Study on Ergonomic Digital Evaluation System for the Naval Shipborne Command Cabin Based on Extended JACK

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Abstract. The naval ship command cabin (NSCC) is an important part and the nerve centre of the whole ship. In order to achieve better evaluation and design improvements of the human-machine interface (HMI) of the naval shipborne command cabin in the design phase, we preliminarily expounded the ergonomic digital evaluation system of the NSCC based on extended JACK. The NSCC human-machine interface evaluation index system was constructed by using the improved Delphi method, and the quantitative and qualitative evaluation method was studied. The ergonomic digital evaluation system for the naval shipborne command cabin was developed by extending the JACK software, in which the mannequin module, human-machine interface design module, evaluation module and design standards module were integrated. Finally, the feasibility and applicability of the proposed ergonomic digital evaluation system were verified by an illustrated example.

1. Introduction

The naval ship command cabin (NSCC) is the working area for the crew to command and control the ship and carry out missions. It is the nerve centre of the whole naval ship, and it is also a typical complex human-machine system that integrates human-machine interfaces (HMIs) of navigation, contact, command, communication and real-time battlefield information display. With the improvement of ship automation and the exponential growth for the information displayed on the control interface, the diversification of information integration and display ways have become a new trend, and also the working methods of operators have gradually changed from manual operation to monitoring-decision control [1]. Therefore, higher requirements have been put forward for the human-machine interface design for the NSCC.

Granting to the domestic and foreign statistics on the causes of water traffic accidents, about 80% of the accidents are related to operational errors to more or less extent [2]. Moreover, the engineering practice has shown that the disadvantages of building ships in our country are often concentrated on the human-machine interface, which often leads to the inconvenience of operation and maintenance [3]. Hence, the study on the ergonomics of the HMI needs to be toned up. Previous studies have shown that foreign countries have formulated relatively perfect ergonomic standards and guidelines for HMI issues [4,5], but there are few studies on the methods of evaluation and inspection for the implementation of standards. At present, there is no specific research on the ergonomic evaluation of the NSCC human-machine interface. Moreover, the existing evaluation methods in ergonomics mainly focuses on participant self-reports [6,7], observation [8,9], virtual simulations [10,11] and direct
measurements[12,13] according to tools and means used. However, as mentioned above, these approaches are all post-hoc analysis methods, and they cannot be directly applied in the design phase.

In this paper, a human-machine interface (HMI) digital evaluation system for naval ship command cabin (NSCC) is studied based on extended JACK and essential ergonomic criteria. The digital evaluation system was realized through secondary development on the JACK ergonomic software platform. The system creates digital 3D human body models based on the GJB4856-2003 military staff’s anthropometric data and physiological experiment data. Rhinoceros digital design platform was adopted to design the 3D digital model database for the HMI of NSCC. Based on the open programming interface attached to JACK software, the linkage between the Jack and Rhinoceros software was realized. The 3D models built in Rhinoceros software can be imported into JACK software in real-time to construct the human-machine interaction system of the NSCC. Then, according to the ergonomic design standards and principles of the NSCC, the accessibility, visibility, equipment layouts and structural parameters design of the shipborne display-control console (SDCC) are evaluated to attain the evaluation in the design phase. According to the evaluation results, the deficiencies in the human-machine interface (HMI) design of the SDCC were analyzed, and the 3D human-machine interface model of the shipborne display console was directly improved and refined in the human-machine interface ergonomic digital evaluation system for NSCC.

The contributions of this paper are as follows:

1. We established the human-machine interface ergonomic evaluation index system of the naval ship command cabin, which can be used as a guide to assist designers.
2. We established the human-machine interface ergonomic digital evaluation system by extending the JACK software, which can test the degree to which ergonomic guidelines are followed in the human-machine interface design of the NSCC, and timely discover the design deficiencies of the human-machine interface.
3. The ergonomic digital evaluation system integrates the JACK software’s parameterized ergonomic evaluation function and Rhinoceros’s engineering digital design function to realize the real-time interaction on human-machine interface design, evaluation and improvement for the naval ship command cabin.

2. The architecture of the digital evaluation system

The human-machine interface (HMI) digital evaluation system for the naval ship command cabin (NSCC) is mainly composed of four modules: mannequin module, human-machine interface design module, evaluation module and design standards module, as shown in Figure 1. The human-machine interface design module and the mannequin module of the NSCC can quickly build the HMI interaction system for the naval ship command cabin.

Figure 1. The composition and relationship of the NSCC human-machine digital evaluation system.
2.1. Mannequin module
The ship crew is an indispensable part of the human-machine system of the naval shipborne command cabin. The mannequin module is used to create standard digital human models (DHMs) for naval personnel whose human body parameters conform to the GJB4856-2003. The functions of digital human model include percentile of human body, working postures, touch domain of hand function, scope of binocular vision and other ergonomic data. Because the JACK software has a complete database of virtual DHM[14], we developed the mannequin model based on JACK’s DHMs database.

2.2. Human-machine interface design module
The HMI design module is used to design the 3D model of the naval ship command cabin’s human-machine interface. In this paper, Rhinoceros, a computer-aided design (CAD) application, which is based on the NURBS mathematical model and can produce a precise representation of curves and freeform surface, was used to build the 3D model library for the HMI of the NSCC, including control console, various manipulators, displays, seats and decks, etc. Through the model library, the 3D human-machine interface model of the ship command module can be designed quickly and accurately, and the modification and later improvement of the design can be made conveniently.

2.3. Evaluation module
The evaluation module is composited by the evaluation index system and the corresponding evaluation methods. It is used to evaluate the human-machine interaction system of the built ship command cabin. The evaluation index system is constructed based on ergonomic criteria and principles related to the HMI design of the NSCC, which can reflect the quality of the ship command cabin’s human-machine interface design. The evaluation method is the research on the quantitative method of evaluation index, including quantitative and qualitative indices.

2.4. Design criteria module
The design criteria module integrates ergonomic standards, principles and other documents on human-machine interface design of naval ship command cabin, whose significance is to assist and guide the later human-machine interface optimization and improved design.

2.5. Other modules owned by Jack
This study is based on Jack, an ergonomic simulation and evaluation product, which provides a great number of basic ergonomic tools to evaluate the DHMs, including view zone, reach zone, measurement tools, comfort assessment tool and other ergonomic functions[15]. In this paper, we utilized its reach zone, view zone and measurement tools to obtain the quantified data.

3. Evaluation index system and evaluation method

3.1. The construction of the HMI evaluation index system
The human-machine interface (HMI) index evaluation system of naval ship command cabin (NSCC) involves many evaluation contents and objectives, and the relationship between them is complex. In this paper, the top-down decomposition way is employed to decompose the index system of the NSCC human-machine interface into an orderly ladder hierarchy structure in the process of building the index system. We divided the system into three layers, namely, objective layer, index layer and element layer. The HMI evaluation index system of objective layer is composed of five parts: display interface design, manipulator interface design, display-control layout design, console design and operation space design according to the HMI ergonomic criteria and principles of the NSCC. According to the component elements of each part, it is further decomposed to form a multi-level evaluation index system analysis model of naval shipborne command cabin (NSCC). Finally, the improved Delphi method[16] is utilized to screen the indexes to form the final HMI evaluation index system of the NSCC, as shown in Table 1. The evaluation index system reflects the overall performance and
3.2. Evaluation method

The elements layer is based on the evaluation index system, which reflects the quality pertained to the human-machine interface design of the NSCC. It is comprised of quantitative and qualitative indices. Since these two kinds of indicators all have their own characteristics and properties, the evaluation approach suitable for quantitative indicators may not be available for qualitative indices, so different methods are needed to quantify the human-machine interface indices.

3.2.1 Quantify quantitative indices

A quantitative indicator refers to the index that has clear evaluation criteria and can be represented numerically. The corresponding evaluation score can be determined by comparing the actual design value with the standard rated value. For quantitative indicators, they include benefit index (the bigger, the better), cost index (the smaller, the better), fixation index (the closer to the target value, the better) and interval index (the better within a fixed interval). Previous studies have provided plenty of methods for quantitative indicators. In the human-machine interface comprehensive evaluation system of the NSCC, the quantitative indexes mainly include[17]:

(1) Benefit index, which membership function is as follows:
\[
\mu_i = \begin{cases} 
1, & (x_i \geq M_i) \\
\frac{x_i - m_i}{M_i - m_i}, & (m_i \leq x_i \leq M_i) \\
0, & (x_i \leq M_i)
\end{cases}
\] (1)

(2) Cost index, which membership function is as follows:
\[
\mu_i = \begin{cases} 
1, & (x_i \geq M_i) \\
\frac{M_i - m_i}{M_i - m_i}, & (m_i \leq x_i \leq M_i) \\
0, & (x_i \leq m_i)
\end{cases}
\] (2)

(3) Fixation index, which membership function is as follows:
\[
\mu_i = \begin{cases} 
\frac{2(x_i - m_i)}{M_i - m_i}, & (m_i \leq x_i < \frac{M_i + m_i}{2}) \\
\frac{2(M_i - x_i)}{M_i - m_i}, & \left(\frac{M_i + m_i}{2} \leq x_i \leq M_i\right) \\
0, & (M_i < x_i < m_i)
\end{cases}
\] (3)

(4) Interval index, which membership function is as follows:
\[ \mu_i = \begin{cases} 
1 - \frac{q_{i1} - x_i}{\max\{q_{i1} - x_i, M_i - q_{i2}\}}, & (x_i < q_{il}) \\
1, & (x_i \in [q_{i1}, q_{i2}]) \\
1 - \frac{x_i - q_{il}}{\max\{q_{i1} - m_i, M_i - q_{i2}\}}, & (x_i \leq M_i) 
\end{cases} \]  
\quad (4)

where \( x_i \) is the characteristic value of index \( i \). \( M_i \) and \( m_i \) are the upper and lower boundary, respectively. \( [q_{i1}, q_{i2}] \) is optimal stable interval of characteristic value \( x_i \). \( \mu_i \) is the membership degree of index \( i \).

3.2.2. The method of quantify qualitative indices based on the fuzzy theory

Qualitative indicators refer to indices that cannot provide specific numerical values or provide specific values and not have clear evaluation criteria. They can only be described in a subjective form and need to be evaluated by experts based on their experience. In this study, the fuzzy theory[18] is applied to quantitatively process qualitative indices of the human-machine interface and the specific steps are as follows:

**Step 1:** Construct expert evaluation fuzzy word set \( G = \{\text{worst, worse, bad, fair, good, better, best}\} \), which was divided into seven categories to describe experts’ representation on different degrees. It is necessary to determine the degree of membership of factors to fuzzy sets when quantifying fuzzy words evaluated by experts. The membership is meant by real numbers between \([0, 1]\) in fuzzy word sets. The specific form is shown in Table 2.

| \( \mu_{ig} \) | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|----------------|---|---|---|---|---|---|---|
| Best           | 1 | 0.7 | 0.3 | 0 | 0 | 0 | 0 |
| Better         | 0.3 | 1 | 0.7 | 0 | 0 | 0 | 0 |
| Good           | 0 | 0.5 | 1 | 0.3 | 0 | 0 | 0 |
| Fair           | 0 | 0 | 0.5 | 1 | 0.5 | 0 | 0 |
| Bad            | 0 | 0 | 0 | 0.3 | 1 | 0.5 | 0 |
| Worse          | 0 | 0 | 0 | 0 | 0.7 | 1 | 0.3 |
| Worst          | 0 | 0 | 0 | 0 | 0.3 | 0.7 | 1 |

where, \( g \) represents the \( g \)th category in set \( G, g = 1, 2, \ldots, 7 \). \( \mu_{ig} \) refers to the degree of membership of a factor in a given range in set \( G, \mu_{ig} \in [0,1] \), and if \( i=m, \mu_{ig} = 1 \).

**Step 2:** Construct the evaluation results feature set \( A \), which was divided into five levels, denoted as \( A = \{\text{poor, bad, fair, good, excellent}\} \). Then, the seven categories were used to define the five levels in set \( A \) to make sure that the fuzzy words in \( G \) are well reflected in \( A \). When the experts’ expression was set as “best”, the corresponding index would be judged as “excellent”. When the experts’ representation was described as “worst”, the corresponding index would be judged as “poor”. The specific form is shown in Table 3.

| \( \mu_{ia} \) | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|----------------|---|---|---|---|---|---|---|
| Excellent      | 1 | 0.7 | 0.3 | 0 | 0 | 0 | 0 |
| Good           | 0 | 0.7 | 1 | 0.3 | 0 | 0 | 0 |
| Fair           | 0 | 0 | 0.5 | 1 | 0.5 | 0 | 0 |
| Bad            | 0 | 0 | 0 | 0.3 | 1 | 0.7 | 0 |
| Poor           | 0 | 0 | 0 | 0 | 0.3 | 0.7 | 1 |

where, \( a \) represents the \( a \)th category in \( A, a = 1, 2, \ldots, 5 \). \( \mu_{ia} \) represents the degree of membership of a factor in a given range in \( A \).

**Step 3:** Calculate the match degree and the membership degree between experts’ fuzzy comments and each level in set \( A \). According to the factor’s definition in set \( G \) and set \( A \), the membership
function of expert e’s fuzzy comments on a certain qualitative index at each level in $A$ can be described as follows[19]:

$$\mu_e^* (a) = \frac{\sum_{i=1}^{7} \min[\mu_{im}, \mu_{ia}]}{\sum_{i=1}^{7} \max[\mu_{im}, \mu_{ia}]} , e = 1, 2, ..., n$$  \hspace{1cm} (5)$$

where $\mu_e^*$ indicates the match degree among the experts’ fuzzy comments and each level in set $A$, $a=1, 2, ..., 5$, $i=1, 2, ..., 7$, $m=1, 2, ..., 7$, then the $\mu_e^*$ can be normalized by the following function:

$$\mu_e~(a) = \frac{\mu_e^*(a)}{\sum_{i=1}^{7} \mu_e^*(a)} , e = 1, 2, ..., n$$  \hspace{1cm} (6)$$

where $\mu_e~(a)$ refers to the degree of membership between experts’ fuzzy comment and each level in set $A$.

**Step 4:** Determine the membership degree among expert e’s fuzzy comments on indicator $t$ and each level in set $A$, which can be described as follows:

$$P_{et} = \{ \mu_e^*(1), \mu_e^*(2), \mu_e^*(3), \mu_e^*(4), \mu_e^*(5) \}$$  \hspace{1cm} (7)$$

**Step 5:** Calculate the comprehensive membership degree $R^*(a)$ on index $t$ for evaluating $a$ level after combining the opinions of $n$ experts. Then, the linear weighting method can be utilized to combine the opinions of $n$ experts.

$$R^*(a) = \sum_{e=1}^{n} P_{et}$$  \hspace{1cm} (10)$$

### 3.2.3. The determination of index weight

The determination of index weight is an indispensable phase of the human-machine interface (HMI) ergonomic evaluation of NSCC. It is not easy to analyze and compare indexes because there are quantitative and qualitative indices in the HMI ergonomic evaluation system and there is no uniform measurement to standardize them. Consequently, different membership functions would be needed to normalize different indexes into the range of 0 and 1.

In this paper, the comprehensive weight is determined by the objective weight and subjective weight. The objective weight is obtained by the standard deviation method, which utilizes the standard deviation of indices to calculate the weight. The greater the variation degree of the index value, the greater the role it plays in the comprehensive evaluation. Thus, the index which holds larger deviations should be assigned a more significant weight. The function of standard deviation is as follows[20,21];

$$\vartheta_j = \sigma_j / \sum_{j=1}^{d} \sigma_j \hspace{1cm} (j = 1, 2, ..., d)$$  \hspace{1cm} (11)$$

where $\sigma_j$ denotes the standard deviation for each column of the initialized data matrix, $d$ refers to the index number.

The objective weight set is denoted as $\vartheta = (\vartheta_1, \vartheta_2, ..., \vartheta_m)$. The subjective weight can be obtained by expert subjective weighting method, which is based on the relative importance of each indicator and it can be a complementary to the standard deviation method mentioned above. The subjective weight set is denoted as $\rho = (\rho_1, \rho_2, ..., \rho_m)$. The combined weight can be obtained by integrating the objective and subjective weight, denoted as $\omega$:

$$\omega = (\vartheta + \rho) / 2$$  \hspace{1cm} (12)$$

### 3.3. Comprehensive evaluation model

Multi-index comprehensive evaluation refers to synthesizing multiple index values into an overall comprehensive evaluation value through a particular mathematical model. Previous studies have shown that there are many integration methods, such as linear and nonlinear weighted integration methods, TOPSIS, etc.
In this paper, we adopted the fuzzy comprehensive evaluation model based on the linear integration method to determine the final evaluation result, which takes the overall index of the evaluation object into consideration. The model is as follows:

$$\psi = \sum_{l=1}^{r} \omega_{l} \mu_{l} \quad (l = 1,2, ..., r)$$  \hspace{1cm} (13)

where $\psi$ denotes the comprehensive evaluation score, $\omega_{l}$ represents the combined weight of index $l$.

4. Verified experiment

The implementation of the JACK dynamic simulation relies entirely on the scripting language. JACK’s underlying code development environment is in C, including Tcl/Tk and JackScript scripts. Tcl/Tk scripts are used to write JACK interfaces and operate platforms, build and modify models, and design model constraints. JackScript is a set of functions written based on Python language. It is mainly used to control the movement and motion analysis of the model and is responsible for writing the model control functions. In this paper, we utilized the Tcl/Tk scripts for secondary development based on the Jack software and the development process is shown in Figure 2.

Figure 2. The secondary development process based on Jack software

In this paper, we integrated the evaluation index system for the HMI of NSCC, the quantification method, design criteria module and modules the JACK software owed. It can ensure the real-time interaction of human-machine interface design, evaluation and improvement.

An example of control-display console in certain naval shipborne command cabin(NSCC) is given to illustrate the evaluation process and method of the digital evaluation system.

(1) The 3D human-machine interface(HMI) model of the naval shipborne command cabin is designed in the interface design module. Then, create the 50th percentile of the digital human model(DHM) for naval personnel that conforms to the GJB4856-2003 in the mannequin module. The mannequin was accurately assembled into each operation and command position in the NSCC model, and the human-machine position relationship between the mannequins and the NSCC model was set, as shown in Figure 3.

(2) This paper chose the human-machine interface(HMI) digital evaluation system for the naval ship command cabin(NSCC) to evaluate the display-control console, which was applied in the NSCC, as shown in Figure 4. The values of quantitative indicators and qualitative indices were obtained using the digital evaluation system and the fuzzy method mentioned in section 3.2.2, respectively. The evaluation results are shown in Table 4.
Figure 3. The human-machine position relationship between mannequin and human-machine interface model of NSCC.

(a) (b)

Figure (a) shows the model of the HMI of NSCC, Figure (b) shows the measurement of quantitative indices.

Figure 4. Human-machine interface evaluation of display-control console,

| Index Layer | Element layer       | Membership degree/$\mu_i$ | Objective weight/$\delta_i$ | Subjective weight/$\rho_i$ | Combined weight/$\omega_i$ |
|-------------|---------------------|---------------------------|-----------------------------|-----------------------------|-----------------------------|
| Monitor     | Aspect ratio        | 0.54                      | 0.15                        | 0.22                        | 0.185                       |
|             | Clarity             | 0.83                      | 0.29                        | 0.28                        | 0.285                       |
|             | Readability         | 0.80                      | 0.27                        | 0.24                        | 0.255                       |
|             | Brightness comfort  | 0.82                      | 0.29                        | 0.26                        | 0.275                       |
| Instruments | Static reading accuracy | 0.78                  | 0.24                        | 0.23                        | 0.235                       |
|             | Range reading accuracy | 0.82                  | 0.26                        | 0.22                        | 0.24                        |
|             | Fluctuation reading accuracy | 0.84              | 0.27                        | 0.27                        | 0.27                        |
|             | Continuous reading accuracy of Multi-instruments | 0.77          | 0.23                        | 0.28                        | 0.255                       |
| Light indicators | Position rationality | 0.75                  | 0.21                        | 0.27                        | 0.24                        |
|             | Color coding rationality | 0.78                  | 0.22                        | 0.22                        | 0.22                        |
|             | Error rate          | 0.66                      | 0.16                        | 0.21                        | 0.185                       |
|             | Anti-interference capabilities | 0.73          | 0.19                        | 0.14                        | 0.165                       |
According to the comprehensive evaluation model in section 3.3, all indices of the element layer in Table 4 can be evaluated. We can obtain the comprehensive evaluation scores of indices layer by integrating the weights and the membership degrees of the element layer, as shown in Table 5. The comprehensive scores of the six indices in index layer are 0.7660, 0.8033, 0.7443, 0.7495, 0.7866, 0.7866, respectively. According to the hundred-mark system, the comprehensive evaluation scores are 76.60, 80.33, 74.43, 74.95, 78.66, 78.66, respectively. The design of instrument is optimal, the operator handle and physical switch are as follows. And the design of console and light indicators are insufficient. In general, the design of the display-control console in the naval shipborne command cabin is good.

Table 5. The comprehensive evaluation scores of indices layer.

| Index layer          | Comprehensive scores | Comprehensive scores (Hundred-mark) |
|----------------------|----------------------|-------------------------------------|
| Monitor              | 0.7660               | 76.60                               |
| Instruments          | 0.8033               | 80.33                               |
| Light indicators     | 0.7443               | 74.43                               |
| Console              | 0.7495               | 74.95                               |
| Operator handle      | 0.7866               | 78.66                               |
| Physical switch      | 0.7866               | 78.66                               |

(4) Improve the model of the NSCC human-machine interface in the digital HMI evaluation for NSCC.
5. Conclusion
In this paper, the human-machine interface ergonomic evaluation index system for the naval ship command cabin was established, which can be used as a guide to assist designers. We constructed the human-machine interface ergonomic digital evaluation system by extending the JACK software, in which the digital human module, the evaluation index system, index quantification methods and design criteria were integrated. It can test the degree to which ergonomic guidelines are followed in the human-machine interface design of the naval ship command cabin, timely discover the design deficiencies of the human-machine interface, and realize the real-time interaction on human-machine interface design, ergonomic evaluation and improvement of the naval ship command cabin. Finally, the practicality and applicability of the proposed ergonomic digital evaluation system were verified by an illustrated example.

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