Design of Wearable Communication Equipment in Metallurgical Noise Environment

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Abstract. The environmental noise and earplug usage in metallurgical industry can easily compromise the information transmission among workers, which increases the risk of accidents. Therefore, in the context of steel rolling operation, developing a wearable device that can transmit instructions through graphical language is necessary to replace the traditional form of body communication. Based on field investigation, questionnaire survey, and in-depth interview, the communication demands of front-line operators were acquired, and information about working site, working language, and communication gestures was collected. The functional operation process and electronic product components were selected based on the wearability, displaying effects, and environmental applicability of image transmission carriers. An intelligent wearable device combining gesture and touch screen controls was designed and further developed. The device is easily put on and taken off, possesses high flexibility, and allows natural interactions. This design minimizes the communication difficulty caused by noise during steel rolling operation, and ensures that information, in required languages, can accurately transmit towards different regions of the metallurgical industry through visual information transmission.

1. Environmental investigation
The environmental noise intensity, brightness, and temperature during steel rolling operation were investigated. The noise intensity of nine representative regions was measured by the method of key points distribution [1] and evaluated using the equivalent A-level (L_Aeq). Then, the average L_Aeq [dB (a)] [2] was calculated. According to GB/T 50087-2013, the 8 h equivalent sound level limit of industrial enterprise production workshop is 85 dB (a). However, the noise intensity in the operational area was higher than the national standard, which introduces significant difficulties in voice signal transmission and operational communications. At the meantime, according to the national standards, on-site workers should wear anti-noise earplugs [3], whereas, the earplugs attenuate both the noise intensity and the voice signal, increasing the difficulty of on-site instantaneous communication during work. Miscommunication or delayed communication not only compromises working efficiency, but also threatens the life and property safety of front-line workers [4].

According to GB/T 5700-2008, the grid distribution method was used to measure the brightness of the factory. The typical operational area was selected for measurement, which was 50 cm × 80 cm away from machines and equipment, and divided by 10 cm × 10 cm grids [5]. The GM1040B handheld illuminance meter, with a range of 0-200000 Lux, was used to measure the illumination of the grid center point at the height of the ground. The average illuminance in the area was calculated as: $E_{av} = \sum E_j (M \times N)$, where $E_{av}$ is the average illumination [6], in the unit of Lx; $E_j$ is the illuminance of the $i^{th}$ measuring point, in the unit of Lx; $M$ is the number of longitudinal measurement points; $N$ is the
number of transverse measurement points \cite{7}. According to the measurements, the average illuminance was 41.8 Lx, and the illuminance of all areas was less than 60 Lx, among which the illumination of heating furnace operational area was higher than other area. In accordance with the value (150 Lx) recommended by the national lighting design standard GB 50234-2013, the overall brightness of the operational area was relatively low.

The heat in the workshop is mainly generated by the heating furnace in billet. The closer to the heating furnace, the higher the temperature will be. The central body temperature of the machine tool was approximately 50°C, which was equivalent to the outdoor temperature when keeping far away from the machine tool. The measurement of temperature ensures an appropriate working environment, and provides the basis for material selection during production.

2. Analysis of user demands

2.1. User investigation

On-the-spot visits and one-to-one in-depth interviews with the workers were performed to collect information about communication mode, communication equipment, and their actual demands and suggestions, for establishing a hierarchical structure model, which was subdivided into three sub-layers. The first layer was the graphic wearable communication device; the second layer included the product appearance (A1), product performance (A2), product structure (A3), and product operation (A4); the third layer was: smooth modeling (C1), easy carrying (C2), good graphic recognition (C3), comprehensive common information (C4), comfortable wearing (C5), strength and durability (C6), easy operation (C7), and convenient maintenance (C8).

2.2. Interactive feature extraction

Using QFD theory (the theory to guide enterprises to design products meeting customer needs), the weight of user demands was obtained, and the weight relationship between user demands and product technical characteristics was determined. Based on the demand analysis, the demand index and weight were input the house of quality, the technical characteristics of nine products and their autocorrelation matrix according to user’s suggestions were determined, and the house of quality was constructed. No mutual inclusive relationship among the technical characteristics was observed, demonstrating that after validating the input, the importance of technical requirements could be obtained by:

\[ M_f = \sum_{i=1}^{I} R_{ij} \times W_i \] \cite{8}, where \( R_{ij} \) is the value of technical requirements in the relationship matrix of the house of quality; \( W_i \) is the importance of the demand of steel rolling workers. In accordance with the calculation, the primary reference factors of the design were as follows: "graphic content", "comprehensive information", "small volume", "simple interface", and "strong material and structure".

3. Designing practice of communication equipment

3.1. Interaction design

Gesture and touch screen inputs were set according to the demands of different works. The users could select the control mode at the main interface. Gesture recognition \cite{9} captures gesture changes through sensors, and then generates operational command, which is convenient for workers to understand operational instructions on time and transmit the command by hand-eye-combination. The arms are naturally drooped at the initial state, and the waving direction conveys instructions of "up, down, left, right, front, and back". For example, "swing up" conveys "move up". In addition, the gestures in each direction can be combined with the "clockwise circle drawing" of "acceleration" and "counterclockwise circle drawing" of "deceleration" to obtain the instructions of acceleration and deceleration in corresponding directions, respectively. For example, "swing up and draw circle clockwise" conveys "fast up".

Interferences caused by a large number of actions during real operation are inevitable. Therefore, the system feedback and mechanism of error gesture revocation were set to improve the gesture
recognition rate of the equipment. Once the user’s hand posture is captured, the device will display graphic feedback with vibration enhancement to ensure that he/she receives the feedback timely and comprehensively, and then selects "confirm sending" or "cancel sending". If the gesture input by the user is incorrect, the signal can be cancelled by "repeatedly swinging the hand".

Screen input can be completed by directly clicking correspondent icons of instructions in the matching app of the wearable device. Once the device is turned on, the user first enters the main interface and selects the receiver of command information. The user can slide the touch screen page left or right to select the required command, and select "confirm sending" or "cancel sending" at the confirmation interface. If "confirm sending" is selected, the user can continue to input; if "cancel sending" is selected, the previous menu will be displayed. In addition, the user can return to the previous menu at any interface by clicking the middle button of the screen toolbar. Eventually, receiver can receive vibration prompts, sender's identity information, and instructive graphics.

3.2. Product function design
To realize the functions including hand tracking, command graphic display, touch control, vibration, and sending/receiving information, the optional materials of each function module were analyzed. Gesture recognition sensor, displaying screen, vibration motor, signal transmission, and power supply module matching with the scheme of product design at the highest degree were selected. Thus, the interactive function and graphic language transmission were realized.

1) Sensor selection. At present, infrared sensors and motion tracking sensors can be used for gesture recognition. Infrared sensing gesture recognition sensor can recognize the direction of hand movement through infrared induction \[10\], but it needs to be worn by one hand and controlled by the other hand, which does not meet the requirements of one hand control in this paper. Motion gesture recognition sensor is based on microchip patented gestic technology. It adopts electric near-field sensing technology and integrates 3D gesture recognition and motion tracking into an interactive sensor. The sensor can recognize the clockwise / counterclockwise rotation direction and the movement direction of the hand within an effective range of 0~10 cm. The instruction can be generated by the movement of one hand, which is suitable for the wearable device research and development in this paper, and provides interactive signal input mode.

2) Displaying screen selection. To serve as the output module of graphics, the displaying screen requires appropriate displaying color, size, and flexibility. Flexible organic light emitting diode (OLED) screen is foldable \[11\] and highly durable, which is associated with low probability of accidental damage. In addition, compared with liquid crystal display (LCD) screen, OLED screen has a smaller size, lower power consumption, and stronger endurance. However, at present, the availability of OLED screen is still low, and the materials, equipment, and technology for production, as well as the packaging approach still have certain limitations. Thin-film transistor liquid crystal display (TFT-LCD) is a technology combining microelectronics and LCD. It has various sizes, the minimum of which can be as little as 1 inch, which meets the requirements of the screen size for the wearable equipment; the high resolution of TFT-LCD screen can guarantee the graphic displaying quality of the product; the tolerable temperature range of TFT-LCD (from -20°C to 50°C) can ensure the production under high temperature in metallurgical industry. TFT-LCD screen can be easily maintained and long lasting, which meets the technical requirements of "solid materials and easy maintenance". Moreover, TFT-LCD screen manufacturing is highly automated, which can be used for large-scale industrial production \[12\]. Therefore, TFT-LCD was selected as the displaying module for the product.

3) Selection of signal transmission module. Serial devices can connect to WiFi network through the signal transmission module, thus realizing transmission of information among devices as well as the control and management of the Internet \[13\], which is compatible with the original software platform. Data transmission through the serial port transparent transmission mode can send and receive data for further analysis \[14\].
4) Selection of vibration motor. Vibration is used to remind the user once information has been received. In this study, flat vibration motor was selected to convert electrical signals into mechanical vibration senses.

5) Selection of motherboard. Arduino Integrated Development Environment (IDE) can sense environments through a variety of sensors. Through light control, the motors and other devices can provide feedbacks and influence the environment. We selected Arduino uno as the main motherboard of the equipment. In addition, codes can be input to IDE through Arduino programming language, compiled into binary files, and burned into the microcontroller on the motherboard to execute operational commands.

3.3. Product modelling design
To fulfill the rigid demands by metallurgical workers, the wearable equipment needs to be long-term integrated into working clothes, but with a flexible disassembly system. Therefore, a piece of 20 cm × 7 cm wool was sewed on cuff for equipment connection [15], as shown in Figure 1.

The main body of the product has a length of 20 cm and a width of 7.5 cm. The upper and lower surfaces were sewn and reinforced with black fabric to protect internal circuits. The middle layer was composed of electronic components, batteries, and circuit-connecting wires. The back was sewn with Velcro hook surface, which covers the equipment to the sleeve of the working clothes. A 2.8-inch touch screen was at the center front, with a U-shaped hole at left and a magic tape (10 cm × 4.5 cm) at right. The bandage can be inserted into the U-shaped hole, folded, and bonded to adjust the tightness of the product, which ensures that the product is sealed from end to end at the wrist to prevent the equipment from falling off. The overall design of the product is shown in Figure 1.

3.4. Product production
An Arduino uno, a 3D gesture recognition sensor, a vibration motor module, a 32 g SD card, a signal transmission module, a 2.8 inch touch screen, a 7.4 V lithium battery, several needles, several DuPont wires, a 20 cm Velcro, a 7.5 cm × 25 cm polypropylene ribbon, an epoxy resin soft adhesive, an epoxy resin curing agent, a cloth flexible adhesive, a thread, an electronic scale, a measuring cup, a stirring rod, and a brush were prepared.

The black nylon polypropylene ribbon used on the surface layer of the product was wearing-resistant and possesses dimensional stability, but without fire and chemical corrosion resistance, which is not sufficient to protect the internal circuits. Therefore, an epoxy resin soft adhesive coating was added on the surface of the ribbon, which enhanced the shell width, fire resistance, and corrosion resistance of the product without compromising its flexibility. The epoxy resin was used as the main body, mixed with the epoxy resin curing agent at a mass ratio of 3:1, and stirred clockwise until no wire drawing was observed. The bubbles in the glue were eliminated via standing. The colloid was applied evenly on the trimmed ribbon surface, and stood for 48 hours under dry condition until completely cured. Finally, the screen window was cut. The entire manufacture process is shown in Figure 2.
Figure 2. Production steps of product surface materials.

Arduino uno circuit board was used as the main hardware for circuit connection. The codes were burned through USB cable. The main control board was first tested, and the blink code was burned to verify if the main board was functioning well. After the icon was converted to the device that can recognize 16-bit RGB-565 format, the screen pin was connected to the motherboard for memory, touching, and image displaying tests. A 7.4 V rechargeable and discharged lithium battery was connected to supply power for the product. With no conflict between the sensor and the screen pin, the gesture recognition sensor and the main control board were welded. Afterwards, other expansion parts of the main control board were connected to finalize the circuits of the entire product.

Figure 3. Connection of components.

The software Arduino IDE was used to input program codes and develop interactive functions. Before the program was written, corresponding libraries of displaying function, touching function, and sensor function were installed. The entire codes were initially built by logic function to improve the
displaying effects and details, and then they were burned to the main control board through USB interface. Finally, the circuit layer and the surface material were stitched. The actual final product is shown in Figure 4.

4. Gesture recognition function test
A total of 20 individuals were randomly selected to wear the product, and each of them performed 14 groups of prescribed gestures twice. The sensor identification results output by the serial port monitor was recorded at each time following completion of the action. A total of 560 groups of gesture input data were collected during the test, and the device recognition is shown in Table 1. We found that the average recognition rate of the product was 87.6%, which validates its effectiveness and feasibility for gesture recognition. Among all gestures, the recognition accuracy of single gesture was relatively high, and that of combined gesture was varied. Specifically, the commands of "accelerating to the right" (drawing a circle to the right and then clockwise) and "decelerating to the left" (drawing a circle to the left and then counterclockwise) were easily confused with the instructions of "accelerating" and "decelerating", respectively. Therefore, gesture recognition training of the products is still essential for the users.

Table 1. Gesture recognition monitoring.

| instructions                  | Correct number | Error situation          | instructions                  | Correct number | Error situation          |
|-------------------------------|----------------|--------------------------|-------------------------------|----------------|--------------------------|
| Move up                       | 39             | 1 Move down              | Shift left                    | 37             | 3 Slow down and move left|
| Accelerate upward movement    | 37             | 1 Move up, 2 Accelerate  | Accelerate left shift         | 31             | 3 Shift left, 4 Accelerate, 2 Move down |
| Deceleration upward           | 36             | 2 Move down, 2 Slow down | Slow down and move left       | 26             | 2 Shift left, 1 Accelerated downshift, 11 Slow down |
| Move down                     | 40             | -                        | Shift right                   | 38             | 1 Accelerate right shift, 1 Shift left |
| Accelerated downshift         | 36             | 1 Move down, 3 Accelerate| Accelerate right shift        | 27             | 2 Shift right, 1 Move down, 10 Accelerate |
| Deceleration down             | 36             | 1 Slow down and move left, 1 Move down, 2 Slow down | Decelerate right shift        | 33             | 3 Shift right, 1 Move up, 3 Accelerate |
| Accelerate                    | 38             | 1 Shift left, 1 Accelerate upward movement | Slow down                   | 37             | 3 Accelerate right shift |

5. Conclusion
Based on the essential demands during work, communication habits, and equipment suggestions of the on-site operators, five designing elements including "graphical content", "comprehensive information", "small volume", "simple interface", and "solid material and structure" are extracted from the results of in-depth interviews and QFD theoretical analyses. Relying on an innovative design practice, an intelligent wearable device with gesture control and touch screen control is developed, which
minimizes the communication difficulties caused by noise during steel rolling operation. In addition, the device is easily installed/disassembled, highly flexible, and naturally interactive.

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