

AI-Assisted 3D Modeling and Engineering Optimization of Artistic Mechanical Parts for TWS Earbud Charging Cases

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Abstract

Under the fast-growing demand for consumer electronic products, traditional computer-aided design contains several issues, like a long design cycle, insufficient cross-link collaboration, and limited creative expression. To explore the application effect of AI-driven technology for the design of consumer electronic products, this study takes True Wireless Stereo (TWS) earbud charging cases as a research object, analyzes the improvement influences of generative artificial intelligence and digital twin for the design process. By integrating multimodal interaction, prototyping process, data interoperability, and other technologies to achieve full-lifestyle design. The results show that the method effectively increasing the design efficiency, engineering feasibility, and decreasing the total costs of business. This study provides a practical reference for balancing artistic expression and engineering performance in consumer electronic products field.

Keywords

AI-assisted 3D modeling, engineering optimization, TWS earbud charging cases, artistic mechanical parts

1. Introduction

Under the fast digital and intelligent development of society, generative artificial intelligence has completely improved the design, production, and consumer experience of consumer electronic products. Acting as a classic portable precision consumer electronic, True Wireless Stereo (TWS) earphones raised higher requirements in product iteration speed, precision of structure design, emotional performance, and other aspects. Traditional design mode that is centered in Computer Aided Design (CAD) software contains several issues, including longer design period, insufficient cross-link collaboration, and limited creative expression, which cause difficulty in meeting dual demands of engineering feasibility and emotional design. Thus, it becomes a major problem in increasing the efficiency of consumer electronics design.

Generative AI technology provides a new way for electronic design with an advanced machine learning techniques, accelerated prototyping process, and improved product features [1]. Besides, a digital twin can achieve the virtual-real synchronization and data interoperability of the product lifecycle, supporting the whole process integration for electronics [2]. In recent years, although many intelligent techniques such as generative Artificial Intelligence (AI), multimodal interaction, and digital twin have been developed at a fast speed,

existing studies mainly focus on the application of a single technology on a product part, lacking a systematic discussion about the full lifecycle intelligent design collaboration.

Taking TWS earbud charging cases as the research object, this paper focuses on the application value of AI-driven technology in designing consumer electronic products and provides a practical path. Also, analyzing the improvement effect of different intelligent technologies on design efficiency, innovative expression, and engineering feasibility. To provide a theoretical reference for the intelligent design and large-scale applications of the consumer electronics field.

2. Background

With the rapid development of electronic devices, True Wireless Stereo (TWS) earphones have become a popular choice among consumers for their portability, miniaturization, and personalization. These necessary characteristics make TWS earbud charging cases, which are an important part of the overall product differentiation of TWS earphones, the most crucial component that decides their market value and competitiveness. In today's electronic market, consumers' demand for products has already changed from simple functionality to artistic design and personal experience. Thus, TWS earbud charging cases have to enhance their aesthetic appearance and high-standard engineering performance to respond to consumers' demands and requirements.

However, TWS earbud charging cases were constrained by the contradiction between artistry and engineering: artistic design often requires products to contain several personalized stylings, including special-shaped curved surfaces, creative contour, and so on. These requirements can consider both earbuds' visual details and integration of brands. But engineering design demands maximum utilization of the internal space of products under the premise of miniaturization. Besides, products should not only satisfy many structural mechanics properties like impact resistance and shockproof performances, but also have to adapt to injection molding and 3D printing, those kinds of mass production processes.

Therefore, these two requirements create the most serious design contradictions because of their different focuses: personal artistic appearance would decrease internal space as well as influence structural intensity, and some special shapes could even increase processing difficulty. Nonetheless, traditional design cannot consider aesthetic properties and functional performance, which extends the design cycle and increases iteration cost.

Under this background, the development of artificial intelligence technology provides an alternative method to address the conflict between artification and engineering design. AI-assisted 3D modeling could utilize the efficient artistic feature extraction, 2D-to-3D conversion, and structural intelligent optimization algorithm to become a key technique that supports the creative design of TWS earbud charging cases.

3. Research Objective

Based on the above issue existing in the market, the author would set the following research objective as the key.

- Research Objective 1: To explore the application value of Generative Artificial Intelligence (GAI) and Digital Twin (DT) in the full-lifecycle design of TWS earphones.
- Research Objective 2: To analyze the limitations of the traditional Computer-Aided Design (CAD) model and verify the optimization mechanism of AI technology in the design cycle and cross-link collaboration.
- Research Objective 3: To construct an AI-driven intelligent design framework to provide practical references for the engineering feasibility and innovative design of consumer electronic products.

4. Literature Review

4.1 Artistic demands for consumer electronic products and limitations of traditional 3D modeling techniques

The deep penetration of the scientific and technological progress and information techniques promotes artistic design transition from traditional, single, and fixed 2D static mode to multi-dimensional and dynamic

interaction's innovation [3]. This transformation is fundamentally based on the User-Centered Design (UCD) theory, a core framework that focuses on aligning product development with users' needs, preferences, and experiences throughout the lifecycle. This theory provides a theoretical foundation for the shift from traditional static design to multi-dimensional interactive design in the consumer electronics field [4]. Thus, this revolution provides a core driving force for the products' design, significantly influencing the whole development direction of the consumer electronics field—miniaturization, personalization, and artification have become the major trend of electronic products to achieve differential competitiveness. Indeed, the development design of interactive electronic products proves that electronic design has transformed into a mode that focuses on both aesthetic performance and engineering properties. Artistic styles have already not only added value as a product, but also a crucial requirement that responds with functionality [5]. TWS earbud charging cases act as a traditional small precision consumer electronic accessory; the artistic design is the key carrier to increase product added value and a necessary method for brands to shape visual recognition. Market's demand for products' aesthetic appearance and high-standard engineering properties increases significantly. This trend aligns with the Aesthetic-Usability Effect theory, which means products with a pleasing appearance are rated as more usable and achieve faster task completion time compared with functionally identical but unappealing appearance alternatives [6].

On the contrary, traditional 3D modeling technology shows an obvious limitation in meeting this demand for design products: first, the manual 2D-to-3D modeling process loses artistic factors easily, and has difficulty in accurately reproducing creativity [7]. Existing research confirms that generative AI design tools can produce higher-quality design artifacts compared to traditional parametric CAD modeling, and also achieve a significant increase in design creativity, engineering feasibility, and work efficiency [8]. During the ordinary 3D modeling process, sketch-based concept design has a long-term process fragmentation with CAD engineering modeling, since the incomplete digitization in the hand-drawn step prevents artistic creativity from fluently transforming to the engineering design process. As a result, products have to be repeated with interactive modification to adapt to structural mechanics, mass production process, and other engineering requirements. This situation both extends the design period and decreases the efficiency of modeling [9].

Next, traditional 3D modeling has high costs for workers, since it depends on AutoCAD, CATIA, and other professional software, which demands that designers possess complex abilities like feature modeling and parametric design. By contrast, interdisciplinary talents are scarce and require high costs for training, which continuously increase businesses' design and labor costs. Thus, the scalable design of consumer electronic products was limited on a large scale [10].

4.2 AI-assisted 3D Modeling Technology and Art-engineering Integration

In response to the limitations of traditional 3D modeling in terms of artistic creativity restoration, efficiency of the process, and talent costs, this study utilizes a deep multi-objective cooperative optimization algorithm to integrate artistic and engineering requirements. The Pareto Optimality model, a core theoretical framework in multi-objective optimization, supports this approach. The model explains that for conflicting design objectives like aesthetics and structural performance, there is a set of optimal solutions where improving one objective cannot be achieved without compromising another. Thus, this eliminates the need for arbitrary trade-offs and instead enables the exploration of balanced, non-dominated design alternatives. Besides, this technique adopts deep neural networks to evaluate user-perceived aesthetics and optimize the design process across multiple conflicting objectives [11]. The integration of CAD technology and artificial intelligence can significantly increase design productivity and the quality of products by using automated simulation analysis and intelligent design optimization. By doing so, repetitive work and iterative revisions in traditional modeling can be decreased, also decreasing the dependence on the professional abilities of designers, which lays the foundation of the artistic scale operation of consumer electronic products [12]. In the deep integration of AI and CAD technology, the 3D model standardization and cross-platform reusability are the main supports for high-efficient design process of consumer electronic products. In fact, the barrier of native format among different CAD software needs a neutral 3D format (like JT and STEP) to break; these standardized formats enable efficient data conversion between supply chain partners, eliminating obstacles to cross-software data interaction and providing a foundation for the reliable transmission of creative modeling data and engineering simulation data [13].

TWS earbud charging cases act as a classical consumer electronic product that contains both cultural and practical properties, which have to not only satisfy engineering structure requirements, but also use emotional design to achieve specific resonance with consumers. With the support of AI technology, integrating emotional design with parametric modeling and the 3D modeling process can significantly promote the appearance, creativity, and cultural value of the products, thus increasing consumer satisfaction and purchasing intention [14]. This requirement that balances both artistic aesthetics and engineering reliability aligns with the major principle of multi-objective optimization theory, which solves trade-offs between competing design goals through Pareto optimal solution sets, also providing a fundamental theoretical structure for the integrated design of TWS earbud charging cases [15].

4.3 Future Development Trend and Industrial Application Prospect of AI-driven Technology

This analysis of AI-driven full-lifecycle intelligent design is based on the AI-integrated Product Lifecycle Management (PLM) framework, which systematically integrates AI techniques in all stages of the production process from design to manufacturing [16].

Today's AI-assisted 3D modeling technique mainly focuses on geometrical modeling and visual rendering, which are auxiliary optimizations of single design stages, and has not yet achieved whole process intelligent coverage. In the future, AI-driven technology will develop toward full-lifecycle intelligent design collaboration, from demand analysis, concept generation, and parametric modeling to structural simulation and production optimization. Generative AI modeling can directly use words and sketches to create 3D modeling with engineering feasibility, significantly shortening the design iteration cycle of consumer electronic products like TWS earbud charging cases [17].

Meanwhile, multimodal interaction and human-AI collaborative design will become the major mode. Multimodal can break the operation barriers of traditional CAD software, supporting a modeling process driven by natural language and hand-drawn sketches. This makes the concept of emotional design and cultural components naturally integrate with product styling development. Zhou demonstrates a nonlinear human-AI co-design framework [18], OptiMuse, which effectively increases design autonomy and creative iteration efficiency by balancing designers and AI in creating design. This produces a new method for TWS earbud charging cases that kind of consumer electronic product, to achieve emotional and personalized design.

Furthermore, the deep integration of AI and digital twin technology enables real-time mapping and dynamic optimization throughout the product lifecycle. Combined with standardized 3D data formats, it can achieve efficient data interoperability across platforms, further promoting the integration of design, simulation, and manufacturing processes [19]. Digital twin technology has shown a broad application potential in the consumer electronics product field, covering the development of product design, performance optimization, supply chain collaboration, and sustainable manufacturing. Therefore, it supports intelligent production and operation for the TWS earbud charging cases and other precision consumer electronic products with a core technology foundation.

5. Key Finding

This study conducts a deep analysis of the application of AI-driven technology in TWS earbud phones and other consumer electronic products, systematically exploring the application value of this technology and industrial implementation potential. The results of the investigation show that the current AI-assisted 3D technology has effectively promoted the efficiency of part of the design stages, like geometric modeling and visual rendering [12, 14]. However, focusing on a single stage of AI-assisted function cannot meet the dual demand of precise structural design and emotional design. There is difficulty in achieving efficient iteration of the full process, which proves that current AI design technology has disadvantages in this field.

Besides, this study further verifies the advantages of the application of full-lifecycle intelligent design collaboration, integrating generative AI with demand analysis, concept generation, parametric modeling, structural simulation, and production optimization [17]. In that case, the design iteration cycle of consumer electronic products can be shortened significantly, also guaranteeing the engineering feasibility of the 3D model.

It can be confirmed that full-lifecycle AI-driven design is the key solution to address the process fragmentation and creative distortion in traditional CAD, which is the core finding of this study.

In the human-computer interaction and design mode level, multimodal interaction and human-AI collaborative design become the major direction of optimization. Multimodal large models break the manual barrier of traditional CAD software, promoting the integration of emotional concept and cultural elements into product styling development with natural language and freehand sketches [18]. This result solves the application gap of the current investigation by broadening the application situation from creative design to precision consumer electronic design.

The study proposes that human-AI collaborative design is the core direction of the future consumer electronics design, which can not only decrease the usage threshold of CAD but also achieve the deep integration of emotional design in precision electronic products, extend the application boundary of generative AI.

From the industrial application aspects, the integration of AI and digital twin technology enables the construction of a real-time mapping and dynamic optimization system for full lifecycle management. Matched with STEP, JP, and other standardized 3D data formats could achieve efficient data interoperability that contains across platforms and the cross-supply chain [19]. It proves the importance of the driving force of AI-driven technology for intelligent manufacturing and supply chain collaboration of consumer electronic products.

All in all, AI-digital twin integration is the critical enabler of the consumer electronics field's intelligent manufacturing, that provides theoretical foundation for the AI-driven technology in a large-scale application.

6. Discussion

However, this study still presents specific research limitations, since it only considers TWS earbud charging cases instead of the whole field, and the universality of the investigation has to be verified. In the future, based on the idea of industrial application in [19], broadening the area of research products scope, combined with digital twin and multimodal AI technology, to deeply explore intelligent design collaboration modes and improve the practicality of technology implementation. Hence, providing more theoretical and practical support for the large-scale application of AI-driven technology in the consumer electronics products industry.

To address the limitation of the product's scope, future research will broaden to a wider range of consumer electronic products, including smart wearables, home appliances, and mobile devices. This extension will investigate the universality of an AI-driven design framework. Also, further technological integration could be conducted to achieve efficient collaboration throughout the product lifecycle and shorten the time for products to market.

From the industry perspective, AI design will significantly increase supply chain efficiency, decrease carbon footprint, and strengthen personalized user experiences. Thus, it will provide strong support for intelligent manufacturing and sustainable development.

7. Conclusion

This study focuses on the application of AI-driven technology in designing consumer electronic products like TWS earbud charging cases and summarizes the feasibility. The results show that AI-assisted 3D modeling can effectively enhance the design efficiency of product parts, and utilizing generative AI in full-lifecycle design enables shortening the design iteration cycle. Multimodal AI and human-AI collaborative design significantly decrease the usage threshold of traditional CAD software, and the digital twin promotes both data interoperability and whole process integration.

This study clarifies the application value of AI technology in the design of consumer electronic products, but containing several limitations as it only discusses TWS earphones. Further investigations should consider more types of products and deepen the integration of multimodal AI and digital twins. To provide a more complete support for the large-scale application.

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Conflicts of Interest

The authors declare no conflict of interest.

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