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Evaluation of Styling Design of Heavy-Duty Industrial Robots Based on Comprehensive Integration Weighting Method

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ABSTRACT

This paper proposes a method for evaluating and screening the appearance design solutions of industrial robots. Firstly, the kansei engineering theory and KJ method is used to collect users' perceptual imagery vocabulary of the appearance of industrial robots, which is used as the evaluation indexes of the appearance design solutions. Secondly, the analytic hierarchy process is used to construct a hierarchical structure to calculate the subjective weights of the 12 evaluation indexes. Thirdly, the entropy weight method is introduced to calculate the objective weights of the 12 evaluation indexes, because the subjective weights reflect the designer's degree of emphasis on the 12 evaluation indexes instead of the actual needs of the users. Finally, the combined weights are calculated using the comprehensive integration weighting method. In order to obtain the scores of the three schemes for each indicator and to weight them to obtain a composite score for each scheme, the questionnaire survey method is used. This study shows that the appearance scheme evaluation and screening method using comprehensive integrated weighting method to calculate the weights of evaluation indexes and weight them to get the total score of each scheme can be applied in the field of appearance design of heavy-duty industrial robots, which can provide a reference for the evaluation of appearance schemes of other types of industrial robots.

Keywords: Appearance design, Comprehensive integration weighting method, Heavy-duty industrial robots

INTRODUCTION

Industrial robots are industrial devices with multiple degrees of freedom, which can rely on their own power to perform specific action commands under complex working conditions (Jian, 2021). The widespread use of industrial robots can increase the level of automation and efficiency of product lines. Since the 1950s, industrial robots have been widely used in various fields such as logistics, machinery, electronics, chemical industry and aerospace, etc. The design of industrial robots needs to make a balance between mechanical function and industrial aesthetics. The styling design of industrial robots needs to make a balance between mechanical function and industrial aesthetics. How to design aesthetically pleasing industrial robotic products while satisfying the premise of mechanical functions has become the next growth point in the industrial robotics field. In other words, products with good industrial aesthetics should be able to adapt to the human-machine environment of the workplace and interact well with the operator. For the styling design of industrial robots, most domestic companies' product styling design stays in the achievement of mechanical functions, but they fail to take into account the aesthetics of the product shape, the design of the workspace and the coordination of the color environment. What's more, the styling of domestic industrial robots is not simple enough, resulting in poor usability and low product competitiveness. The industrial robotics field abroad has a long history of development. From a brand perspective, the companies with the largest market share of industrial robots are dominated by Japan and Europe, such as KUKA Robotics, FANUC Robotics, YASKSWA Robotics and ABB Robotics. They are mainly used in the automotive and electronics industries for precision tasks (Lin, 2022). From a product styling perspective, foreign industrial robot products have better product styling. For example, ABB industrial robots are designed to be more minimalist, the extensive using of curves not only spread the load but also conveying a sense of power, using orange for larger loads industrial robot to bring a sense of strength, and white for smaller loads industrial robot to bring a sense of calmness and neatness (Yanhong, 2008). In summary, China's industrial robotic products need to improve the quality of styling design, and further consider the human-machine environment in which the product is located, so as to design industrial robotic products that are more in line with the physiological and psychological characteristics of users.

PRODUCT STYLING DESIGN

In terms of industrial aesthetics, the beauty of industrial products has two distinctive features, namely the "formal beauty" of the product in its external sensual form and the "technical beauty" of the product in the harmony and order of its internal structure. For the formal beauty of the product, the styling design of industrial robots should follow the design of ten product design principles which are Proportion and scale, symmetry and balance, stability and lightness, rhythm and cadence, harmony and contrast, unity and variety, dominance and emphasis. For the technical beauty of the product, the styling design of industrial robots should follow six product design principles which are functional beauty, structural beauty, craftsmanship beauty, material beauty, comfort beauty and specification beauty (Jianning, 2004). The styling design of industrial robots belongs to the category of large-scale mechanical product design, which can adopt the methods of analysis and enumeration, bionic creation, fine addition and de-complication to optimize the design of the appearance of industrial robots (Jianning, 2017).

From the perspective of human factors engineering, colour conditioning has a wide range of applications in workspace design, plant and production equipment colour application, visual management, etc. In addition, colour conditioning can be directly applied to the human psyche and is not limited by time and space. Based on the theoretical knowledge of industrial aesthetics and ergonomics, and combined with the product styling designed by ABB, KUKA, FUNUC and other industrial robotics, three initial options for product styling are designed.

SCHEME A

The scheme adopts the de-complication method for product styling optimization. We designed concave styling on the big arm and small arm of the industrial robot, eliminated the snap structure for wire harness storage, used the form of virtual space uniformly at product junctions, and simplified the product styling to create specification beauty of the product. The styling design of the base is referred to the design elements of the KUKA Robot, which fully reflects the unity and change, transition and echo of the law of form beauty. The connection between the base and the big arm, the big arm and the small arm highlights the unity of styling, and the transformation of the base to the big arm highlights the change in styling, which gives people a sense of calmness and rich visual aesthetics. In terms of colour, orange is chosen as the main tone, lime green as an auxiliary colour. Orange is a warm tone and symbol of a good harvest, which can make the operator feel excited and happy, and lime green brings the workers a feeling of calmness and neatness (Min, 2005). As shown in Figure 1.

Figure 1: Rendering picture of scheme A.

SCHEME B

The scheme adopts the method of de-complication and bionic creation for product styling optimization. Industrial robot arm design references the physiological curve of the muscle, apart from this, we changed flat surfaces into curved surfaces in the original scheme. This design enhances the industrial aesthetics of the product and is more in line with the user's visual movement patterns. What's more, orange is changed as the main color, and black as the secondary color to emphasize the base of the product. Black color gives people a dignified and stable visual impression, such a product color scheme reduces the visual center of the product and relieves the user's visual fatigue (Su, 2020). As shown in Figure 2.

Figure 2: Rendering picture of scheme B.

SCHEME C

The scheme adopts the de-complication method and the limit method for product styling optimization. The base of the industrial robot is redesigned, and the big arm and the base are fused in form, which highlight the formal beauty of the product's transition and echo, and the harmony and contrast. Cyan is adopted as the main color, which can reduce the visual center of gravity to convey a sense of stability according to the theory of color psychology. As shown in Figure 3.

Figure 3: Rendering picture of scheme C.

PERCEPTUAL IMAGERY SPATIAL CONSTRUCTION

In order to accurately obtain users' perceptual understanding of industrial robots, a total of two experts from a robotics company and four experts in the field of mechanical design and industrial design were invited to conduct a brainstorming session in order to collect respondents' perceptual imagery of industrial robots to describe the vocabulary. The KJ affinity diagram method is a method proposed by Professor Jiro Kawakita of Tokyo Institute of Technology to collate cluttered information, the main content of which is to analyze the different hierarchies between words based on the correlation between words, and the method can collate cluttered vocabulary into a hierarchically structured framework of information (Kunifuji, 2016). In this step, the vocabulary obtained from brainstorming is collated into hierarchical structures using the KJ method, as shown in Table 1. In the hierarchical structure, the adjectives are divided into three categories: "appearance", "modelling style" and "brand impression", which constitute the criterion layer of the hierarchical structure, and all the adjectives of perceptual imagery are corresponded to each of the three criterion layers, so as to construct a semantic space of perceptual imagery, which are as follows: exquisite, perceptual, high-quality, rich, tough, simple, futuristic, safe, high-end, professional, innovative and reliable.

Table 1. Hierarchy of industrial robot modelling evaluation.

Evaluation Goal	Standardized Level	Indicator Level
Evaluation of appearance quality of heavy-duty industrial robots A1	Appearance B1	Exquisite C1
		Perceptual C2
		High-quality C3
		Rich C4
	Modelling style B2	Round C5
		Simple C6
		Futuristic C7
		Safe C8
	Brand impression B3	High-end C9
		Professional C10
		Innovative C11
		Reliable C12

COMPREHENSIVE INTEGRATED WEIGHTING METHOD

The analytic hierarchy process and entropy weighting method are used to determine the weights of 12 groups of evaluation indexes. Firstly, the subjective weights of 12 groups of evaluation terms are calculated by analytic hierarchy process. Secondly, the objective weights of 12 groups of styling evaluation terms are calculated by entropy weighting method, and then the combined weights of the subjective and objective weights are calculated by comprehensive integrated weighting method. Finally, the scores of the three solutions under each group of evaluation indexes are obtained by questionnaire, and the solution with the highest weighted total score is the optimal appearance styling solution for industrial robots, so as to complete the selection of schemes.

CALCULATION OF SUBJECTIVE WEIGHTS

The steps that need to be carried out to calculate the weights of indicators by the analytic hierarchy process are: (1) Establishment of the hierarchical structure (2) Establishment of the judgement matrices for the criterion and indicator levels (3) Consistency test for the judgement matrices (4) Calculation of the subjective weights for the indicator levels.

ESTABLISHMENT OF THE HIERARCHY STRUCTURE

In the hierarchical structure, the appearance quality of industrial robots (A1) is the general objective of the hierarchy. The appearance realism (B1), modelling style (B2) and brand impression (B3) are the criterion layer of the hierarchy, and the three indicators in the criterion layer correspond to four sub-indicators, which make a total of 12 pairs of perceptual imagery vocabulary as the bottom evaluation indicators of the hierarchical structure (C1, C2,...C12).

ESTABLISHMENT OF THE JUDGEMENT MATRICES

In this step, we compare the indicators at the same level of the hierarchy two by two to get the relative importance of the indicators. Firstly, A number of experts in the field of industrial robot design were recruited to distribute an "Expert Score Sheet", in which the experts indicated the relative importance of two indicators in the same tier using 1, 2, 3,···7 and its reciprocal. The scales and definitions of the judgement matrix are shown in Table 2. Next, the average of all expert ratings is taken to establish the judgement matrix for "appearance", "styling" and "brand impression" in the criterion layer and the indicator layer. The judgement matrix is constructed as shown in equation (1). Where n is the order of the judgement matrix. Because of space constraints, the four judgment matrices are not shown in this paper.

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ \frac{1}{a_{12}} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \dots & a_{\mathrm{nn}} \end{bmatrix} \tag{1}$$

Table 2. Scaling and definition of judgment matrices.

Scaling	Definition
1	Equal importance of the two indicators compared to each other
3	Compared to the two indicators, the row indicator is slightly more important than the column indicator
5	Compared to the two indicators, the row indicator is much more important than the column indicator
7	Compared to the two indicators, the row indicator is extremely important compared to the column indicator
2, 4, 6	The relative importance of the two indicators falls between the two scales mentioned above.
Reciprocal	Degree of importance of a column indicator over a row indicator compared to two indicators

CALCULATION OF SUBJECTIVE WEIGHTS

The eigenvalues and eigenvectors of each judgement matrix are calculated by equation (2). If the judgement matrix A is a consistency matrix, the eigenvector corresponding to the maximum eigenvalue ($\lambda_{\max}$) of each indicator is the weight vector W_{AHP}.

$$Ax = \lambda x \tag{2}$$

CONSISTENCY TEST FOR JUDGEMENT MATRICES

To perform the consistency test of the judgement matrix, we need to calculate the Consistency Index (CI) of the judgement matrix and the Consistency Ratio (CR) of the judgement matrix respectively. when the CR of the judgement matrix is less than or equal to 0.1, we consider that this judgement matrix has good consistency. CI and CR are obtained from equation (3) and equation (4), where λ is the maximum eigenvalue of the judgement matrix, n is the order of the judgement matrix, RI is the Average Consistency Index, and the values of RI are shown in Table 3. The calculation shows that the four judgement matrices have good consistency. The subjective weights of the indicators are shown in Table 4.

$$\mathrm{CI} = \frac{\lambda \max - n}{n-1} \tag{3}$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{4}$$

Table 3. RI.

Matrix Order	0	1	2	3	4	5
RI	0	0	0.52	0.89	1.12	1.26

Table 4. The subjective weights of 12 indicators.

Standardized Level	Weights (%)	Indicator Level	Weights (%)
Appearance	70	Exquisite	3.5
		Perceptual	16.8
		High-quality	40.6
		Rich	8.4
Modelling style	21	Round	9.87
		Simple	0.84
		Futuristic	6.93
		Safe	3.36
Brand impression	9	High-end	0.45
		Professional	1.35
		Innovative	4.68
		Reliable	2.52

CALCULATION OF OBJECTIVE WEIGHTS

Entropy weight method is born from the basic principles of information theory. Information is a measure of the degree of order of the system. If the indicator is more informative, then the lower the information entropy, the greater the role of the indicator in the comprehensive evaluation and the higher the weight of the indicator. Entropy weight method is an objective assignment method that assigns weights to different evaluation indicators by calculating the information entropy and entropy weight of the evaluation matrix. The calculation steps of entropy weight method are: (1) data standardization (2) normalized evaluation matrix (3) calculation of information entropy and entropy weight.

In the analysis hierarchical process, the designer relies on his own design experience and expert advice to establish the judgement matrix, so the weights are more in line with the designer's own understanding of the product, but this will lead to a lack of objectivity in the styling design, which is contrary to the "user-centered" design guidelines. In order to overcome the limitations of the analysis hierarchical process, this study introduces the entropy weighting method to calculate another set of weights for 12 groups of indicators, and then obtains the combined weights of the evaluation indicators of industrial robot styling through the comprehensive integration weighting method.

SCORING BY QUEATIONNAIRE SURVEY METHOD

Questionnaire survey is an important tool for market research. Questionnaire survey method requires the researcher to prepare a series of questions according to the purpose of the study and analyze the information gathered to develop conclusions. Using this methodology, formatted information can be obtained from survey respondents for user requirements mining and product development (Liping, 2019).

In this study, six experts in the field of mechanical design and industrial design were selected as survey respondents, and a questionnaire was prepared to allow the six respondents to rate each of the 12 indicators for each of the three scenarios, resulting in a rating scale for the three scenarios. As shown in Table 5.

Table 5. Scheme scoring sheet.

Indicator Level	Scheme A	Scheme B	Scheme C
Exquisite C1	4.67	5.83	5.67
Perceptual C2	7.67	7.67	4.67
High-quality C3	7.83	6.83	6.00
Rich C4	7.17	7.17	4.67
Round C5	8.50	6.67	6.67
Simple C6	8.33	8.00	7.00
Futuristic C7	7.17	8.00	7.00
Safe C8	6.83	6.17	7.17
High-end C9	7.00	6.50	6.83
Professional C10	7.33	7.00	7.17
Innovative C11	8.50	8.00	7.17
Reliable C12	5.33	6.83	8.17

DATA STANDARDIZATION

There are 12 evaluation indicators in this topic, and the evaluation matrix is normalized to obtain the normalization matrix R, which is calculated as equation (5) and (6) (Liping, 2019). Where i is the column indicator, j is the row indicator, max (ri) is the maximum value of the jth row, min (rj) is the minimum value of the ith column, m is the number of appearance programs, n is the number of evaluation indicators, and the normalized evaluation matrix of the indicator layer is shown in Table 6.

$$\gamma_{ij}^{'} = \frac{\gamma_{\mathrm{ij}} - \min(\gamma_i)}{\max(\gamma_i) - \min(\gamma_i)} \tag{5}$$

$$R = \left(r_{ij}^{'}\right)_{m\times n} \tag{6}$$

Table 6. The normalized evaluation matrix.

Indicator Level	C1	C2	C3	C4	C5	C6
Scheme A	0	1	1	1	1	0.49
Scheme B	1	1	0.45	1	0	0
Scheme C	0.86	0	0	0	0	1
Indicator Level	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**
Scheme A	0.17	0.66	1	1	1	0
Scheme B	1	0	0	0	0.62	0.53
Scheme C	0	1	0.66	0.52	0	1

CALCULATE INFORMATION ENTROPY AND ENTROPY WEIGHT

Next, the Information Entropy Ej of each indicator is calculated as in equations (7) and (8). The Information Entropy Ej of the 12 indicators is shown in Table 7.

$$p_{\mathrm{ij}} = \frac{\gamma_{\mathrm{ij}}}{\sum_{i=1}^{m} \gamma_{\ddot{y}}} \tag{7}$$

$$E_j = -\ln(m)^{-1} \sum_{i=1}^{m} P_{\mathrm{ij}} \ln P_{\mathrm{ij}} \tag{8}$$

Table 7. E_j of the 12 indicators.

Indicator Level	C1	C2	C3	C4	C5	C6
E_j	0.63	0.63	0.57	0.63	0	0.58
Indicator Level	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**
E_j	0.38	0.61	0.61	0.58	0.61	0.59

Next, the Information Entropy Ej is used to calculate the Information Utility Value Dj and Entropy Weight Wj of each indicator, and the resulting entropy weight is the objective weight of each of the 12 evaluation indicators. The calculation formula is shown in equation (9) and (10), and the Information Utility Value Dj and Entropy Weight Wj of the 12 indicators are shown in Table 8.

$$Dj = 1 - E_j \tag{9}$$

$$w_j = \frac{\mathrm{Dj}}{\sum_{j=1}^{n} D_j} \tag{10}$$

Table 8. D_j and W_j of the 12 indicators.

Indicator Level	C1	C2	C3	C4	C5	C6
D_j	0.37	0.37	0.44	0.37	1	0.42
W_j(%)	6.47	6.60	7.78	6.60	17.89	7.56
Indicator Level	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**
D_j	0.62	0.39	0.39	0.42	0.39	0.41
W_j (%)	11.14	6.95	6.95	7.45	7.04	7.39

CALCULATION OF COMBINED WEIGHTS

The hierarchical analysis method used in this topic is a subjective assignment method, the disadvantage of which is that it overemphasizes the subjectivity of the designer; the entropy weight method is an objective assignment method, the disadvantage of which is that it fails to reflect the importance attached by the decision makers to different indicators (Yu, 2016). Therefore, the comprehensive integrated assignment method is used to calculate the combined weight of the two groups of weights to make up for the shortcomings brought by the single assignment method, and the calculation formula is as equation (11) (Yu, 2016). Where W_{AHP} is the indicator weights obtained through hierarchical analysis, $W_{Entropy}$ is the indicator weights obtained through entropy weighting, k is the ordinal number of indicators (k = 1,2,3...12), and n is the total number of indicators (n = 12). The combined weights of the indicators were calculated as shown in Table 9 (Yu, 2019).

$$\mathrm{w}_k = \frac{w_{\mathrm{AHP}} w_{\mathrm{Entropy}}}{\sum_{k=1}^{n} w_{\mathrm{AHP}} w_{\mathrm{Entropy}}} \tag{11}$$

Table 9. The combined weights of the indicators.

Indicator Level	C1	C2	C3	C4	C5	C6
W_k (%)	5.67	12.39	20.91	8.76	15.63	2.97
Indicator Level	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**
W_k (%)	10.34	5.68	2.08	3.73	6.75	5.08

The scores obtained from the questionnaire (as shown in Table 5) were weighted to obtain an overall score. Scheme A scored 7.45 points, Scheme B scored 7.07 points, and Scheme C scored 6.3 points, making A the best scheme.

CONCLUSION

This paper proposes a screening method for heavy-duty industrial robot product design solutions, collecting perceptual vocabulary through brainstorming and categorizing the vocabulary with the KJ method so as to construct a hierarchical structure for evaluating industrial robot styling solutions. On the basis of hierarchical analysis and entropy weight method, the score of each scheme based on evaluation indexes is obtained by using comprehensive integration weighting method, and the scheme selection is realized by comparing the scores. Apart from this, this paper proposes an evaluation system for heavy-duty industrial robots, which is conducive to subsequent designers to design industrial robot products based on this evaluation system. Moreover, the creative thinking method is fully used to create the appearance of heavy-duty industrial robots.

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