Integrated innovation of smart materials and product design from the perspective of design intelligence

DOI: 10.35530/IT.074.05.2022121

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ABSTRACT – REZUMAT

Integrated innovation of smart materials and product design from the perspective of design intelligence

Materials are the physical basis and carrier of product design, and the selection of materials is an important part of product design. With the continuous exploration of materials, smart materials have become a hot topic in science and technology innovation. This study uses the winning entries of industrial design awards in the past five years as the data source, and 54 design entries using smart materials for innovative design were obtained after retrieval. The current status of the application of smart materials in product design has been summarised through classification analysis, case analysis and comparative analysis. It is found that the integrated innovation of smart materials and product design is still relatively simple. There is still a lot of space for the development of the application of smart materials in product design. In terms of the existing ways of integration of smart materials and product design, this study proposes that the future integration of product design and smart materials can be innovated from biology, ecology, sensing and computing perspectives through methods such as bionic design, sustainable design, personalised design and parametric design. This study provides a reference for the application of smart materials and new creative expressions in future product design and proposes a new trend for the integration of smart materials and product design in the future.

Keywords: *design intelligence, smart material, product design, integrated innovation, design method*

Integrarea inovativă a materialelor inteligente și a designului de produs din perspectiva inteligenței designului

Materialele reprezintă baza fizică și purtătorul designului de produs, iar selecția materialelor este o parte importantă a designului de produs. Odată cu explorarea continuă a materialelor, materialele inteligente au devenit un subiect important în inovația din știință și tehnologie. Acest studiu folosește lucrările câștigătoare ale premiilor de design industrial din ultimii cinci ani ca sursă de date, iar 54 de elemente de design care utilizează materiale inteligente pentru design inovator au fost obținute după recuperarea datelor. Starea actuală a aplicării materialelor inteligente în designul de produs a fost sintetizată prin analiza de clasificare, analiza de caz și analiza comparativă și s-a constatat că integrarea inovativă a materialelor inteligente în designul de produs este încă relativ simplă și există încă destul loc pentru dezvoltarea aplicării materialelor inteligente în designul de produs. În ceea ce privește modalitățile existente de integrare a materialelor inteligente și a designului de produs, acest studiu propune ca viitoarea integrare a designului de produs şi a materialelor inteligente să poată fi inovată din perspective biologice, ecologice, de detecție și calcul prin metode precum designul bionic, designul sustenabil, designul personalizat și designul parametric. Acest studiu oferă o referință pentru aplicarea materialelor inteligente și a noilor expresii creative în proiectarea viitorului produs și propune o nouă tendință pentru integrarea materialelor inteligente și a designului de produs în viitor.

Cuvinte-cheie*: inteligență de proiectare, material inteligent, design de produs, integrare inovativă, metodă de proiectare*

INTRODUCTION

The development history of materials is a witness to the history of human civilization. Christian Thomsen, a famous Danish archaeologist, divided the process of human civilization into the Stone Age, the Bronze Age and the Iron Age according to the changes in the materials used for production tools [1]. These epochs named after materials are important symbols of the development of the Times, showing the important position of materials in human history. From the evolution of the Stone Age, Bronze Age and Iron Age, we can see that the exploration and application of materials are constantly deepening, and the emergence and wide application of each generation of materials is greatly changing people's lives and production modes. Research into innovative materials is critical to the long-term success of any technology sector and industry in today's society, it is a fast-growing field full of challenges and opportunities and is considered to be one of the important manifestations of the development of scientific and technological strength [2]. Smart material is not only an important part of contemporary high technology, but also an important pillar and breakthrough in the development of high technology.

As materials evolve, design evolves simultaneously. The journey of design development also happens along with the history of human civilization. Material is the physical basis of product design, material not only can greatly change the structure and function of the product but also can bring a new leap in product design and form a new design style [3]. The discovery and use of each new material have led to tremendous progress in product design, and designers have constructed the history of human creation with materials [4]. From the Neolithic small-mouthed peaked bottom bottle to the world-renowned Ming-style chairs, the design 1.0 character of the agrarian era was manifested. From the AEG electric kettle of Peter Behrens of the Deutscher Werkbund to the Model T car of Henry Ford, the design 2.0 character of the industrial era was manifested. From the mobile phone invented by Martin Cooper to the global Internet, the design 3.0 character of the knowledge and information era was manifested. But after the beginning of the first year of artificial intelligence, a new challenge began, and design entered a new stage from the information age, ushering in the 4.0 period of the intelligent age of design.

An endless stream of new materials is being continuously applied to daily life and production, people's understanding of materials is deepening, and the relationship between materials and design and production is becoming closer. But with the advent of the intelligent age, the development of design and materials is facing new challenges. The arrival of the intelligent age is prompting people to continuously expand the development space of design and materials. Combined with ubiquitous digital sensors, networks and software-based automation, intelligence is transforming our economy and defining a new era of industrialization. With the opportunities of the times, the emergence of new materials makes it possible to innovate the form, form and function of products, and the changeable characteristics of smart materials also bring changes to the design interaction form [5]. Meanwhile, the demand for product innovation also promotes the emergence of new materials and drives the development of new materials. A mutually beneficial symbiotic relationship is formed between new materials and new designs, which can help designers generate more creativity, it also promotes the application and development of materials.

In the context of the intelligent era, design practice has changed dramatically in terms of design materials, design objects and design processes [6], and intelligence has become a main feature of design. Smart material is a new functional material derived from the background of design intelligence, which is one of the important directions of the development of modern high-tech new materials [7]. The characteristics of smart materials are different from traditional materials, and the methods of material-oriented design mode are also different from the traditional design mode [8]. Therefore, this study will summarize the current situation of the application of smart materials in product design from the perspective of design intelligence, and explore the new path of the future application of smart materials in innovative product design.

RELATED WORKS

The evolution of design materials

Materials are the tangible carriers on which technological progress depends, and they are the physical basis for the development and continuation of human civilization [9]. In the Paleolithic Age, primitive people used natural materials such as stone, bone and wood to make tools, clothes and daily necessities. As processing levels increased, artificial materials such as textiles and ceramics emerged, which were used to produce more household items. From natural materials to processed materials, to the current composite materials, organic polymer materials, etc., all provide different possibilities for product innovation. At the stage of product design using traditional materials, designers pay more attention to the inherent characteristics of materials such as mechanical properties, stability and safety, as well as the functional structure, processing process, mechanical properties, morphological texture and sustainability of materials when selecting materials.

The rapid development of design has placed higher demands on materials, and smart materials have emerged as the times require. Emerging technological platforms require more complex solutions that include versatile, controllable, sustainable and reliable materials [10]. Similar to traditional materials, smart materials can serve as physical carriers for products, and combined with new processing techniques, they can achieve breakthroughs in product modelling. In addition, the versatile characteristics of smart materials can bring new experiences and interactions for users. Smart materials have become innovative self-healing products that can facilitate changes in their physical properties by altering the environmental conditions in which they normally operate [11]. At this stage, the material properties that designers focus on are also changing. For example, designers need to consider how to integrate the functions of smart materials, how to combine smart materials with parametric design and so on. From traditional materials to smart materials, design and materials are evolving together with social development, and design concepts and material properties are changing in the evolution of design and iteration of materials (figure 1).

The basic application of smart materials in design

Smart materials have special physical or chemical properties that can solve technical problems that are difficult to solve with traditional materials and have great application potential in designing next-generation sensing platforms [12]. The smart material industry is the key technology to build the commonality of modern industry and can be widely used in medical care, furniture, architecture, wearable devices, etc. Its downstream industries also include many manufacturing industries, such as energy, computer, transportation, aerospace, electronic information, automobile, etc.

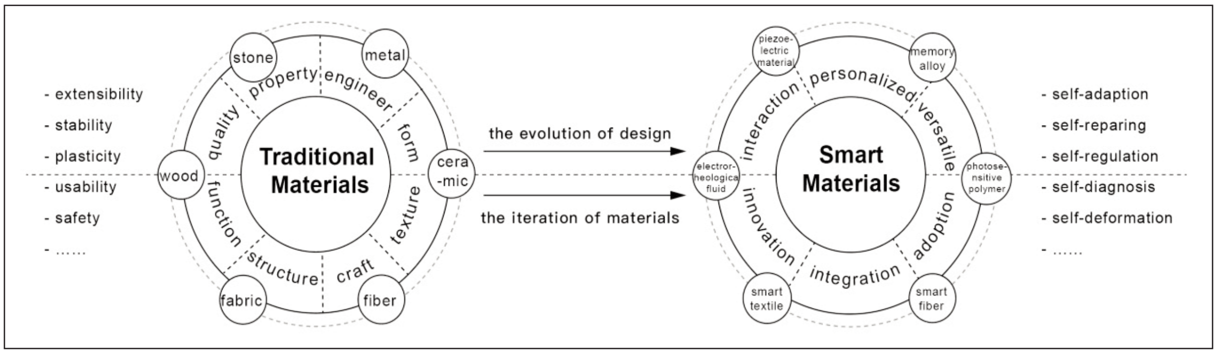


Fig. 1. Change in design concepts from traditional materials to smart materials

There are two main forms of smart materials, one is the material itself has smart functions, which can automatically change its performance with external changes [13]. The other is embedded smart materials, which means that the basic material carrier is embedded with sensing elements to detect the surrounding environment through the sensing elements. Generally speaking, smart materials have both sensing and response properties. Smart materials can detect and recognize external stimuli, such as changes in light, temperature, stress, pH, etc., and then drive themselves to respond to external changes, such as deformation, discolouration, self-adaptation, self-healing, etc. [5]. Table 1 provides a brief introduction from the variability perspective of smart materials.

METHODOLOGY

Research framework

This study obtains design entries from three industrial design awards: DIA, Red-dot, and iF. and explores the application status of smart materials in product design through design entries analysis. There have been many studies using Design Award entries for academic research [14, 15]. Design awards are open participation events that produce a large number of works each year that represent the cutting-edge design for that year and have become benchmarks for good design practice across industries. This study focuses on winners that integrate innovation in smart materials and product design for analysis. The methodological framework is illustrated in figure 2.

Table 1

BRIEF CLASSIFICATION OF SMART MATERIALS

Change	Trigger mechanism	Example of application	Representative material
Shape	(1) Electricity: Electrochromic materials change shape by applying voltage.	Aircraft, automobiles, construction, household goods, etc.	High-strength alloys, carbon fibres, polymeric materials, etc.
	(2) Stress: bend, expand or contract through mechanical stress.		
	(3) Temperature: Deformation is caused and recovered by temperature change.		
Colour	(1) Light: Photochromic materials respond to light.	Defence industry, fashion costume, etc.	Textile, rubber, plastic, coating, fibre and other polymer materials
	(2) Temperature: the colour change of thermochromic materials depends on their temperature.		
	(3) pH: change the colour or transparency by different pH values.		
Temperature	(1) Energy: Adjust the temperature according to the perceived body energy.	Sportswear, medical supplies, etc.	Textile materials, fibre materials
	(2) Humidity: adjust the temperature according to the ambient humidity.		

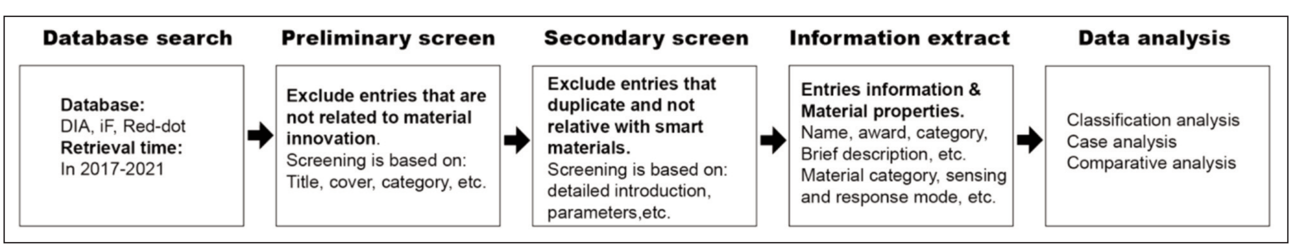


Fig. 2. Research framework

Database search

The reasons for choosing DIA, Red-dot, and iF as the database are as follows:

1) Globalization: These three awards, as internationally influential awards, attract several world's outstanding design and intelligence innovation works to participate every year.

2) Award concept: All three awards are global competitions for cross-border innovation combining art, technology and business, all focusing on intelligence and innovation.

3) Award settings: There are industry groups and concept groups, which can represent different levels of industrial design work.

Since the results of the 2022 awards have not yet been completed, to discuss the application of smart materials within a unified framework, the search period is set from 2017 to 2021, that is, to screen the winners in the past five years.

Entries select

The selection of entries was conducted in two stages. The first stage is the preliminary screening, which is mainly to quickly screen out entries related to material innovation by browsing the title, cover, and category of the entries. The second stage of screening is mainly through browsing the detailed introduction of the entries, including the parameters of the entries, graphic introduction, video introduction, as well as the query of extended materials, etc., to understand in detail the innovation point of each entry and the use of materials, and to exclude entries unrelated with the application of smart materials. Meanwhile, it is necessary to eliminate the duplicate entries between different awards in this round.

Information extraction

Extract information from the selected entries. It mainly contains two types of information, the first type is the basic information, such as the item name, the year of the award, the type of award and a brief description. The second type is the material properties information, such as the category of the material used, and the induction and response mode of the smart material. These two types of information are extracted and coded in Excel.

RESULTS

In this study, we searched a total of three design award winners for the last five years, with a total of 1,650 winning entries for DIA between 2017 and 2021, 10,535 winning entries for iF between 2017 and 2021, and 13,194 winning entries for Red-dot between 2017 and 2021. These entries constitute the original database for this study. After screening according to the established criteria, 19 DIA works, 10 iF works, and 25 Red-dot works were finally eligible, for a total of 54 works.

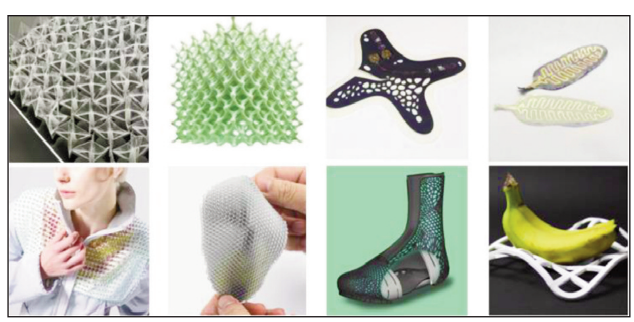
Current status of smart material application in product design

The category information of the 54 winning entries is statistically analysed, and the results are shown in table 2. We can learn the following information: In the award category, the winning entries of smart materials in the industry group are much higher than those in the concept group. In the product type, smart materials are currently the most widely used in the costume category, followed by wearable accessories, etc., and the exploration of the raw materials is also the focus of attention. In the application area, the most winning entries are currently applied in outdoor sports and healthcare, followed by costume design, furniture, fashion, food packaging and others. In terms of material used, most of the traditional materials are still used as carriers for intelligent combination, mainly textile materials, followed by organic plastics, etc. In terms of sensing and response, temperature sensing and regulation are still some of the most used functions, such as smart material deformation and discolouration, etc. Meanwhile, embedded intelligent material is also a hot spot at present.

New trends in the application of smart materials in product design

To find the joint point of integrated innovation between smart materials and product design, all the selected entries were summarized. Then, four representative linkages were summarized through sorting: biology, ecology, sensing and computing. These four types of cases are shown in figure 3.

Biology is a common link between smart materials and product design, the functional principles and behavioural characteristics of biological systems are often applied to product design. The two entries in the group (a) are Dynamic Interactive Bionic Wall and Illusional Fashion In Motion. The Dynamic Interactive Bionic Wall imitates the rhythm of deep-sea creatures when they breathe to achieve the effect of indoor sound regulation. Illusional Fashion In Motion is a clothing design inspired by the colour-changing mechanism of chameleons, which uses nanocrystal properties to adjust the refraction of light and thus change the colour of the skin. Both works use the bionic design method to construct technical systems by imitating the functional principles and behavioural characteristics of biological systems, applying the



a *b* *c* *d*

Fig. 3. Product design case

Table 2

INFORMATION ON THE CATEGORY OF WINNING ENTRIES			
Item	**Detailed information**	**N**	**Proportion**
Categories			
– industry group	Entries that have been on the market for less than 2 years.	39	72.22%
– concept group	Unlisted works that are still conceived and envisioned, are capable of presenting the complete design concept.	15	27.78%
Product type			
– costume	Mainly includes sports warm garments, fashion garments, etc., with temperature regulation function or shape change function.	33	61.11%
– wearable accessory	Mainly including motion detection wearable accessories, and medical aid accessories, such as "electronic band-aids" that can monitor body data.	8	14.81%
– raw material	Mainly refers to innovations based on the material itself, such as changing the structure of a fibre or textile material so that it can adapt to changes in its surroundings and make changes.	6	11.11%
– package	Mainly related to food packaging, capable of detecting food spoilage through food temperature and reflected in colour changes.	3	5.56%
– footwear	Mainly refers to footwear entries, including rapid-forming sole materials, and shoes adapted to the human form.	3	5.56%
– food	For example, foods that can change shape by heating	1	1.85%
Application area			
– outdoor sports	Refers to designs in the field of outdoor sports, mainly outdoor sports equipment.	24	44.44%
– healthcare	Refers to entries for healthcare purposes, including human data monitoring, diagnosis, feedback, etc.	10	18.52%
– costume design	Refers to garment-related designs, such as self-adapting women's underwear for body size.	7	12.96%
– furniture	Refers to entries in the category of household items, such as deformed furniture, wall skins that can regulate sound, etc.	5	9.26%
– fashion	Refers to entries that apply the visible changeable properties of smart materials to the field of fashion, such as colour-changeable clothing.	4	7.41%
– food packaging	Refers to food-related smart material applications that can detect and visually represent the status of food	4	7.41%
Materials used			
– textile	Mainly the combination of textile materials and smart materials, or textile materials as a carrier, and then embedded sensors	38	70.37%
– organic plastics	including pu plastics, 3D/4D printing materials, etc.	10	18.52%
– others	Including flexible composite materials, biomaterials, photosensitive resins, food materials, organic polymers, etc.	6	11.11%
Sensing			
– temperature	Monitor temperature changes in the surrounding environment or human body.	33	61.11%
– sensor	Monitoring of ambient environmental data or human data through embedded sensors.	12	22.22%
– light	Perceiving natural or artificially altered changes in ambient light.	4	7.41%
– others	Including environmental sound perception, human behaviour perception, morphological perception, energization, etc.	5	9.26%
Response			
– temperature regulation	Automatic regulate the temperature according to the conditions to keep the temperature in balance.	28	51.85%
– deformation	Morphological changes occur after induction changes	9	16.67%
– feedback control	Refers to the process where the sensor monitors the data, feeds it back and waits for the next instruction	8	14.81%
– discolouration	Change in colour after induction change	7	12.96%
– others	Includes sound modulation and intelligent display after sensing changes	2	3.70%

superior system performance of nature and society to artificial systems, and improving the form, function, structure and other design elements in product design [16]. Bionic design is an important research method in industrial design and an important means of innovation [17]. However, Smart Materials fabrication and integration into biosystems remain in their infancy [18].

Ecological characteristics are also regarded as an important link between smart materials and product design. Environmental factors in the ecosystem, such as temperature and light, are often used as sensing mechanisms to trigger smart materials to respond. The two entries in group (b) are Futurecraft 4D and Optical Textiles, in which Futurecraft 4D uses light to induce a polymerization reaction of polymeric resin to complete the curing process of the shoe sole material. Optical Textiles uses optical principles to create optical illusion materials with a prismatic refraction effect. Both of these works interact with the ecological environment in their production or use. Smart materials can change their physical and chemical features in response to external stimuli in an adaptive, interactive and self-regulating mode [19], For example, with the help of environmental temperature and humidity changes to achieve the deformation of smart materials or temperature regulation function, there are ecological environmental parameters involved.

Embedded smart materials are also a popular trend in materials development. Many functions of product design need to rely on algorithms to achieve. Smart materials can be designed in different forms, such as watches, wristbands, shirts, shoes and glasses, for health monitoring and to respond to inform users [20]. The two entries in group (c) are Electronic Band-Aid and Adaptiv. The Electronic Band-Aid is a future electronic wearable device, which integrates the network composed of all electronic components required for sensing, signal processing, and wireless communication. Adaptiv contains a series of sensors that measure foot and body movement in real-time and adjust the shoes to accommodate the body's movement. Technological progress is enabling more and more sensors to be used in product design, but how to reduce people's perception of sensors and make them naturally integrated into products still needs to be considered.

Computing is an indispensable element for smart materials and design intelligence. Many functions of product design rely on algorithms to achieve, and the mode of smart materials sense and response can be regulated by algorithms. The two entries in group (d) are ShapeTex and 4D Printed Morphing Furniture. ShapeTex is a programmable morphing fabric that contains a three-layer structure of polymer, metal and fabric that produces a morphing effect when energized. 4D Printed Morphing Furniture can transform the three-dimensional model into a flat model through the calculation of the software, and then obtain the desired shape by soaking in hot water. The use of computer-aided product design has turned out to be a popular area of research, and the use of computerized parametric interventions in smart materials can help us make more creative and controllable works.

DISCUSSION

The selection of materials affects the form, function and use of the product, and is one of the important ways of product innovation. One of the tasks of designers is to try to creatively use the available materials and explore their potential [4]. From the analysis of the current winning entries, the smart materials in the industry group are much higher than those in the concept group, and most of them are limited to sportswear and other wearable products, which shows that the application potential of smart materials can be greatly developed. Designers should base on the functionality and technicality of smart materials to inject more innovative solutions into product design. Besides, from the perspective of the application mode of smart materials, smart materials have become mature in temperature change sensing and response technology. However, the integration of smart materials and product design is still relatively simple, looking at the application of smart materials in product design in the past five years, it is easy to see that the use of smart materials is still in a state of weak intelligence, only with the basic characteristics of smart materials to achieve simple interaction, the future of smart materials still need to make breakthroughs to the level of strong intelligence.

Meanwhile, the integrated innovation of smart materials and product design in the design intelligence era should consider combining with more elements, such as biology, ecology, sensing, and computing. Smart materials and product design naturally develop different design methods when they are combined with external elements (as shown in figure 4). In the combination of smart materials and biology, a bionic design method is formed to map biological properties into product design. In the combination of smart materials and ecology, the sustainable design method is a hot spot, applying environmental ecological characteristics to the use of design materials, which improves the ecological effectiveness of the ecosystem while bringing new ideas to product design, such as temperature regulation or generating response through the temperature sensing characteristics of smart materials to achieve the purpose of recycling resources and improving ecological effectiveness. In the combination of smart materials and sensing, personalized design is the main focus, and embedded smart materials are characterized by the ability to monitor changes in human data and trigger feedback mechanisms, which can promote the emergence of more personalized design. In the combination of smart materials and computing, parametric design emerges as the times require. Parametric design can quickly complete a large number of complex operations, improve the efficiency of manufacturing, and also lay a solid foundation for some popular manufacturing

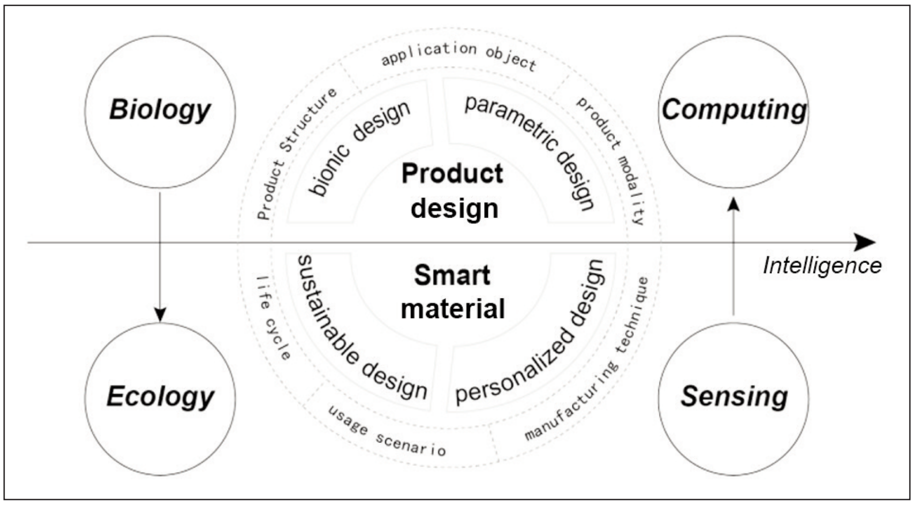


Fig. 4. New trends in the integration of design intelligence and smart materials

methods of smart materials nowadays, such as 4D printing and flexible manufacturing.

CONCLUSION

The integrated innovation of design intelligence and smart materials has brought new methods to product design, as well as more possibilities for product design in terms of function, form and structure, but also brings new problems, needs and challenges. From the perspective of design intelligence, this study analyses the current situation of the application of smart materials in the winning entries of internationally influential industrial design awards and explores new ways for the integration of product design and smart materials. Combining the development of natural science and life science, future product design and smart materials can be integrated and innovated from the perspective of biology and ecology, mapping the laws of nature to product design through the use of smart materials, and promoting the symbiotic relationship between nature and design and materials. Combined with the development of industrial and information technology, sensing and computing will also be an important way to integrate product design and intelligent materials, and sensing technology and computing technology can achieve more creative functions in product design and promote the generation of innovative design solutions.

In the era of intelligent design and manufacturing, the integration and development of product design and intelligent materials are not only a single-chain connection. In the process of integration and innovation of product design and intelligent materials, different dimensions need to be coordinated to establish a new integration relationship, such as The integration of biological science, integration with natural ecology, integration with intelligent sensing, and integration with computing science, etc., reconstructs a new relationship and new network between design and material integration in the intelligent era, and explores the more possible application of intelligent materials in product design.

ACKNOWLEDGEMENTS

This research was funded by the National Social Science Foundation of Arts Major Project (Grant Number: 20ZD09).

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