages (Fig. 3). In this hierarchy, the live stage performance is divided into six layers: component, state, sequence, behavior, condition, and interaction. This hierarchy offers a virtual stage more similar to the physical one.

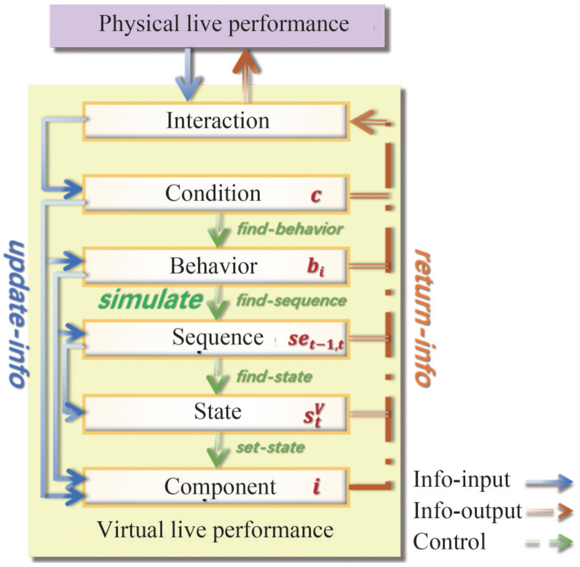

Fig. 3 Flowchart of multi-layer constraint hierarchy for live stage performance

The component layer covers all the basic components of the stage, including screens, props, lighting, and other indispensable equipment. The state layer contains the information on the basic live performance components (e. g., location and mapping texture) expressed as $s_{i,t}^V$ in Section 2.1. The sequence layer, containing information about the changes between two scenes, performs a timing function for the stage. The behavior layer records the movement rules, such as the order of scene changing in a program. The condition layer records the conditions that motivate the live performance component to execute a specific behavior, for example, the beginning of a program. The interaction layer, including interactive devices and data acquisition (DAQ) devices, allows the platform to exchange information between the physical and virtual stages.

To build the hierarchy, this paper presents the definition of each layer in the Vienna Development Method (VDM) [27] in Table 1.

Table 1 Definition of hierarchy

Layer	Symbol	Example	Structure
Condition	*Cons*	Programs	condition-name; condition-component; condition-behavior
Behavior	*Bs*	Order of scene changing	behavior-name; behavior-component; behavior-sequence
Sequence	*Ses*	Data changing between two scenes	sequence-name; start-time; end-time; state
State	*Sts*	Location and mapping texture	state-name; state-info
Component	*Coms*	Stage blocks	component-name; component-state

Regarding parallel stage simulation, a constraint relationship exists between two adjacent layers. Specifically, top-down mappings among the layers exist, for example, the mappings from the condition layer to the behavior layer. Moreover, the start time of each sequence segment should be ahead of the end time. In VDM, the constraints are defined as follows

inv mk_*Virtual-performance* (*cons*, *bs*, *ses*, *sts*, *coms*)Δ

∀*con*∈*cons* (*con.condition-behavior* ⊂ *bs*)∧

∀*b*∈*bs* (**elems** *b.behavior-sequence* ∈ *ses*∧

(∃*com*∈*coms com.component-name*=*b.behavior-component*)) ∧

∀*se*∈*ses*(*se.start-time*<*se.end-time*∧*se.state*∈*sts*)

where *cons* is the set of conditions in the parallel simulation system for stage space; *bs* is the set of behaviors in the live stage performance; *ses* is the set of sequences; *sts* is the set of states of live performance components; *coms* is the set of components of the stage.

Three operations are performed to update and iterate the data: *update-info*, *simulate*, and *return-info*. Virtual control data are information generated from the virtual stage, while physical control data are real-time data from the physical stage. When physical control data pass through the interaction layer, they are transferred top-down through the layers according to the hierarchical constraints. *Update-info* is achieved by this process. As the program starts, scenes change in order on the virtual stage. The states of the stage blocks in the current scene and those in the next one are calculated in the sequence layer. According to the current states recorded in the state layer, the locations of the live performance components in the component layer are modified. This process fulfills the *simulate* operation. The virtual control data from each layer of the virtual stage are fed back in a bottom-up manner to the interaction layer by *return-info*. The synchronization between the physical and virtual stages is achieved through information transmission and inner simulation. Furthermore, the future state of the physical stage is predicted.

The optimal feasible live stage performance scheme can be obtained by comparing the benefit ratios of the schemes. The optimal scheme is selected by

$$\begin{cases} \max\limits_{bs,\, coms} K(bs, coms) = \dfrac{\sum\limits_{b \in bs} \theta(b)}{\sum\limits_{c \in coms} \beta(c)} \\ \sum\limits_{b \in bs} \alpha(b) + \sum\limits_{c \in coms} \beta(c) \leqslant \delta \\ \prod\limits_{s \in ses} \xi(s) = 1 \end{cases} \tag{2}$$

where K is the benefit ratio of the live stage performance scheme; *bs* is the behavior set; *coms* is the component set; *ses* is the sequence set; θ is the benefit ratio of the behavior; β is the consumption of constructing the component; α is the consumption of implementing the behavior; δ is the maximum acceptable consumption; ξ is the feasibility of the sequence. The value of ξ is 0 or 1. If it is 1, the sequence is feasible. Otherwise, it is not.

3 Application of parallel stage space simulation

3.1 Structure and working process

After a parallel stage simulation system was built, it has been applied continuously to a theater for 10 years. The stage of the theater is almost fully covered by LEDs (439~4 250 m^2). In addition, it contains hundreds of movable stage blocks with three degrees of freedom (DOF). Fig. 4 demonstrates the construction of the system. In this system, the simulation engine is a platform for the virtual stage to generate data. Shared memory provides the space for data storage, and such data include spatial information, creative copies, videos, and mechanical data. Directors and creators accomplish identity authentication by security management and design the live performance through the user interface. The input data that pass through the feasibility analysis are managed and processed by data management and are stored in the shared memory. The system uses the information in the shared memory to generate and visualize the preview. The real-time data from the physical live performance stage are acquired with a DAQ (data acquisition) card. Then, the system compares the virtual control data with the physical control data to achieve real-time monitoring. The proposed stage simulation system for live performances is based on the above processes.

The working mechanism of the parallel stage simulation system is shown in Fig. 5. In this system, live performance information is first transmitted to the virtual stage through the interaction layer. According to this information, each basic stage block is modeled and stored in the component layer. Once the state data, such as the mapping texture and location, on each stage block are set, each component receives the spatial and visual information. As a time parameter *t* is introduced into the system, each stage block changes its mapping texture and location in a sequence. When the performance of a program starts, the video of the program is played, and the scenes change in order. All the programs together constitute the entire live performance. Through the DAQ card, the virtual stage updates with the information from the physical stage. Finally, the virtual stage feeds back the visual effect and generates data through the stage console.

The parallel stage simulation system is used throughout the entire process, and its working process is illustrated in Fig. 6. During the stage design phase, stage designers first model the stage. They set the location and rotation with the three DOFs of each component by maneuvering basic stage blocks, screens, lighting, props, and stereos. The directors set the location of movable stage blocks through the interaction interface so that the stage forms a special scene to serve as the background of programs. Then, video designers edit the video to make it coordinate with the scenes formed by movable stage blocks. When a dynamic stage set is built, the virtual stage generates a verification texture for video-playing with each screen's number. The verification texture can then assist the screen workers to check and modify the installation. When movable stage blocks are set at certain locations, the virtual stage also generates mechanical verification files that can be used to test the mechanism of the physical stage. Furthermore, with the data sampled from the DAQ card, the system compares the location of each movable stage block on the physical stage with its location on the virtual one and returns the faulty equipment. During the rehearsal phase, the system computes the locations of each block during the programs and generates mechanical files for the console. During the live performance, the system obtains real-time data from the physical stage through the DAQ card. It then monitors the video stream of the screens and the locations with the three DOFs of each movable stage block. If the gap exceeds the threshold, the system generates alarms.

3.2 Key technologies

Modern live performances utilize movable stage blocks, which involves three state changes: that from static to dynamic, that from dynamic to static, and motion direction change. For example, the motion state-changing points with one DOF on the virtual stage are shown in Fig. 7, in which H means the height of the movable stage block, and T represents the time during the movement.

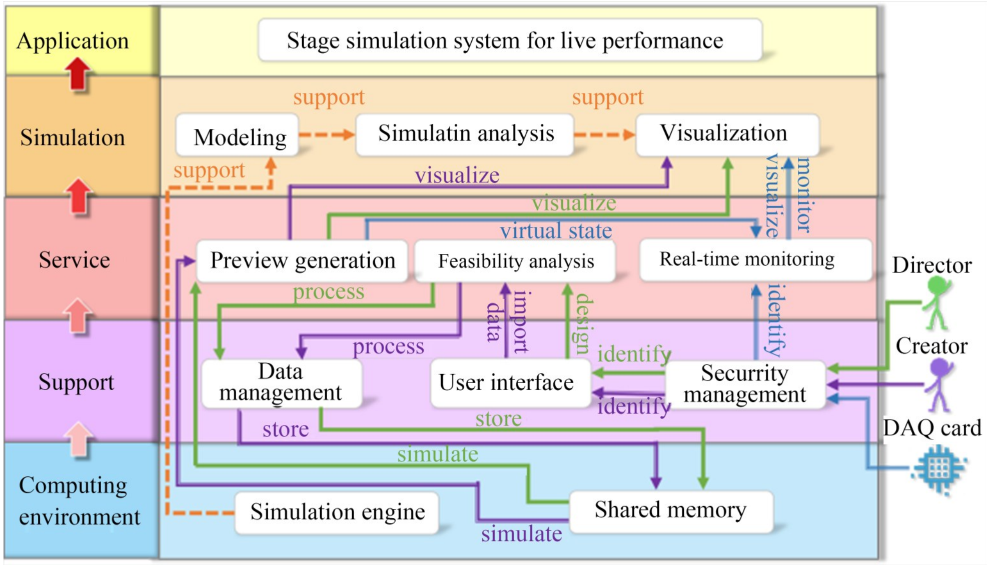

Fig. 4 Construction of the parallel stage simulation system

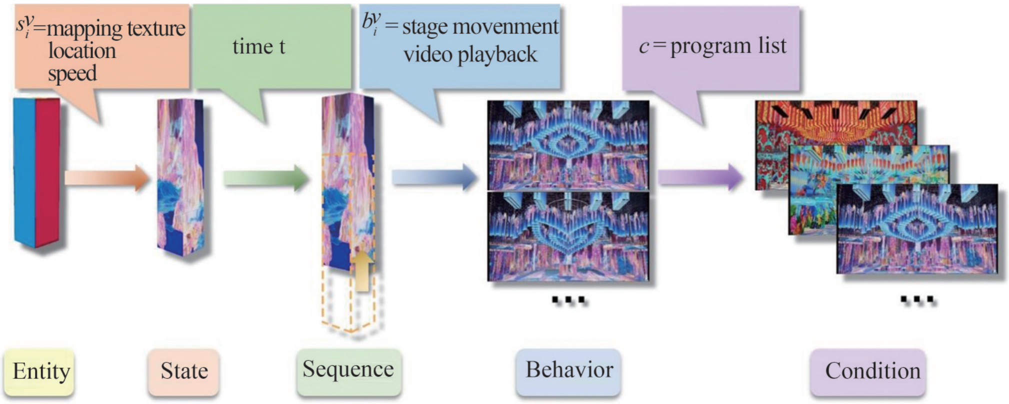

Fig. 5 Working mechanism of the parallel stage simulation system

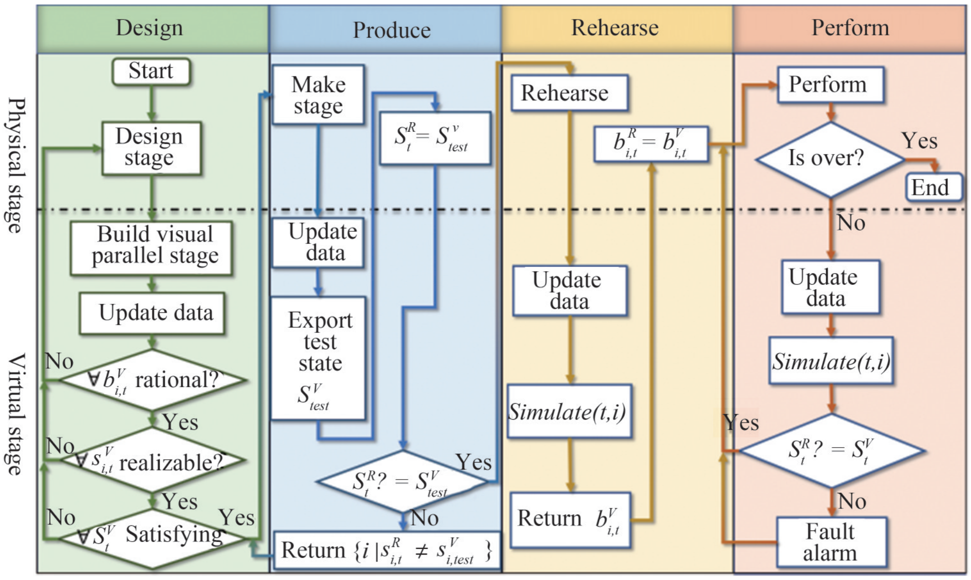

Fig. 6 Working process of parallel live performance simulation

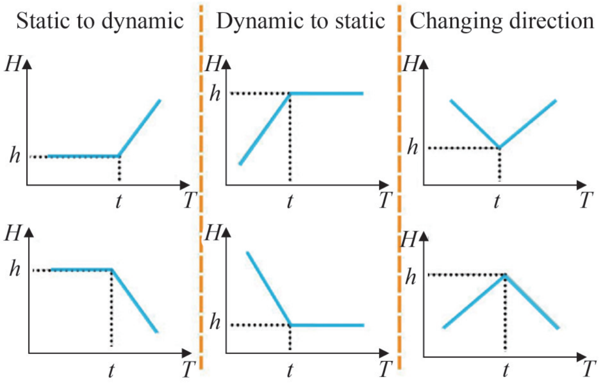

Fig. 7 Motion state-changing points

However, the mechanical movements on the physical stage present a parabola effect. When the linear method is used to simulate the motion trajectories on the virtual stage, errors occur due to the accelerations at the motion state-changing points on the physical stage. This problem is more severe during the mechanical motion of stage blocks, as the motion directions change many times (Fig. 8). A parabola fitting region is thus added to the field of the motion state-changing points (Fig. 9) to reduce the cumulative error in the mapping between the virtual and physical stages. In Fig. 9, t_b is the accelerating point; t_m is the halfway point of the moving time; H_b is the height at t_b; H_f is the final height during the mechanical movement

The corrected velocity v between two motion state-changing points is calculated by

$$v = \frac{at - \sqrt{a^2t^2 - 4a(l_f - l_0)}}{2} \tag{3}$$

where a is the acceleration; t is the moving time; l_f is the final location during the mechanical movement; l_0 is the initial location.

3.3 Simulation results

With the development of hardware equipment, the stage of the theater becomes increasingly magnificent. Fig. 10 illustrates the data on the movable stage blocks of the theater during the 10 years 2011–2020. In this figure, the number of movable ceiling blocks increased from 0 to 120, and that of movable floor blocks increased from 10 to 154 over the 10 years. In total, the number of movable stage blocks grew by a factor of 27. These changes add more difficulties to the design of live performance stages and the management of the stage machine.

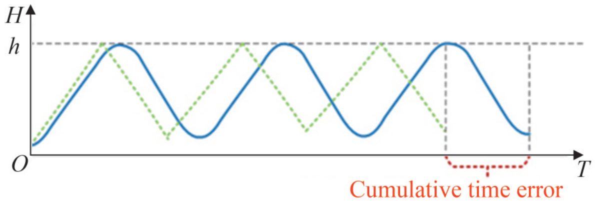

Fig. 8 Cumulative time error in continuous movement

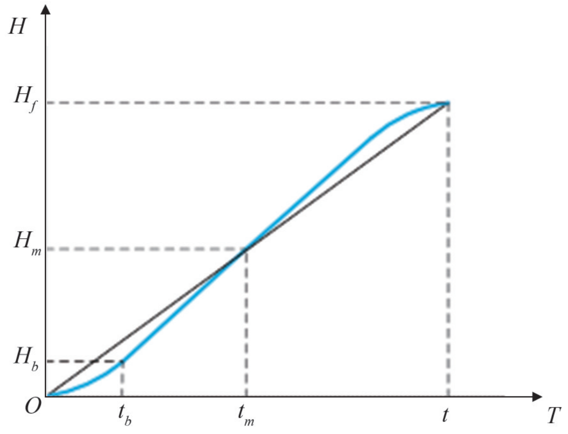

Fig. 9 Fitting motion trajectory in the simulation

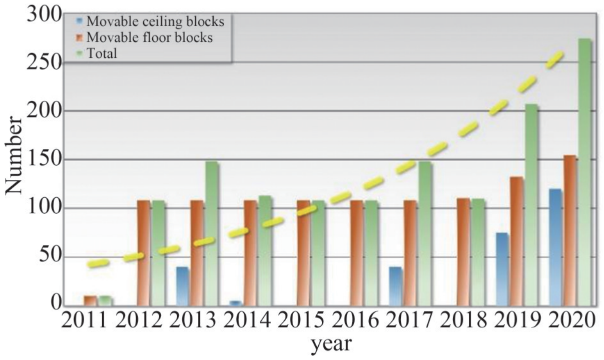

Fig. 10 Number of movable stage blocks

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Fig. 11 illustrates the utilization of movable stage blocks. The utilization rate rose from 5% in 2011 to 38.7% in 2020. The movement frequency of the stage in 2020 was about three times that of the frequency in 2011. The rehearsal time was reduced from 78 days to 18 days. All these changes prove that the system has improved the utilization rate of movable stage blocks as well as the coordination between ceiling blocks and floor blocks.

Furthermore, the video processing data also increased steadily from 2011 to 2020 (Fig. 12). The number of video files rose from 10 to 46, while that of video players remained at about 15, which makes video broadcasting management more difficult. However, owing to the employment of the parallel video processing method, the number of frames computed per minute increased from 45 to 65, and that of programs processed per day rose from 1.18 to 5.56, which provided the video creators with more time to refine the videos. These results demonstrate that the parallel stage simulation system can significantly speed up video processing.

The current system has not only improved the efficiency of live stage performances but also promoted the structure of the physical and virtual live performances. From 2011 to 2020, the stage layout of the physical stage has also been refined, and assigned profiles, stage verification, video mapping, and interactive preview have been added to the virtual stage. As the physical stage becomes increasingly well equipped, the application of the proposed system has also extended from the virtual stage for specific programs to the whole live performance process.

The circulation and iteration of the system are achieved through the data transmission among the physical stage, virtual stage, and console. The coordination between the virtual stage and the physical one also becomes more harmonious. The visual effect of the parallel stage simulation system is shown in Fig. 13.

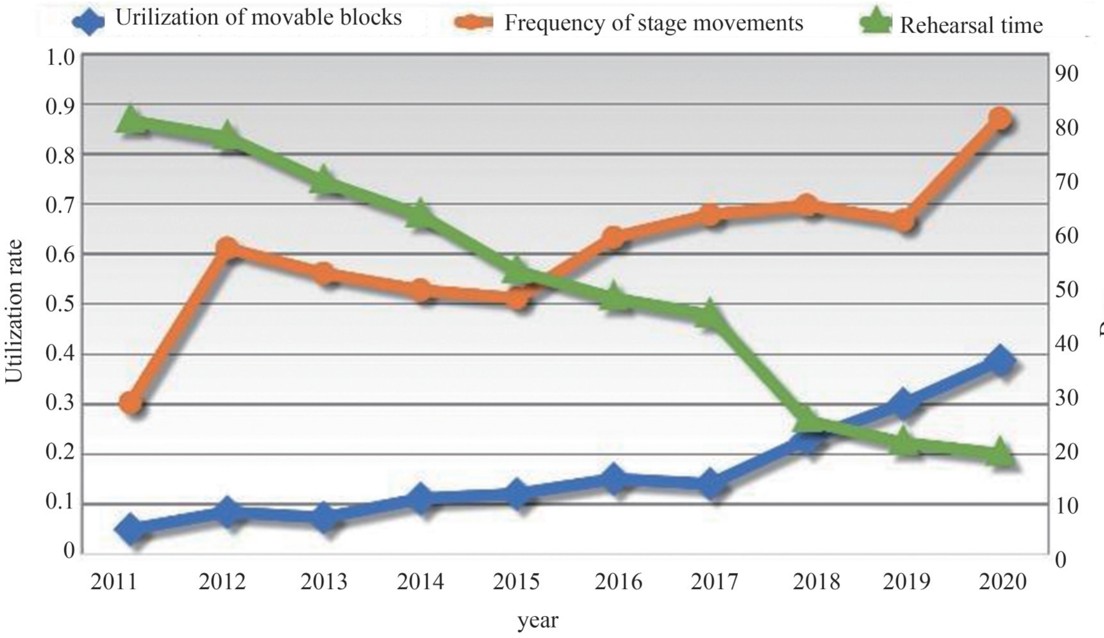
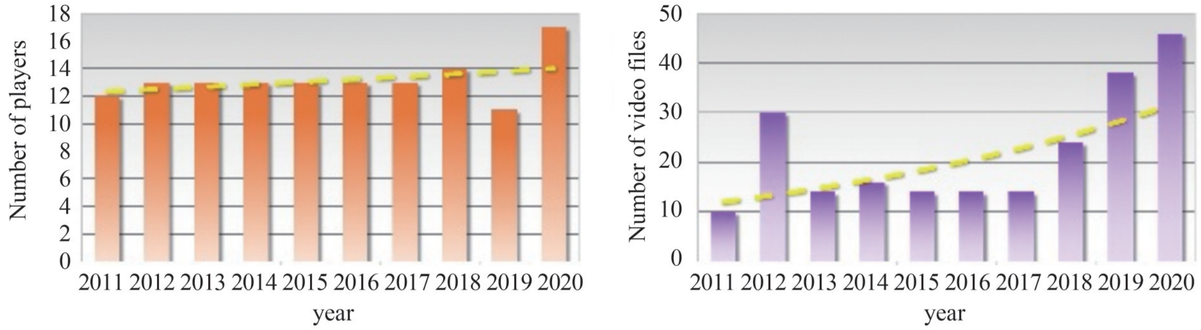
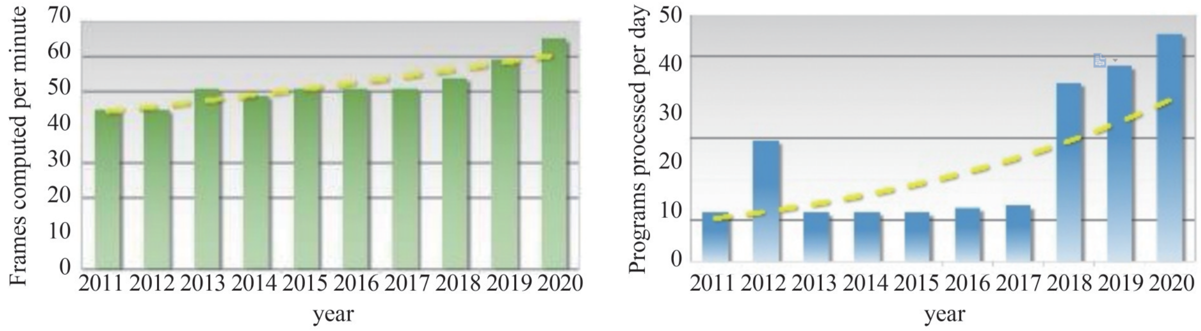


Fig. 11　Utilization rate of the mobile stage from 2011 to 2020



(a) Statistics of players

(b) Statistic of video files



(c) Computing efficiency

(d) Processing efficiency

Fig. 12 Video processing data

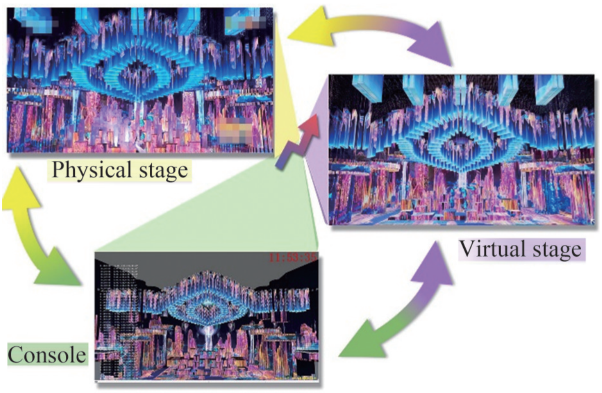


Fig. 13 Visual effect of the parallel stage simulation system

4 Conclusions

In this paper, a parallel simulation method for live performance is proposed, and a multi-layer constraint hierarchy is constructed. Complex live performances are divided into a multi-layer structure with clear logic based on the top-down stratification of live performances. The complex architecture is gradually decomposed into multiple simple ones that can be worked on. The interaction of data between the physical and virtual stages provides a way to improve live performances. The assistance of the virtual stage can facilitate the physical stage in conveying the creators' ideas to the audience.

Although the parallel stage simulation system has been gradually improved, the data of the whole live performance process are still insufficient for building a knowledge base for constructive simulation (as described in Section 3) and conducting stage prediction. Moreover, the security of the information transmission between the virtual and physical stages also needs to be further improved.

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