Research and Application of Key Technical Stages in Film Virtual Digital Human Production: Postprint

Authors: Cheng Xiangyi

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Abstract

【Objective】In recent years, with the digital evolution of high-tech paradigms such as mobile internet, artificial intelligence, and virtual reality, "virtual digital humans" as an emerging technological format have demonstrated unique value in the film domain. However, the conceptual boundaries of "film virtual digital humans" remain ambiguous, and the production technical workflows have yet to be systematically organized. 【Method】In response to the film industry's demand for virtual digital human applications, it is necessary to clarify the boundaries of "film virtual digital humans"and elucidate their essential concepts, while also systematically organizing the production workflows to better serve the creation of high-quality industrialized films. This paper takes the virtual digital human character "Li Bai" produced in our research project as a case study to conduct in-depth research on the key technical aspects of film virtual digital human production. 【Results/Conclusion】This paper defines the concept and characteristics of "film virtual digital humans," dissects and breaks down the key production stages and key technologies of film-grade virtual digital humans, and identifies existing problems in current film-grade virtual digital humans, providing technical references for future large-scale industrialized applications.

Full Text

Preamble

Research on Key Technical Aspects and Applications of Cinematic Virtual Digital Human Production [China Film Science & Technology Institute (Film Technology Quality Inspection Institute of the Publicity Department of the CPC Central Committee), Beijing 100086]

Abstract

[**Objective**] In recent years, with the digital evolution of high-tech formats such as mobile internet, artificial intelligence, and virtual reality, "virtual digital humans" have emerged as a novel technological paradigm and have begun to play a unique role in the film industry. However, the conceptual boundaries of "cinematic virtual digital humans" remain ambiguous, and the technical production workflow has yet to be systematically organized. [**Methods**] To address the application needs of the film industry for virtual digital humans, it is necessary to clarify the boundaries of "cinematic virtual digital humans" and define their essential concepts, while also mapping out the production workflow to better serve high-quality industrial filmmaking. This paper takes the virtual digital human character "Li Bai," produced for a research project, as a case study to investigate the key technical aspects of cinematic virtual digital human production. [**Results/Conclusion**] This paper defines the concept and characteristics of "cinematic virtual digital humans," breaks down the key production stages and critical technologies for film-grade virtual digital humans, and identifies current challenges in film-grade virtual digital human production, providing technical references for future large-scale industrial applications.

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1. Definition and Characteristics of Cinematic Virtual Digital Humans

Cinematic virtual digital humans (Movie Digital Humans) refer to digital representations applied in the film industry that achieve cinema-grade technical specifications. Through advanced technologies such as computer graphics, machine language, deep learning, and intelligent science, these virtual entities are constructed with multiple human characteristics—including appearance, behavior, and even thoughts or values—centered on the principles of "hyper-realism and interactivity."

Virtual digital humans originated in the film industry and have been maturely applied in major productions such as *The Lord of the Rings* and *Avatar* since the early 21st century. These digital representations, created through CG (Computer Graphics) technology, typically exist in two primary application identities: "digital doubles" and "digital avatars." Their characteristics can be summarized in two aspects:

First, **hyper-realistic human physical characteristics** enable cinema-grade visual effects, allowing them to serve as digital doubles in film productions. These virtual digital humans must possess appearances similar to real-world individuals, including facial expressions, skin texture, and other details, while exhibiting fluid and natural movements, lighting environments, and visual effects that achieve photorealism. In the 2015 film *Furious 7*, after actor Paul Walker' s death during production, the filmmakers employed facial replacement technology to combine his existing footage with another actor' s body, creating a virtual character to complete unfinished scenes.

[Figure 1: see original paper] *Furious 7* Paul Walker (Project Production)

Second, **interactive authentic emotional experiences** enable intelligent recognition of user intentions through smart technologies, driving subsequent voice and motion interactions, typically serving as digital avatars in film productions. Cinematic virtual digital humans can provide audiences with natural and realistic visual experiences through highly anthropomorphic production quality, offering creators greater creative space—an essential criterion for virtual digital humans to replace real actors in film production. In the 2019 film *Alita: Battle Angel*, the character Alita represented Weta Digital' s first fully CG humanoid character created through facial capture. Her distinctive features of large eyes and a small mouth emphasized her origins as a manga character, marking a breakthrough in fully CG humanoid characters.

[Figure 2: see original paper] *Alita: Battle Angel* Alita Character Facial Capture (Project Production)

2. Cinematic Virtual Digital Human Production Workflow

Whether existing as "digital doubles" or "digital avatars," the basic production workflow for cinematic virtual digital humans can be divided into four stages: digital human modeling, model rigging, driving/motion capture, and rendering.

Step 1: Digital Human Modeling. This process uses computer technology and related tools to digitize real human body shape, structure, and movement information, generating a virtual human model that can be simulated, emulated, and analyzed in a computer environment. Current modeling methods primarily fall into three categories: manual modeling, image-based modeling, and instrument-based modeling. Manual modeling, though widely used, involves long production cycles. Image-based modeling reconstructs 3D facial structures from several photographs but lacks sufficient precision for high-quality models. Instrument-based modeling represents the current focus of modeling technology development, achieving precision up to 0.1mm, though at higher costs. Among these, camera array scanning reconstruction technology has become the mainstream approach for character modeling.

The virtual digital human character "Li Bai" was created using a combination of traditional manual digital sculpting and real-person light field capture. Based on the facial muscle and bone structure of a real person, manual digital sculpting precisely controlled every detail of the facial structure to obtain realistic human facial texture maps.

[Figure 3: see original paper] "Li Bai" Character Image (Project Production)

Step 2: Model Rigging. Digital human model rigging connects the digital human' s skeletal system and animation control system to external controllers or data sources to enable motion performance. Rigging methods primarily include manual rigging, motion capture rigging, physics simulation rigging, and deformation rigging. Manual rigging involves manually connecting the skeletal and animation control systems to external controllers, requiring meticulous adjustment and optimization to achieve realistic and natural movements. Motion capture rigging connects the skeletal system to motion capture equipment, typically requiring post-processing to correct noise and errors in captured data. Physics simulation rigging connects the skeletal system to physics engines, requiring appropriate physical parameters and constraints to ensure movements comply with physical requirements. Deformation rigging connects the skeletal system to deformation data, employing complex deformation algorithms and optimization to achieve facial expressions, muscle, and skin morphological changes.

The virtual digital human "Li Bai" utilizes the industry-leading MetaHuman facial expression rigging system, employing complex expression control panels, dynamic normal maps, and hundreds of expression blend shapes to present delicate, realistic, controllable, and rich expression variations.

[Figure 4: see original paper] "Li Bai" Expression Rigging (Project Production)

Step 3: Driving/Motion Capture. 3D virtual human motion generation primarily relies on high-precision motion capture and skeletal binding of 3D models, using motion capture equipment or specialized cameras with image recognition to capture movement variations in body shape, expressions, eye movements, gestures, and joints. This is achieved through forms such as live actor motion capture (human-driven) or trained driving models (algorithm-driven). Current motion capture can be implemented through optical, inertial, electromagnetic, or computer vision-based methods.

Optical motion capture primarily uses Markers—reflective points attached to actors that are tracked by optical sensor cameras. The placement and reflectivity sensitivity of these markers determine capture precision. Inertial motion capture relies on Inertial Measurement Units (IMUs) attached to specific skeletal nodes, using algorithms to calculate measurements from integrated accelerometers, gyroscopes, and magnetometers. Computer vision-based motion capture captures depth information through acquisition and calculation, and has become a frequently used solution due to its simplicity, ease of use, and low cost.

"Li Bai" employs Optitrack optical motion capture, attaching markers to various actor joints to bind actor movements to the skeletal model.

[Figure 5: see original paper] "Li Bai" Character Motion Capture and Rigging (Project Production)

Step 4: Rendering. This final stage involves compositing scenes, characters, roles, special effects, and voiceovers for final rendering. Based on required presentation effects and elements, components and models are rendered to achieve optimal visual quality. Rendering technology enhances virtual human realism, and real-time interaction requires real-time rendering capabilities. Rendering determines the final work' s quality and style. Rendering technologies are divided into offline rendering (pre-rendering) and real-time rendering, with the essential difference being the ability to render instantly. Offline rendering is primarily used for film and television animation with high requirements for realism and detail, requiring substantial computing resources. Real-time rendering emphasizes interactivity and immediacy, suitable for scenarios with frequent user interaction such as games, virtual customer service, and virtual anchors. While advances in graphics hardware and precompiled information have improved real-time rendering performance, quality remains constrained by rendering time and computing resources. Hardware limitations and algorithmic improvements will bring significant advances to rendering, substantially enhancing rendering speed, effects, and photorealism, particularly through major improvements in real-time rendering capabilities that enable digital virtual characters to become true substitutes for real humans.

"Li Bai" plays offline animation data and renders in Unreal Engine to complete high-quality video production.

[Figure 6: see original paper] "Li Bai" Offline Rendering (Project Production)

3. Key Technologies in Cinematic Virtual Digital Human Production

Based on the fundamental definition of cinematic virtual digital humans and supported by technology stacks including graphics recognition, visual technology, 3D modeling, CG rendering, motion capture, artificial intelligence, computer voice technology, and natural language processing, production involves numerous hardware devices and software algorithms across multiple domains. The foundation of cinematic virtual digital human production is "achieving high-fidelity visual presentation + real-time rendering," primarily influenced by key technologies such as CG modeling/image migration, speech synthesis TTS, NLP, automatic speech recognition ASR, and CV deep learning models.

3.1 CG Modeling/Image Migration Technology Affects Presentation: Embodied in Virtual Digital Human Appearance Anthropomorphism

Cinematic virtual digital humans exhibit high anthropomorphism, particularly in appearance, visual effects, and interactive behavior. External appearance and interaction quality have become critical development pathways. Virtual digital human appearance encompasses facial features and overall image, influenced by factors such as character type (direct use of real-person likeness, high-fidelity modeling, stylized), production details (modeling of fine details like hair, skin, and hair rendering), rendering quality, and design aesthetics. Virtual digital human behavior relates to facial expressions, body language, and voice expression, affected by driving methods (human-driven, algorithm-driven, pre-adjusted), driving model categories (fine facial muscle driving, processing of interjections and prosody in speech synthesis models), training data, and driving model precision.

Alita: Battle Angel replaced the specialized Light Stage and Medusa Rig technologies for creating realistic human face models with a camera capture system, deploying 60 cameras to cover 180° around the actor and capture 4D data. For key plot sequences, the team had actors reenact performances within this system, providing reference and supplementary data for deep learning processes.

[Figure 7: see original paper] *Alita: Battle Angel* Camera Capture (Project Production)

3.2 Speech Synthesis TTS/Automatic Speech Recognition ASR Technology Affects Language Processing: Embodied in External Language Conversion

ASR (Automatic Speech Recognition) technology converts human speech to text. Speech recognition is a multidisciplinary field closely connected with acoustics, phonetics, linguistics, digital signal processing theory, information theory, and computer science. TTS technology (Text-to-Speech) belongs to speech synthesis, converting text information to voice output through intelligent computer synthesis. The output effects can be transformed through database calculations. iFLYTEK has conducted in-depth research in speech synthesis, conversion, and translation, developing mature voice large model products for market application. TTS technology primarily solves the conversion of text information to audible sound information—enabling machines to speak like humans.

Cinematic virtual digital humans using ASR technology can extract features from external audio signals, improving speech recognition effectiveness and enabling voice interaction devices to distinguish target sounds, ultimately achieving voice interaction. TTS technology helps virtual digital humans output natural and fluent speech streams, making interactions more natural and vivid.

[Figure 8: see original paper] External Language Conversion (Project Production)

3.3 NLP Interaction Technology Affects Interactive Experience: Centered on Dialogue Capability

NLP interaction technology continues to play a central role in digital virtual humans, following text dialogue assistants and voice AI assistants, and can be considered the brain of digital virtual humans. AI interaction assistants have achieved ideal results, such as Xiaoice, which possesses good general interactive capabilities. Companies like Zhuiyi Technology enhance business interaction capabilities through knowledge graphs, business Q&A databases, and conversational engineering engines.

Cinematic virtual digital humans can achieve cross-language communication and intelligent Q&A systems through NLP interaction technology, performing sentiment analysis on input text to understand emotional information (positive, negative, neutral words) and provide language feedback.

3.4 CV Deep Learning Models Affect Driving Effects: Ability to Present Natural Facial and Body Movements

The ability to present natural facial expression and body movement changes depends heavily on the effectiveness of speech-driven deep models, profoundly influenced by data volume, computing frameworks, and key feature points. Whether special designs for emotional factors can be implemented also significantly impacts results.

Cinematic virtual digital humans can import actor facial expression information (training data) using this technology. Markers enable computers to recognize how different facial muscles move through deep learning. Deep learning decomposes actor facial expressions, activating corresponding facial muscles to drive the facial model to generate expressions autonomously. This approach better facilitates the reconstruction of digital human expressions.

4. Challenges in Cinematic Virtual Digital Human Production

Among the top 10 highest-grossing films worldwide (exceeding $1 billion), four have earned over $2 billion: *Titanic*, *Avatar*, *Avengers: Infinity War*, and *Furious 7*—all of which extensively employed virtual digital human technology. While cinematic virtual digital humans deliver unparalleled visual impact to audiences, the technical and capital barriers behind these films constrain large-scale application and promotion. With the rise of blockchain technology, metaverse concepts, and LED virtual production, cinematic virtual digital humans are experiencing renewed popularity. The full integration of new technologies, art, and commerce brings new economic growth and visual impact to the film industry, but also presents new problems and challenges.

4.1 Lack of Unified Authoritative Definition and Industry Standards

The virtual digital human industry is in its early development stage, with production companies, technology firms, operation companies, application companies, and various capitals entering the market. However, significant differences exist in technical capabilities and product quality among enterprises, and relatively unified service production and evaluation standards are lacking, hindering high-speed and high-quality industry development. Traditional film and television digital character production companies maintain relatively closed technology holdings, seeking to ensure advantageous positions through technical barriers and professional experience, which to some extent slows overall virtual digital human technology development. Establishing technical, product, and evaluation standard systems will effectively promote healthy industry development.

In terms of international standards, the *IEEE Digital Human Quality Assessment Draft* was officially promulgated on March 21, 2023, providing a prescribed digital human quality assessment framework that evaluates the authenticity of digital humans used in immersive content services. The China Academy of Information and Communications Technology (CAICT) Cloud Computing and Big Data Research Institute first proposed digital human evaluation standards globally, officially releasing two digital human standards on July 29, 2022: *Basic Framework and Evaluation Metrics for Digital Human Application Systems* and *Requirements and Assessment Methods for Non-Interactive 2D Real-Person Image Digital Human Application Systems*. These standards focus on digital human application systems, first clarifying the definition of "digital human" and proposing a reference framework for digital human application systems.

Regarding domestic standards, searches on the "National Standard Information Public Service Platform" show no officially released national or industry standards for "virtual digital humans," though relevant technical specifications and group standards are actively being promoted. CAICT has led research and formulation of *Basic Capability Requirements and Evaluation Methods for Digital Human Systems* and initiated *Technical Requirements for Trusted Virtual Human Generated Content Management Systems* and other technical specifications and industry standards. The Shenzhen Artificial Intelligence Industry Association, Zhongguancun Internet of Things Industry Alliance Standards Committee, and others have led the release of group standards such as *Technical Specifications for Virtual Digital Humans Supporting Voice and Visual Interaction* and *Metaverse Virtual Digital Human Full-Process Developer*.

According to standard research, no industry standards or definitions have yet been proposed for cinematic virtual digital humans, requiring authoritative and unified definitions and specifications.

4.2 Technical Barriers and High Costs

From a technical perspective, the rise of digital virtual humans has created channels for merging real and virtual worlds, but intelligent and anthropomorphic digital virtual humans will require further improvement in the era of massive computing power. To achieve complete industrial film production content and truly realize virtual-human intelligence integration, deeper research and breakthroughs are needed in technical implementation and computing power support.

On one hand, cinematic virtual digital human technology research and application are developing toward intelligence, but nodes in the production industry chain remain relatively fragmented, particularly lacking in collaborative work and complementary differences. This creates technical barriers in production and adjustment processes, where service scenarios and performance scenarios are not effectively connected—performance-oriented digital humans lack required business capabilities, while service-oriented digital humans lack character personas and struggle to emotionally connect with users. Market surveys indicate most companies currently only handle one or several segments of the full digital human production and operation workflow.

On the other hand, costs remain high for meeting high-mobility and high-frequency demands. Cinematic virtual digital human production involves long cycles, high costs, and insufficient capacity. Currently, most virtual digital human production still employs traditional 3D modeling + motion capture methods. While this has formed a refined, proprietary cinema-grade virtual digital character production workflow capable of producing cinematic-quality virtual humans with exquisite detail and high aesthetic and technical standards, costs remain prohibitively high, preventing mass production and failing to meet diverse modern film production scenarios and applications.

4.3 Talent Shortage Leading to Homogenized Competition

Currently, film industry technical talent is relatively weak, and films lack imagination driven by technology. Many virtual digital humans lack differentiation, with most companies basically developing applications based on open-source technologies like UE5, rarely possessing overwhelming technical advantages. Most can only make superficial changes in content, operations, and creativity. However, due to the shortage of professional film and television technical personnel, specialized film and television subfields such as rendering, color grading, and other post-visual effects, as well as scene art and lighting, still lack professional technicians. Many companies subcontract and outsource production, lacking experience and awareness in talent cultivation, resulting in insufficient professional talent reserves and production motivation.

Summary and Outlook

With the development of new technologies such as AIGC and real-time rendering, cinematic virtual digital humans, as an entirely new technological form, are currently developing toward "hyper-realism, interactivity, and intelligence." The acquisition and production workflow for cinematic virtual digital humans will gradually simplify, production cycles may be significantly shortened, and costs will gradually decrease. Particularly with continuous improvements in vertical domain AI large models and cross-modal research capabilities, the perceptual abilities of cinematic virtual digital humans will be significantly enhanced, enabling more authentic and delicate expressions across different scenes, emotions, and dialogues in film production. Additionally, with increasing training data, cinematic virtual digital humans may possess perception and decision-making capabilities in the future, enabling film production to develop in a more industrialized direction. In the future, virtual digital humans may become our avatars in the virtual digital world, interacting in digital spaces and bringing us more intelligent and immersive experiences. In response to the challenges posed by cinematic virtual digital human production, we hope that future technology fusion research and applications will bring new business forms to different industries and fields, collectively providing technical support for high-quality film development.

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Author Introduction: Cheng Xiangyi (1994–), female, from Yuncheng, Shanxi, Master' s degree, Engineer, research direction: digital film technology

and film standard research.

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Author Introduction: Mao Lina (1978–), female, from Zhengzhou, Henan, Associate Editor, Master' s degree, main research direction: editing, publishing, and cultural communication.

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Note: Figure translations are in progress. See original paper for figures.