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Research on Computational Aesthetics-Based Model Evaluation Method for Industrial Robots

Shuai Ding and Beibei Sun

School of Mechanical Engineering, Southeast University, Nanjing, China

ABSTRACT

Based on existing research on the development of an evaluation system for industrial robot modeling and beauty assessment, this paper proposes a method to evaluate the aesthetic appeal of industrial robot models. The method initially establishes a set of beauty indices based on the morphological characteristics of industrial robots and computational aesthetics theory. Subsequently, hierarchical analysis is employed to determine the weights assigned to each index, enabling the calculation of a comprehensive evaluation value for industrial robot modeling that can be ranked accordingly. Finally, subjective questionnaire evaluations are conducted in order to experimentally compare and verify the feasibility and accuracy of this method. The results demonstrate that by utilizing hierarchical analysis and computational aesthetics, it is possible to accurately and objectively assess the beauty of industrial robots, thereby providing a novel approach for evaluating their aesthetic qualities.

Keywords: Aesthetic calculation, Hierarchical analysis, Industrial robots, Modelling evaluation

INTRODUCTION

Industrial robots play a pivotal role in the equipment manufacturing industry, significantly enhancing production efficiency and product quality, thereby bolstering the international competitiveness of these products. This is evident in the recognition given to industrial robots at the State-owned Assets Supervision and Administration Commission meeting, highlighting their crucial role at the national level. Currently, designers primarily focus on precision, material strength, force distribution, and other scientific and technological factors. However, the aesthetic aspect of industrial robots has been largely overlooked, with limited exploration of their artistic function in their design. The form and aesthetic evaluation of industrial robots hold both theoretical and practical significance. Consequently, the aesthetic design and evaluation of industrial robots have emerged as prominent areas of research in the field of robot design.

In the field of industrial robot modeling design, Wang Peiwen introduced finite element analysis in the design of mechanical structures into the process of optimizing industrial robot modeling (Peiwen, 2018). This method was implemented to enhance the design of industrial robot morphology and improve the theoretical rationality of structural design in modeling. Based on the theory of perceptual engineering, Xuejie Wang utilized eye tracking technology to investigate the relationship between perceptual imagery vocabulary and the modeling of industrial robots (Xuejie, 2016). Wang extracted elements from this relationship to be used in the design of 6-degree-of-freedom and 7-degree-of-freedom industrial robots, which fulfill the perceptual requirements of users. Bu Dingyi incorporated design elements from ancient military armor to create a modern industrial robot shape that embodies sturdiness, strength, technology and aesthetics (Yiding, 2016).

Birkhoff was the first scholar to propose quantifying the aesthetic index. He pioneered the mathematical model of macroscopic aesthetics, expressing the "Aesthetic measure" as the ratio of "Order" and "Complexity," i.e., $M = O/C$. This laid the theoretical foundation of computational aesthetics (Birkhoff, 1933). Hu Ningfeng proposed a morphological evaluation method that enhances the CRITIC-TOPSIS and aesthetics computation (Ningfeng, 2023). This method determines the weight of the indexes using the CRITIC method, thereby improving the weight of the aesthetics evaluation results and enhancing the objectivity and accuracy of the beauty evaluation results. Zhou Lei proposed a method for evaluating interface design aesthetics based on the limitations of current research on aesthetics and aesthetic computation (Lei, 2023). This method combines perceptual engineering, systems engineering, psychophysics and other disciplines. Based on the principles of visual attention and processing characteristics, Jin Yutong proposed an evaluation method for assessing the aesthetics of information interface layouts (Yutong, 2020). This method is based on cognitive characteristics and aims to enhance the rationality of information interface layouts and the objectivity of evaluation results.

Based on research on the design and modelling of industrial robots, this paper proposes a method for evaluating industrial robot models using computational aesthetics. Firstly, the morphological aesthetic evaluation system for industrial robots is constructed based on the structural and morphological elements of industrial robots. This system calculates and ranks the comprehensive aesthetic evaluation value of industrial robot samples. Secondly, the method of subjective evaluation is used to create a beauty ranking table for industrial robots based on subjective criteria. Finally, the ranking of the schemes derived from the objective beauty calculation is analyzed and compared with the results of the subjective questionnaire research, thereby verifying the feasibility of the method.

INDUSTRIAL ROBOT BEAUTY METRICS

Industrial product styling is influenced by various factors such as structure, function, and the usage environment. Zhou Aimin proposed an aesthetic comprehensive evaluation model based on the principles of formal aesthetics and cognitive psychology, from the perspective of system evolution (Aimin, 2018). The modeling of modern industrial robots is mainly influenced by their function and the distribution of internal mechanical components.

Divided by the functional dimension, industrial robots have various branch functions, including palletizing, welding, and assembling (Tianmiao, 2014). These functions primarily determine the external dimensions and weight of industrial robots. On the other hand, internal mechanical components such as motors, wiring harnesses, and control boards mainly determine the shape profile of industrial robots. The shape of industrial robots can be divided into eight morphological elements, from bottom to top: base, control panel, wiring harness, adapter, big arm, adapter arm, small arm, and wrist (Huabing, 2013). After analyzing and comparing them, we have identified the five elements that have a greater influence on the shape of industrial robots: base, adapter, big arm, adapter arm and small arm.

The contour line of the side-view projection of the industrial robot is "Z". Taking into account the site layout conditions, the lateral length of the base is generally shorter, while the big arm is longer. Considering the center of gravity factor, the small arm is generally thinner. Since the side view angle can provide an intuitive sense of the stability of the industrial robot's shape, the arrangement of the side components is particularly important. After conducting user interviews and focusing on the visual aspects of industrial robots, the designers combined the theory of morphological aesthetics with elements such as balance, Center of gravity stability, simplicity, sense of regularity, wholeness, and denseness. These elements were chosen as the quantitative system for calculating the morphological aesthetics of industrial robots. The relevant indexes and formulas for calculating aesthetics are as follows (Ngod, 2003).

Balance

Balance can be divided into three indicators: coordination, balance and symmetry, which are primarily influenced by the distribution of screen design elements in the axisymmetric direction or center symmetry. Balance is calculated by comparing the difference between the overall weights of components on both sides of the horizontal and vertical symmetry axes.

The arrangement of the functional components of an industrial robot has an impact on its balance. Therefore, achieving balance involves distributing the components in a way that allows for an equilibrium state. The formula for balance is as follows:

$$\begin{aligned} B &= \mathrm{VAR}\,(W_L + W_R) + (W_T, W_D) \\ D_{b,a} &= 1 - \frac{\left(\left|\frac{W_L - W_R}{\max(|W_L|,|W_R|)}\right| + \left|\frac{W_T - W_B}{\max(|W_T|,|W_B|)}\right|\right)}{2} \\ W_j &= \sum_{i}^{n_j} a_{ij} d_{ij},\ j = L, R, T, B \end{aligned} \tag{1}$$

VAR $(\cdot)$ is the variance function; W_j is the distribution of the center of gravity for an orientation. $W = \sum n_{ij} = 1/\left(a_{ij} \cdot d_{ij}\right)$; "$i$" denotes the element to be cloth; $j \in \{L, R, T, D\}$, denote the left, right, up and down orientation of the interface to be fabricated, respectively; "a, i, j" denote the area of the element to be fabricated "*i*" in azimuth *j*; d_{ij} denotes the distance between the center of the area of element i to be fabricated and the center of the interface in orientation *j*; n_j is the number of elements in each orientation of the interface to be fabricated.

Center of Gravity Stability

Center of gravity stability is a measure of how far the center of gravity of a morphological element has shifted from the center of gravity of the smallest outer rectangle of the contour line; the smaller the shift, the more stable the psychological perception.

Industrial robots are typically large in size and are highly prone to instability due to their structurally extended functionality. Therefore, the form profile of industrial robots needs to possess specific stabilizing characteristics. The formula for center of gravity stability is as follows:

$$\begin{aligned} \mathrm{EN} &= 1 - \frac{|\mathrm{CDM}_x| + |\mathrm{CDM}_y|}{2} \\ \mathrm{EN}_X &= \frac{2\sum_{i=1}^{n} a_i (x_i - x_c)}{b_f \sum_{i=1}^{n} a_i} \end{aligned} \tag{2}$$

EN is the stability of the center of gravity, ENx and ENy are the stability of the center of gravity in the x-axis and y-axis directions, respectively. a_i is the area of structural element *i*; and x_i is the x-coordinate of the center of gravity of structural element *i*, and x_c is the x-coordinate of the center of gravity of the smallest outer rectangle of the product contour line. b_f is the width of the smallest external rectangle of the overall shape of the industrial robot.

Simplicity

Simplicity refers to the level of simplification and alignment of the layout of screen elements, which is a crucial factor in determining how well the elements of the screen work together.

The overall design of industrial robots and the relationship between their structural elements should be consistent with the human visual requirements for simplicity. The simplicity of the industrial robot's overall shape can give the user the impression that the equipment is efficient and easy to maintain. The definition of simplicity is not limited to the number of visual elements. Having too many structural components will make the industrial robot look complex and chaotic, while having too few structural components will make the structure of the industrial robot too simple, thus affecting its performance. Therefore, the simplicity of industrial robots needs to strike a balance between meeting functional requirements and avoiding redundancy. The simplicity formula is as follows:

$$\mathrm{SM} = \frac{3}{n_v + n_h + n} \tag{3}$$

n_v and n_h represent the number of alignment points for the coordinates of the elements in the horizontal and vertical directions. "n" represents the number of elements in the whole interface.

Sense of Regularity

Regularity refers to the degree of consistency between the elements of an industrial robot's components. A sense of regularity in modelling allows the user to quickly identify the function of each component of the industrial robot and improves the efficiency of its use. The formula is as follows:

$$\begin{aligned} \text{RM} &= \frac{|\text{RM}_{\text{alignment}}| + |\text{RM}_{\text{spacing}}|}{2} \in [0,1] \\ \text{RM}_a &= \begin{cases} 1 & \text{if } n = 1 \\ 1 - \frac{n_s - 1}{2(n-1)} & \text{otherwise} \end{cases} \\ \text{RM}_S &= \begin{cases} 1 & \text{if } n = 1 \\ 1 - \frac{n_v + n_h}{2n} & \text{otherwise} \end{cases} \end{aligned} \tag{4}$$

n_v, n_h, n_s represent the number of alignment points in the horizontal and vertical directions. It also represents the number of starting points at different distances between rows and columns respectively. Meanwhile, n represents the number of elements in the entire interface layout.

Integrity

"integrity" refers to a system goal composed of intrinsically linked localities. Unity is a measure of the compactness of the layout of the structural elements of an industrial robot. The higher the degree of unity, the lower the complexity of the form, making it easier to identify and more coordinated. The formula is:

$$\text{UM} = 1 - \frac{a_m - \sum_{i=1}^{n} a_i}{a_q - \sum_{i=1}^{n} a_i} \tag{5}$$

UM is the degree of unity, and a_m is the area of the smallest outer rectangle of the group of structural component elements, and a_q is the area of contour line form.

Density

Density is a measure of proportional beauty, indicating the compactness between each design element in the interface. The density index of the target interface can be obtained by calculating the difference between the density of the target interface and the density of the optimal interface.

Density is a measure of how much of the area within the contour of an industrial robot is occupied by morphological structural elements. The larger the area covered, the more crowded it appears. Conversely, the smaller the area, the more hollow it appears. Additionally, the closer the final calculation is to 50%, the more appropriate the density is. The formula for density is as follows:

$$\text{DM} = 1 - \left|1 - \frac{2\sum_{i}^{n} a_i}{a_{\text{frame}}}\right| \in [0,1] \tag{6}$$

a_i is the area of a single structural element and a_f is the total screen area, and n is the number of elements in the interface.

COMPREHENSIVE BEAUTY CALCULATION

The Analytic Hierarchy Process (AHP) was used to calculate the weight of each factor in beauty imagery. Firstly, the experts assess the relative importance of the two beauty imagery factors by assigning values from 1 to 9, then calculate the maximum eigenvalue of the judgment matrix and evaluate the consistency of the matrix. If the consistency is satisfactory, the matrix is standardized to determine the weight of each beauty imagery factor. Otherwise, the values are reassigned.

Let the judgment matrix $C = [c_{ij}]$ n × n be obtained by using 1 to 9 assignments. Calculate the eigenvectors of each column of C and normalize the eigenvectors to $w = \{w_1, w_2,..w_n\}$ T, and there are $w_1 + w_2 + ... + w_n = 1$. Taking the largest eigenvalue of the matrix C as γ_{max}, then:

$$C \times w = \gamma_{max} \times w \tag{7}$$

Using the square root method, the elements in C are processed to derive the importance vector w, which is calculated as:

$$\overline{w}_a = \sqrt[n]{\prod_{j=1}^{n} uc_{ij}} \tag{8}$$

$$w_a = \overline{w}_i \Big/ \sum_{i=1}^{n} \overline{w}_i \tag{9}$$

A matrix consistency test is performed to determine whether the consistency of the matrix is acceptable. The consistency ratio is:

$$\text{C.R.} = \text{C.I.}/\text{R.I.} \tag{10}$$

C.I.=(γ_{max}-n)/(n-1). R.I. is the average random consistency index, the value of which is given in the literature (Wang, 2010). Make the importance degree of each beauty imagery be obtained as w_i, then the comprehensive beauty imagery value of the human-machine interface morphological element layout is:

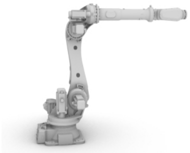
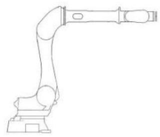
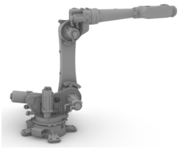
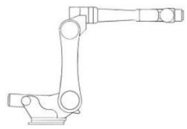
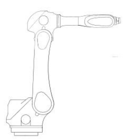
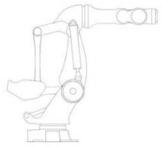
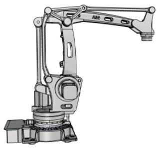
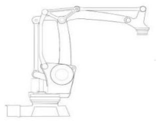
$$D = \sum_{i}^{b,u,s,c} D_i \cdot w_i \tag{11}$$

INSTANCE VALIDATION

Evaluation of Industrial Robot Aesthetics

Through data review and online collection, six samples of industrial robots were collected in the preliminary stage. After generalization, classification, and analysis, six representative samples were selected based on their morphological features (the six aesthetics computation indexes mentioned above). The industrial robots underwent morphology semantics extraction and simplified processing, which will facilitate the measurement and computation of the aesthetics indexes in the later stage. The results are presented in Table 1.

Table 1. Simplified industrial robot model.

Number	Model	2D Graph
Option 1		
Option 2		
Option 3		
Option 4		
Option 5		
Option 6		

A 2D parametric measurement coordinate system is established using the left view perspective of the industrial robot, as depicted in Figure 1. The origin of the two-dimensional coordinate system is located at the geometric center of the industrial robot arm. Using two-dimensional plane software, Figma, we mapped the coordinates of each structural component onto the coordinate system and obtained the length and width values. These values were then used in the calculation of beauty indexes, as shown in Table 2.

According to equations (1) to (6), the values of balance, center of gravity stability, simplicity, integrity, sense of regularity and denseness of each scheme are calculated respectively, and the corresponding data are obtained as shown in Table 2.

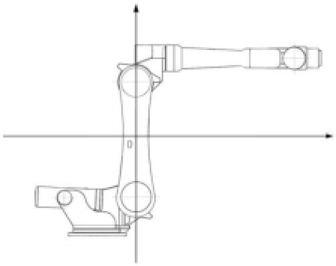


Figure 1: Establishment of 2D coordinate system for industrial robots.

Table 2. Simplified industrial robot model.

	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
EM	0.3420	0.3807	0.5168	0.3538	0.2781	0.3167
EN	0.1765	0.1668	0.1666	0.1875	0.1765	0.1660
SM	0.7500	0.7500	0.7500	0.7500	0.7500	0.7500
RM	0.1417	0.0500	0.0500	0.2333	0.1314	0.0500
UM	0.6163	0.5964	0.5168	0.6170	0.5644	0.5398
DM	0.5088	0.5133	0.6774	0.7732	0.6931	0.4113

EM: Balance; EN: Gravity stability; SM: Simplicity; RM: Regularity; UM: Integrity; DM: Denseness

Five industrial design experts were organized to calculate the weights of the aesthetic imagery indicators for the morphological elements of industrial robots using equations (7) to (10). The weights for each indicator were obtained and are presented in Table 3.

Table 3. Weights of industrial robot aesthetics indicators.

Metrics	Balance	Center of Gravity Stability	Simplicity
Weights	0.137	0.167	0.332
Metrics	Integrity	Sense of Regularity	Intensity
Weights	0.225	0.077	0.062

According to formula (11), the aesthetic imagery values of the layout scheme of the morphological elements of industrial robots are obtained as Table 4:

Table 4. Aesthetic values of layout schemes for industrial robot morphological elements.

Programme	Option 1	Option 2	Option 3
Meadow Imagery	0.077	0.062	0.332
Order	5	6	1
Programme	Option 4	Option 5	Option 6
Meadow Imagery	0.167	0.225	0.137
Order	3	2	4

Comparison of the above calculations shows that the beauty values of the options are: Option 2 < Option 1 < Option 6 < Option 4 < Option 5 < Option 3. Option 3 is the preferred option.

Validation and Discussion of Results

In order to verify the accuracy of the aesthetics calculation formula, the perceptual imagery evaluation method is used for verification (Shuzhi, 2017). To ensure the accuracy and reliability of the perceptual vocabulary source, as well as to accurately capture the user's aesthetic experience of the industrial robot view, the following specific steps are taken.

Imagery Vocabulary Selection and Evaluation Matrix Acquisition

Firstly, we obtained 30 words related to industrial robots' sensual imagery through the official website of industrial robots, academic papers, and other relevant information. Then, we selected 6 pairs of representative sensual words with similar meanings based on the six beauty indicators chosen by the beauty index system. These pairs are shown in Table V. Finally, we created a questionnaire using a Likert scale, which combined the words of sensual imagery and sample pictures. This allowed us to construct an evaluation matrix for assessing the beauty of the morphology view of industrial robots. Finally, the Likert scale was used to create a questionnaire with sample pictures in order to construct an evaluation matrix for assessing the aesthetic appeal of the industrial robot's physical appearance. In order to ensure the research results are authoritative and representative, a panel of experts consisting of 20 students as well as 5 senior design teachers.

Table 5. Aesthetic values of layout schemes for industrial robot morphological elements.

Norm	Imagery Vocabulary
Balance	Balanced - Imbalanced
Center of gravity stability	Stable - Wobbly
Simplicity	Simple - Redundant
Norm	Imagery vocabulary
Sense of Regularity	Orderly - Arbitrary
Integrity	Simple - Complex
Density	Dense - Loose

Evaluation Process

A total of 25 questionnaires were distributed. The six dimensional indicators of beauty calculation were scored separately using a Likert scale, with each dimension rated from 1 to 7. After collecting the questionnaires, the mean score for each beauty indicator was calculated. The final composite scores for each program are presented in Table 6.

Table 6. Composite score of subjective evaluation of industrial robots.

Programme	Option 1	Option 2	Option 3
Aggregate Score	30.83	30.77	36.72
Order	5	6	1
Programme	Option 4	Option 5	Option 6
Aggregate Score	33.89	34.24	33.16
Order	3	2	4

Discussion of Results

Comparing the numerical ranking calculated by the aesthetics evaluation method with the ranking of scores obtained from the subjective evaluation questionnaire, it can be observed that they are consistent. Therefore, the aesthetics evaluation method can effectively reflect the user's perception of the aesthetics of the industrial robot modeling. Furthermore, it is more scientifically and accurately compared to the subjective evaluation.

CONCLUSION

Aiming to address the issues of subjectivity and arbitrariness in evaluating the aesthetic appeal of current industrial robot designs, this paper identifies six beauty indicators: balance, center of gravity stability, simplicity, regularity, integrity and density. The weight values for these indicators are determined using the hierarchical analysis method, resulting in the development of a comprehensive beauty evaluation model for assessing the visual appeal of industrial robots. Twenty-five Likert scale questionnaires were collected and analyzed to subjectively evaluate the industrial robot scheme. The results were then compared and verified with the beauty evaluation model. The findings demonstrated that the beauty evaluation model is advantageous in assisting designers in selecting the industrial robot styling design scheme. This research holds practical significance. In this paper, we studied the aesthetics of the side layout of industrial robots. However, the overall aesthetics of industrial robots should also consider factors such as color and material, in addition to the model elements. Therefore, the next step in our research is to comprehensively evaluate these factors for aesthetics.

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