The Layout Optimization Design of Command Control Cabin Display and Control Panel

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Abstract. According to the type and quantity of the control panel of the weapon and equipment control panel, the operation difficulty is big, the repetitive movement, the blocking posture, the accumulated task load, easily induced Musculoskeletal disorders, the impact of task performance, this paper comprehensive ergonomics criteria and the characteristics of human upper limb movement, and through the human in the loop simulation equipment. In the operation, the operation time data of a certain type of equipment operation interface is collected and analyzed, and the positioning movement time of each area of the equipment interface is obtained. Distribution map, to provide data basis for the model, the establishment of the control panel layout model based on linear programming and Fitts' law, and the use of LINGO software 0-1 programming model to solve the programming. The results show that the operating loss distance and operation time are optimized by 28% and 16% respectively, and the optimization effect is remarkable.

1. Introduction

In man-machine system operation, the human-machine interface is the concept space of information and force exchange between the user and the machine. The layout of the manipulating interface plays a vital role in the interaction efficiency. In the early days, the research on the layout of the manipulative interface was mainly based on the qualitative optimization of the interface between the ergonomic guidelines. In 1993, Sanders and McCormick proposed four basic principles for user interface layout: importance, frequency of use, functional similarity, and order of use. It forms the basis for research and is widely used in the design of user interfaces for various products and systems [1]. In 1995, ESJUNG detailed the ergonomics criteria affecting layout, refined into ergonomic criteria affecting relative position decisions, and ergonomic guidelines affecting absolute position decisions, and proposed CSP (Constraint Satisfaction Problem) techniques for solving Multi-constraint satisfaction problem [2]. In 2003, Grady T. Holman optimized the control panel design using the linear programming method from the perspective of ergonomics for the first time, and demonstrated that the ergonomic design based on ergonomics significantly reduced skeletal muscle disorder and its severity. In 2008, Mauricio Alves C designed a nuclear power plant virtual control panel, which has significantly improved the efficiency of operation and training due to its flexible layout design and its low cost.[3] In 2013, Isaac José Antonio Luquettidos Santos reconfigured the alarm panel of the nuclear control room with a human factors questionnaire and an operator action analysis method based on a cognitive function model to improve the safety level of the control room of a nuclear power plant [4]. In 2015, Cem Alppay used ergonomics guidelines and user perspectives and preferences to
quantitatively evaluate interface layout principles through interviews with professional pilots, and creatively presented a paper prototype method that allows pilots to optimize display devices on the instrument panel. The layout forms the methodology for optimizing aircraft instrument layout [5].

In recent years, the domestic operation control interface layout design mainly focuses on the rail vehicle driver console, aircraft cockpit, industrial control room and other fields. In 2014, Chen Dejun and Fang Weining proposed an optimization design model for console layout based on factors of human factor and geometric position matching. The particle swarm optimization algorithm was used to solve the model and optimized the comfort operation requirements of the rail vehicle driver console [6]. In 2010, Wang Rui and Zhuang Damin used anthropometric data and Lagrange equations to establish an upper limb operating dynamics model, which was successfully applied to the ergonomics analysis of cabin manipulator layout [7]. In 2011, Deng Li proposed an optimization model for workspace layout based on human posture driving, and optimized the layout of manipulators in the right-hand area of the drillier's console of the oil rig [8]. In 2013, Niu Song proposed the use of genetic algorithms to optimize the layout of the civil cockpit, solved the quantification of layout principles, and optimized the layout of a certain aircraft cockpit. The results showed that the genetic algorithm was suitable for layout optimization [9].

At present, there are relatively few researches on human upper body reachability probability and positioning movement characteristics of the man-machine interface. There are few mathematic models to apply the human upper limb reachability probability and positioning movement characteristics in the man-machine interface layout optimization model. Although Grady T. Holman's study considers the loss of the operating distance, it is based on the fact that foreign body data does not meet domestic equipment requirements, and then does not consider the optimization of the operating time. The ergonomic guidelines for ergonomics are only qualitatively applied.

Based on the improved Grady T. Holman's model, this paper proposes a prediction model for the layout optimization design of command and control console panel based on linear programming (LP) and Fitts' law. The LINGO software is used to program the objective function of the linear programming. Through the iterative optimization of the decision variables, the best combination of the decision variables with the shortest loss distance and the shortest operating time is finally sought, and the overall layout scheme is optimized.

2. Control panel layout optimization design model

2.1. Description of the layout problem of the equipment control panel

After a long-term investigation, it is found that in the stressful task, the layout of the equipment interface could not well meet the movement characteristics of the human upper limbs. It is easy to cause repetitive operation, muscle fatigue damage, which leads to low operation efficiency and high operation error rate, and reduces the efficiency and reliability of human-machine interaction. How to improve the ergonomic design level of the human-computer interaction interface has become an urgent issue that needs to be resolved. Based on human upper limb movement characteristics and ergonomic guidelines, this paper improves the effectiveness of operating distances and operating time, and meets the basic ergonomic requirements such as frequency of use, importance, order of use, and spatial compatibility, and fundamentally addresses poor human-machine matching. Human-computer interaction problems.

2.2. Technical methods and modeling basis

2.2.1 Linear programming. Linear Programming (LP) is an important branch of mathematical planning and has been widely used in military operations, national defense construction, and engineering technology. The problem of linear programming is to find the maximum or minimum value of linear objective function under linear constraint conditions. Decision variables, constraints, and objective functions are the three elements of linear programming. The standard form is [10]:
\[ \min c^T x \]
\[ \text{st. } Ax = b, x \geq 0, \]
\[ c \in R^n, b \in R^m, A \in R^{m\times n} \]

2.2.2 Fitts' law. Fitts' law is widely used in the field of human-computer interaction and provides a scientific basis for the design of human-computer interaction interface. It is an important quantitative prediction model [11]. It is used to study how long it takes for a pointing device to locate a target object in a positioning movement. This article selects the 1989 MacKenzie revised formula. The MacKenzie model is the most commonly used, and proved to be the best in accordance with the experimental results, mainly because of:

The model is better fitted to the results observed by the experiment, and the information theory implied by the Fitts' law is accurately simulated. The expression is as follows:

\[ MT = a + b \log_2 \left( \frac{A}{W} + 1 \right) = a + b \cdot ID \]

Fitts’law is a continuous, fast, and purposeful movement model. It shows that the time required to use a pointing device to reach a goal is related to the following two factors:

1) The distance between the current position and the target position of the device (A). The longer the distance, the longer it will take.

2) Target size (W), the greater the goal, the shorter the time spent.

2.3. Mathematical model based on linear programming and Fitts' law

The above various layout optimization models have achieved good results in terms of ergonomics criteria, minimum distance, etc., but they still cannot meet the high standards of equipment requirements. Operation time is the main factor restricting the efficiency of the equipment. In the layout problem, it is necessary to consider the distance between the optimization operation and the optimization of the operation time. It can be seen from the mathematical expression of Fitts’ law that the operating time is not only affected by the operating distance, but also related to the orientation of the operation and the target size. In addition, the general algorithm cannot effectively solve the multi-objective linear programming model. This article uses LINGO programming to solve such problems efficiently.

According to a commonly used type of equipment control panel size design panel layout as shown in Figure 1. The panel consists of 15 small panels, represented by panel \( j \) \( j=1,2,\ldots,15 \), each panel size is 147x92 (unit: mm), panel numbers are arranged from left to right. The ellipse represents the operator, the circle represents the initial position of the operator's hand, and the dashed line length represents the horizontal distance of the hand to each small panel and is recorded below the small panel, as shown in Figure 1.

![Figure 1](image-url)
the upper arm is in a natural droop, such as the arc line 2; the solid inner line represents the reach of the center of the elbow in the horizontal state of the upper arm, such as the arc 1. According to the RULA criterion, when the elbow rotates around the shoulder joint normally and the wrist moves normally, the area within the arc 1 will be 100% efficiently used, and the probability of reaching the upper sagittal plane closer to the human body will decrease correspondingly. Applying the same criteria, the effective use probability of arc 3 is about 70%, and the effective use probability outside this area is less than 30%. Figure 2 shows the probability distribution of effective use of small panels by 50-percentile Chinese men.

![Figure 2](image)

**Figure.2** The effectiveness of upper limb movement area up to a probability distribution

2.3.1 **Objective function.** From the above analysis, it can be seen that the effectiveness of the positioning and operating movements of the upper limbs varies among different regions. In order to optimize the effective operation distance, the loss of upper limb movement distance caused by invalid operation is minimized, and the operation time is optimized. Apply the human upper limb movement law and Fitts’ law and the ergonomic layout guidelines of the console to establish the following layout optimization model, the objective function is:

\[
\min F(x) = (f_1, f_2)
\]

\[
f_1 = \sum_{i=1}^{m} \sum_{j=1}^{n} C_{ij} X_{ij}
\]

\[
f_2 = \sum_{i=1}^{m} \sum_{j=1}^{n} E_{ij} X_{ij}
\]

In the formula, the optimization goal \( \min F(x) \) is to minimize the loss distance \( f_1 \) and operating time during operation \( f_2 \); \( C_{ij} \) is the loss distance cost variable, which represents the distance loss where function module \( i \) is placed at position \( j \), \( C_{ij} = f_i \Delta \beta_j = f_i (1 - P_j) S_j \), \( \Delta \beta_j \) is the operating loss distance at panel \( j \), \( f_i \) is the frequency of use of functional module \( i \), \( P_j \) is the reachability probability of panel \( j \), \( S_j \) is the distance from the starting point O to panel \( j \); \( E_{ij} \) is the operating time cost variable, which represents the required positioning movement time when the functional module \( i \) is placed at position \( j \), \( E_{ij} = f_i MT_j = f_i (a_j + b_j \log_2 \left( \frac{A_j}{W_j} + 1 \right)) \), \( MT_j \) is the operating time for positioning movement starting point to panel \( j \), \( f_i \) is the frequency of use of functional module \( i \), \( A_j \) and \( W_j \) are the distance from the starting point of operation to panel \( j \) and the width of
panel \( j \) respectively; \( X_{ij} \) is a decision variable for judging whether the function module \( i \) is placed in the position of the panel \( j \), which is 1, if not 0; \( f'_{i} \) is the frequency of use of module \( i \).

2.3.2 0-1 planning model constraints. (1) Control panel model basic constraints. The manipulation panel model consists of two basic constraints, and each panel \( j \) can only place one function module \( i \), that is: \( \sum_{i=1}^{n} X_{ij} = 1, i = 1,2,L ,n \); each function module \( i \) can only occupy one panel \( j \), that is: \( \sum_{j=1}^{m} X_{ij} = 1, i = 1,2,L ,m \). The constraints are as follows:

\[
\begin{align*}
\sum_{i=1}^{n} X_{ij} &= 1, \quad j = 1,2,L ,n \\
\sum_{j=1}^{m} X_{ij} &= 1, \quad i = 1,2,L ,m \\
X_{ij} &= \{0,1\}
\end{align*}
\]

(2) Constraint conditions based on Ergonomics

To facilitate the application of man-machine efficiency criteria, define variables \( S_{ij}, I_{ij}, PV, CR \). \( S_{ij} \) represents the interaction between functional modules \( i \) and \( j \), as \( S_{ij} = \{3,5\} \), the representation module \( j \) can be placed on the right and right side of the \( i \), as shown in Figure 3. \( I_{ij} \) represents a module that can be placed between \( i \) and \( j \). \( PV \) stands for a module that can be placed in the main visual area, \( CR \) represents a module that can be placed in a comfortably accessible area.

![Figure.3 Between the orientation of the function-module constraints schematic](image)

1) Ergonomic criteria affecting relative position decision

Spatial compatibility: According to the relationship between controllers \( i \) and \( j \), determine the relative position between them.

Functional grouping: Controllers and displays with similar functions should be arranged together.

Sequence-of-use: The completion of a task requires multiple controllers to be used simultaneously, and the controllers should be arranged in order of operation (from top to bottom, from left to right).

2) Ergonomic criteria affecting absolute position decision

Frequency-of-use: High-frequency controllers should be placed in the most accessible range of limbs.

Importance: More important controllers and displays should be arranged in the best field of vision and the most accessible area of the body.
3. Study on the motion characteristics of the upper limb
In this paper, the virtual simulation environment is used to collect experimental data by using the body motion controller Leap Motion and the virtual simulation software Unity3d [12]. By collecting and analyzing the operation time data of a certain type of equipment control panel by people in the loop simulation equipment operation simulation experiment, the positioning movement time allocation maps of each area of the equipment interface are obtained, and the data basis is provided for the model establishment.

3.1. Experimental design of control panel data measurement
The purpose of the experimental design is to measure the operating time of the upper extremities when performing the positioning exercise, and to provide data basis for the objective function $f_2$. The experiment is carried out on the 736mmx276mm equipment control panel. It is divided into 15 small panels of the same size. Each small panel size is 147mmx92mm, and the center location is respectively arranged with 1 trigger button S1, S2, … S15, the sequence number order is the same as that in Figure 1, as shown in Figure 4:

![Figure 4 Experimental data test function modules](image)

3.2. Experimental steps
The virtual simulation scene is designed by using the virtual simulation software Unity3D. The equipment console in the virtual environment is consistent with the actual equipment size, and the Leap Motion is used to read the hand data and complete the operation task. The experimental scene is shown in Figure 5.

![Figure 5 Index finger positioning exercise test renderings](image)

(a) human in the loop (b) Virtual experiment environment

The white sphere in the virtual environment is the starting point of the finger movement, that is, the position of the O point in Figure 4. When the index finger triggers the sphere, the program starts timing. The subject rapidly leaves and clicks the button on the console. The button triggers red, the program ends timing, and a positioning motion is completed. The time data is recorded in the text file. Before the experiment, 10 students with normal eyesight and computer skills were invited to take part in the experiment, and the ability of virtual hand control in virtual environment was repeatedly practiced, so as to achieve a quick and accurate proficiency of one click task. After each click of the
task is completed, the index finger returns to the white ball position to start the next button. To avoid interference between the left and right hands, the right hand hits the right three column, and the left hand clicks the left two column. Click order follows from left to right, near and far. The experimental process satisfies the experimental requirements of Fiits’ law.

4. Case study and analysis

4.1. Case study
Taking the man-machine control console of the command and control cabin of certain weapon equipment as the experimental research object, as shown in Figure 6. The functions of the control devices are grouped. Correspondences of the functional modules are shown in Figure 6. The size of the control panel is 736mm x 276mm, which is divided into 15 areas, and the size of each small panel is 92mm x 147mm.

![Figure 6: Certain allegations cabin console original layout](image)

The author invites ten operational trumpeters of a certain type of weaponry equipment to fill out in detail the frequency of use and the degree of importance of each module of the control panel of the command and control panel. Finally, the experts are asked to check the experimental data and obtain reliable experimental data. It lays a solid foundation for the control panel layout optimization design model. Through the analysis of the model, LINGO can be used to solve the problem. Layout of the control panel is performed by integrating the global optimal solution of the objective functions $f_1$, $f_2$ and the ergonomic constraint relationship, the final layout optimization result of Figure 7 can be obtained.

![Figure 7: Optimize the layout of the final results](image)

4.2. Layout analysis
The blue curve in Figure 8 represents the distribution of operation loss distance and operation time in the panel area of the panel layout before the optimization in Figure 6. The red curve represents the distribution of operating distance loss and operating time MT of each panel area in Figure 7 after optimization of layout results. The new layout reduced the total operating loss distance from 487.60cm to 348.64cm, and the optimization ratio reached 28%, as shown in Figure 8(a). The operating time is reduced from 38976ms to 32804ms, and the optimization ratio reaches 16%, as shown in Figure 8 (b). From this we can see that the 0-1 linear programming model of this paper has played a significant role in optimizing the operation loss distance and operation time of the control panel layout.
5. Conclusion
(1) In this paper, the upper body reachability probability distribution map of the upper limbs is obtained by performing upper body reachability statistics for each area of a certain type of equipment operation panel.

(2) The upper limb positioning movement characteristics research experiment is designed. Through the simulation of the upper limb positioning movement in the loop simulation equipment operation, the operation time data of a certain type of equipment manipulation interface is collected and analyzed, and the positioning movement time distribution maps of various areas of the equipment interface are obtained.

(3) A 0-1 linear programming model of equipment operation panel is established and solved. The layout results play a very good optimization effect in minimizing distance loss and operation time. The final layout results meet the frequency of use, importance, sequence of use in the ergonomics criteria.

The research method can provide theoretical and methodological basis for the future design of the new ground-to-air missile weaponry equipment manipulator interface and other industrial control room control panel multi-objective design, optimize operation efficiency in multiple directions and improve the fluency and accuracy of the operation.

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