

Design Translation and Revitalization of Quanzhou Puppetry Art from the Perspective of Digital Twins

Dongdong He, Yaping Zhang

Quanzhou University of Information Engineering, Quanzhou 362000, Fujian, China

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Abstract: Digital twin technology, which creates high-precision digital models to simulate, map, and interact with physical entities, offers new possibilities for the living transmission of intangible cultural heritage (ICH). Currently, the application of digital twin technology in ICH protection mainly focuses on the digital archiving of static cultural relics, while research on dynamic performance recording, interactive experience design, and multimodal data fusion for performing ICH, such as puppetry, is still in its early stages. From the perspective of digital twins, this paper constructs a “four-dimensional, three-stage” theoretical framework for design translation of Quanzhou puppetry art. It proposes that the digital translation of puppetry should proceed along three dimensions: the material level, the technical level, and the narrative level, ultimately elevating it into a vehicle for disseminating local cultural brands. On this basis, the paper systematically elaborates on three technical pathways, 3D modeling, motion capture, and mixed reality interaction and explores the revitalization of puppetry art in scenarios such as digital performance, virtual teaching, and interactive experiences. It also proposes an overall plan for building a digital twin platform for puppetry art, aiming to provide theoretical reference and practical pathways for the digital and intelligent preservation of performing ICH in China.

Keywords: Digital twin; Quanzhou puppetry art; Design translation; Revitalization; Intangible cultural heritage

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1. Introduction

Digital twin technology, which creates high-precision digital models to simulate, map, and interact with physical entities, is rapidly extending from industrial manufacturing to the cultural sector. In 2025, the Guizhou Intangible Cultural Heritage Digital Museum, through the integration of digital twins, VR, and AI technologies, achieved immersive display and interactive manipulation of ICH items, transcending geographical and temporal limitations. In the field of puppetry, the Guangxi Puppet Troupe has initiated the construction of an “AIGC + Digital Twin Theater Project,” exploring new pathways for the digital transformation of ICH. Meanwhile, the “Living Legacy Project” at the National Museum of Australia employs technologies such as 3D scanning and motion capture to generate digital twin datasets for puppet performances, enabling the recording and intergenerational transmission of performance heritage. These practices indicate that digital twin technology is moving from “static archiving” towards “dynamic revitalization,” opening new spaces for the transmission of performing ICH.

Quanzhou, as a city rich in intangible cultural heritage, saw its puppet theater inscribed on the first batch of China’s

national-level ICH protection list in 2006 and was selected as one of the top ten outstanding cases of ICH and tourism integration in Fujian Province. To date, it has preserved over 700 traditional plays and a unique musical genre known as “Puppet Tunes,” consisting of more than 300 melodic types. Puppeteers manipulate 30 to 40 strings through refined techniques such as releasing, hooking, lifting, and pressing, enabling puppets to perform difficult actions like “pouring wine with a pot” or “sword dancing,” achieving a narrative effect of “man-puppet unity.” Glove puppetry, on the other hand, uses the index finger to control the head and neck while the middle finger and thumb manipulate the hands, creating a “palm universe.” However, the transmission of Quanzhou puppetry art faces practical challenges, including a cognitive disconnect among younger audiences, difficulties in mastering string-manipulation techniques, and limited cultural dissemination channels. Digital means are urgently needed to achieve the coordinated development of “authentic” charm and innovative expression.

2. Dimensions of design translation for Quanzhou puppetry art

The design translation of Quanzhou puppetry art is a multi-dimensional and systematic transformation process, which can be analyzed along three progressive dimensions: material, technical, and narrative.

2.1. Material level: Digital replication and morphological reconstruction of puppet forms

The material level of Quanzhou puppetry includes visible physical entities such as puppet heads, costumes, props, and stages, forming the material foundation of design translation.

The carving of Quanzhou marionette heads follows the “five forms and three bones” principle. The “five forms” refer to the basic shapes of the facial features, and the “three bones” refer to the facial skeletal structure. Character traits are expressed through exaggerated and emphasized facial lines. Colors follow operatic conventions, where loyalty, treachery, goodness, and evil each have their symbols, forming an intuitive emotional coding system. Glove puppets, though small in size, feature puppet heads with movable facial mechanisms and cloth bodies and limbs capable of performing difficult actions such as martial arts and walking, with a level of detail no less than that of marionettes.

From the perspective of digital twins, design translation at the material level includes 3D digital modeling, high-fidelity texture and material restoration, and reconfiguration of movable structures. Through high-precision 3D scanning and photogrammetry, the puppet head, torso, limbs, and other parts can be transformed into editable 3D digital models. Through texture mapping and material simulation, the carving texture, painting traces, and costume texture can be reproduced with high fidelity in digital form. More critically, through systematic analysis and parametric modeling of movable structures such as the puppet head’s facial mechanisms and shoulder and elbow joints, the digital puppet can retain its degrees of freedom in virtual space, this is precisely the core difference between digital twins and simple 3D scanning: it is not “taking a photo” but “modeling a digital creature that can move.”

2.2. Technical level: Motion analysis and parameter transformation of string-manipulation skills

The essence of Quanzhou puppetry art lies in “man-puppet unity.” The puppeteer’s manipulation skills give life to the puppet, making the static puppet “come alive” on stage. The digital transformation of this tacit knowledge is one of the core links in design translation.

Quanzhou marionette puppeteers manipulate 30 to 40 strings through techniques such as releasing, hooking, lifting, and pressing, enabling puppets to perform difficult actions such as pouring wine with a pot, sword dancing, cycling, and playing the guitar. The technique of “conveying emotions through strings” is not merely a technical skill but also an accumulation of bodily memory; the amount of force, the rhythm of movements, and the range of motion are all formed into muscle memory through decades of repeated practice. The “palm universe” of glove puppetry, where the index finger controls the head and neck while the middle finger and thumb manipulate the hands, similarly reflects the profound bodily skill of the puppeteer. This “body knowledge” is highly embodied, and its transmission has long relied on oral

instruction and demonstration from master to apprentice. The introduction of digital twin technology offers the possibility of overcoming this limitation.

In design translation, the goal at the technical level is to convert this tacit body knowledge into visualizable, analyzable, and learnable digital resources. Motion capture technology records the puppeteer's manipulation parameters; through analysis of motion trajectories, joint angles, speed, acceleration, and other data, the core features of various performance actions are extracted; by binding these parameters to the 3D puppet model, the digital puppet can reproduce the puppeteer's classic actions in virtual space. The "Living Legacy Project" at the National Museum of Australia has already demonstrated that digital twin datasets generated through 3D photogrammetry, motion capture, and biomechanical analysis can serve as an effective means of recording and transmitting performance heritage.

However, motion capture alone only solves the problem of "recording." Design translation at the technical level should also move towards "participatory learning" and "creative re-application." Learners can operate virtual puppets in real time within a virtual environment, with the system providing multimodal feedback (visual, tactile, etc.) to indicate movement errors, enabling an immersive "learning by doing" experience. Through parametric design tools, learners can also adjust the puppet's posture and movement amplitude while preserving the patterns of classic actions, generating new performance movements and achieving a leap from "imitation" to "creation." This precisely addresses the core tension between "transmission" and "innovation" in living heritage.

2.3. Narrative level: Cultural encoding and emotional reconstruction of play stories

The narrative level of Quanzhou puppetry art encompasses the story content, emotional expression, and cultural connotations of over 700 traditional plays. It is the deep dimension of design translation and a key bridge linking "technique" with "cultural identity."

Quanzhou marionette theater constructs a unique artistic language through a highly codified visual symbol system. The shapes and colors of the puppets are highly symbolic, and the "five forms and three bones" sculptural principles, together with the color coding, form an intuitive emotional coding system. The audience can immediately discern the character's loyalty, treachery, social status, and moral alignment. While preserving core elements such as "Puppet Tunes" and "Yajiaogu" (a type of drum), the stage and repertoire are continuously innovated. Classic plays such as *Zhong Kui Drunk*, *Monkey Fun*, and *The Monk Descending the Mountain* showcase the humorous, lively, and life-affirming narrative style of puppetry.

From the perspective of digital twins, design translation at the narrative level needs to transform the emotional coding of plays into immersive interactive experiences. Designers can extract classic image elements from the visual symbol library of Quanzhou puppetry and reconstruct narratives in virtual space. Users are no longer passive spectators but become co-participants in the story and co-constructors of meaning by choosing different character perspectives and triggering different plot branches.

3. Three-dimensional framework and overall model of design translation

Based on the above analysis, this paper proposes a three-dimensional framework for design translation of Quanzhou puppetry art, the "material level–technical level–narrative level." These three dimensions form a progressive structure from surface to depth, from form to spirit.

- (1) **Material Level:** Digital replication and morphological reconstruction of puppet forms, corresponding to the digital collection and data management dimensions in the terminology specification for ICH digital twin systems, laying the data foundation for subsequent levels of translation.
- (2) **Technical Level:** Motion analysis and parameter transformation of string-manipulation skills, corresponding to the interactive experience and educational transmission dimensions, incorporating the bodily dimension of tacit knowledge into digital expression.

- (3) Narrative Level: Cultural encoding and emotional reconstruction of play stories, corresponding to the cultural dissemination and digital output transformation dimensions, ultimately achieving the social dissemination and cultural identity of Quanzhou puppetry art.

The three-dimensional framework is not one-way but mutually supportive and progressively layered. The material level provides an accurate structural model of the puppet body for action analysis at the technical level; the technical level provides authentic performance data and physical paradigms for interactive experiences at the narrative level; and the narrative level endows the previous two levels of translation with cultural meaning, bringing the technical outcomes back to the experience and identity of “people.” Together, they form a complete closed loop of “data acquisition–action mapping–meaning construction,” which is precisely the essence of “semantic twin” as distinct from technology-driven digital twins.

4. Technical pathways for digital twin-driven revitalization of puppetry art

4.1. 3D modeling: From physical puppets to dynamic digital puppets

The primary task in building a digital twin of Quanzhou puppetry art is to establish high-precision 3D digital models. This includes two levels: static puppet models and dynamic character models.

Static puppet models focus on the high-fidelity restoration of the puppets’ material properties. Using 3D scanning and photogrammetry, the puppet heads, costumes, props, and other parts are digitally captured with high precision, creating detailed 3D geometric models and restoring carving textures, painting traces, and costume textures. Dynamic character models, built upon the static models, involve rigging and weight painting based on the puppet’s movable structures (facial mechanisms, shoulder and elbow joints, etc.), allowing the puppet model to perform actions in virtual space that are consistent with the real puppet. This provides an accurate character carrier for action mapping at the technical level.

4.2. Motion capture: Datafication of string-manipulation skills and construction of motion libraries

String-manipulation skills are the dimension of Quanzhou puppetry art that contains the most “tacit knowledge” and also represents the most technically challenging and innovative part of design translation.

To achieve the datafication of string-manipulation skills, sensors or markers are placed at key points, and an optical or inertial motion capture system records the puppeteer’s operations in real time, capturing motion data. During data processing, raw data are filtered and smoothed to remove noise, and motion analysis and parameter extraction are performed to identify basic action patterns such as “releasing, hooking, lifting, pressing” and their motion parameters. After binding the processed manipulation data to the 3D puppet model, the digital puppet gains the ability to reproduce classic performance actions. After standardized annotation, these data can be stored in a database to form a motion library for Quanzhou puppetry art, available for teaching, experience, re-creation, and other scenarios.

From the perspective of design translation, the significance of motion capture lies not only in “recording” manipulation actions but also, through data annotation and classification, in converting the puppeteer’s “feel” into knowledge resources that can be learned and transmitted. Behind each motion data point lies the condensation of decades of skill. Making these data accessible to learners essentially extends the boundaries of traditional “oral instruction” transmission, allowing digital twins to become a new channel for the intergenerational transmission of ICH skills.

4.3. Mixed reality: Immersive experience and interactive narrative design

After completing 3D modeling and accumulating motion data, mixed reality (MR) technology opens up entirely new scenarios for immersive experiences and interactive narratives in the revitalization of puppetry art.

Using mobile phones, tablets, or MR head-mounted displays, the public can “summon” virtual puppets into real space and experience the joy of manipulating a puppet to perform classic play segments through gesture recognition or physical controllers. At the level of interactive narrative, users are no longer passive spectators but deeply participate in the

storytelling of puppetry by choosing character perspectives, triggering plot branches, and more.

5. Constructing a digital twin platform for Quanzhou puppetry art

The construction of a digital twin platform for Quanzhou puppetry art should be systematically advanced at three levels: data layer, platform layer, and application layer.

- (1) **Data Layer:** The foundational layer, responsible for the development and management of various digital resources of puppetry art. According to the requirements of relevant digital twin group standards, the data layer should establish unified data formats and interface specifications to ensure data interoperability and collaboration among modules.
- (2) **Platform Layer:** The technical hub, hosting core modules such as a 3D rendering engine, motion driving engine, knowledge graph engine, and AI generation engine, enabling dynamic presentation, action mapping, knowledge association, and intelligent generation of digital puppets.
- (3) **Application Layer:** The user-oriented interface, supporting diverse scenarios such as digital performance, teaching experiences, cultural and creative development, and academic research, meeting the differentiated needs of various user groups.

Platform construction is not an isolated digital project but should be embedded within the ecosystem of ICH protection and transmission. At the construction level, the technical strength of local universities and research institutions in Quanzhou can be leveraged, in collaboration with organizations such as the Quanzhou Marionette Theater Heritage Protection Center and the Glove Puppetry Art Heritage Protection Center, to establish a “university–ICH center–practitioner” collaborative development mechanism. At the operational level, the platform can serve as an important digital node for Quanzhou’s cultural tourism, integrated into the “Maritime Silk Road City” development strategy, promoting the dissemination and revitalization of Quanzhou puppetry art through online–offline integration.

Immersive dissemination focuses on the deep integration of puppetry art with cultural tourism and education. By embedding the digital twin platform for puppetry art into Quanzhou tourist attractions, cultural venues, and school campuses, setting up interactive experience zones, puppetry art can enter the daily lives of the public. Quanzhou puppet shows are consistently sold out, creating a “Quanzhou phenomenon” unprecedented in traditional Chinese opera: “one play brings people to one city.” The intervention of digital twin technology can extend this phenomenon from “offline viewing” to “online participation,” further amplifying Quanzhou’s cultural radiation as a “World Minnan Cultural Exchange Center.”

Academic research provides theoretical support for the continuous optimization of the digital platform. Opening the platform’s digital resources to academia supports interdisciplinary research in fields such as ICH studies, design studies, and digital humanities, exploring new methods and paradigms for the digital preservation of performing ICH, forming a virtuous cycle of theory–practice mutual empowerment.

6. Conclusion

Quanzhou puppetry art, as an important representative of China’s intangible cultural heritage, faces the dual challenges of a diminishing number of practitioners and shifting contemporary contexts. The rise of digital twin technology offers new opportunities for its living transmission, while design translation provides a methodological pathway. This paper has proposed and systematically elaborated a three-dimensional design translation framework for Quanzhou puppetry art, “material level, technical level, narrative level,” and a “four-dimensional, three-stage” overall model. Supported by three technical pathways, 3D modeling, motion capture, and mixed reality, a complete solution from theoretical analysis to platform construction has been constructed. Future research should further deepen the integration of technology and cultural ethics, exploring deeper issues such as the protection mechanisms for inheritors’ intellectual property rights in digital twin scenarios and the standards for defining the authenticity of digital puppetry art.

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