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A Study on the Design of Elderly-Following Monitoring Robots Based on AHP

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Abstract: This study constructs a design model for elderly-following monitoring robots based on the Analytic Hierarchy Process (AHP), establishing four evaluation dimensions: functional adaptability, interaction usability, environmental adaptability, and safety reliability. Design priorities were determined through expert scoring and weight analysis, followed by practical optimization of structure and interaction. Results indicated that this approach can effectively enhance the scientific rigor of robot design and improve user satisfaction, providing a feasible solution for the design of intelligent elderly-care products.

Keywords: Analytic hierarchy process; Human-robot interaction; Industrial design; Follow-up monitoring robot; User experience

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1. Introduction

With the acceleration of global population aging, the demand of elderly individuals for medical care, daily life assistance, and emotional companionship has increased significantly. Traditional home-based elderly care models are gradually becoming insufficient to meet these growing needs, highlighting the necessity of intelligent and multi-layered elderly care service systems. Intelligent follow-monitoring robots, which integrate artificial intelligence and Internet of Things technologies, can provide health monitoring, emotional interaction, and daily assistance, offering both safety assurance and companionship for older adults living alone [1]. However, existing follow-monitoring robots still face challenges in interaction design, functional performance, and safety assurance. Interface designs often fail to fully consider the perceptual and cognitive characteristics of elderly users; the functional modules are insufficiently matched to individual needs; and data security protection remains inadequate, resulting in low user acceptance.

Based on Human-Computer Interaction (HCI) theory, this study applies the Analytic Hierarchy Process to construct an optimization model for the design of follow-monitoring robots [2,3]. The research quantifies the influence weights of design elements across four dimensions: functional adaptability, interaction usability, environmental adaptability, and safety reliability. It then proposes interaction optimization and safety design strategies tailored to the characteristics of elderly users. The findings aim to provide theoretical foundations and methodological support for the systematic design of intelligent elderly care products.

2. Research methodology

2.1. Overview of the analytic hierarchy process

The Analytic Hierarchy Process is a systematic multi-criteria decision-making method proposed by operations researcher Thomas L. Saaty in 1980 [4]. It decomposes complex problems into three levels, goal, criteria, and indicators, to structure decision-making tasks hierarchically, making the problem clear and manageable. In practice, designers can conduct pairwise comparisons of indicators at each level and calculate their weights based on expert scoring or experiential judgments. This approach converts subjective experience into quantitative data, thereby providing a scientific basis for complex design decisions.

In this study, AHP is applied to the design of a follow-monitoring robot for older adults, as illustrated in **Figure 1**. The design process begins with defining design objectives through literature review, user research, and competitive product analysis, followed by the establishment of an indicator system covering functional adaptability, interaction usability, environmental adaptability, and safety reliability [5]. Experts' evaluations and user feedback are integrated to construct a judgment matrix, and weight coefficients for each dimension are calculated using the eigenvalue method, followed by a consistency test [6]. Experts then score each indicator, and the corresponding weights are derived. Finally, structural design and interaction optimization are carried out based on the weight results, leading to the formation of the robot design solution and its iterative improvement process. This methodology combines AHP with practical design practice, providing a systematic and scientific decision-making foundation for robot design.

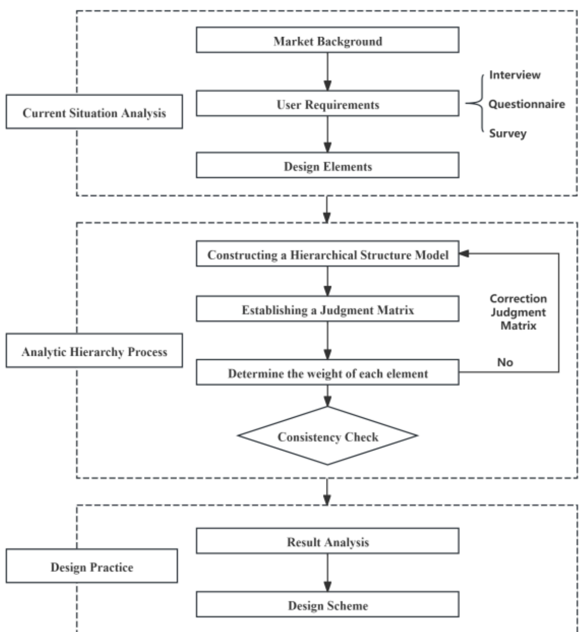

Figure 1. Design process of the elderly follow-up monitoring robot based on analytic hierarchy process.

2.2. Construction of the design indicator system

This study adopts a mixed-method approach to conduct a comprehensive user needs analysis [7]. In-depth interviews were carried out with elderly individuals of varying cognitive abilities and health conditions to understand their primary needs and usage preferences when interacting with follow-monitoring robots. 12 mainstream commercial products were analyzed in terms of their functions and user experience to identify existing shortcomings in health monitoring, interaction design, and safety performance, thereby clarifying the key directions for product optimization. Lastly, 100 standardized questionnaires were distributed to elderly users and caregivers, with 87 valid responses collected. These quantitative data serve as the foundation for the subsequent design model development.

Based on multi-source data, a user needs analysis model was constructed. The goal level is the design of an age-friendly follow-monitoring robot, aimed at developing interactive, user-friendly and safe, reliable intelligent devices [8]. The criteria level includes four core dimensions: functional adaptability, interaction usability, environmental adaptability, and safety security. The indicator level is further refined into 18 measurable parameters, as illustrated in **Figure 2**.

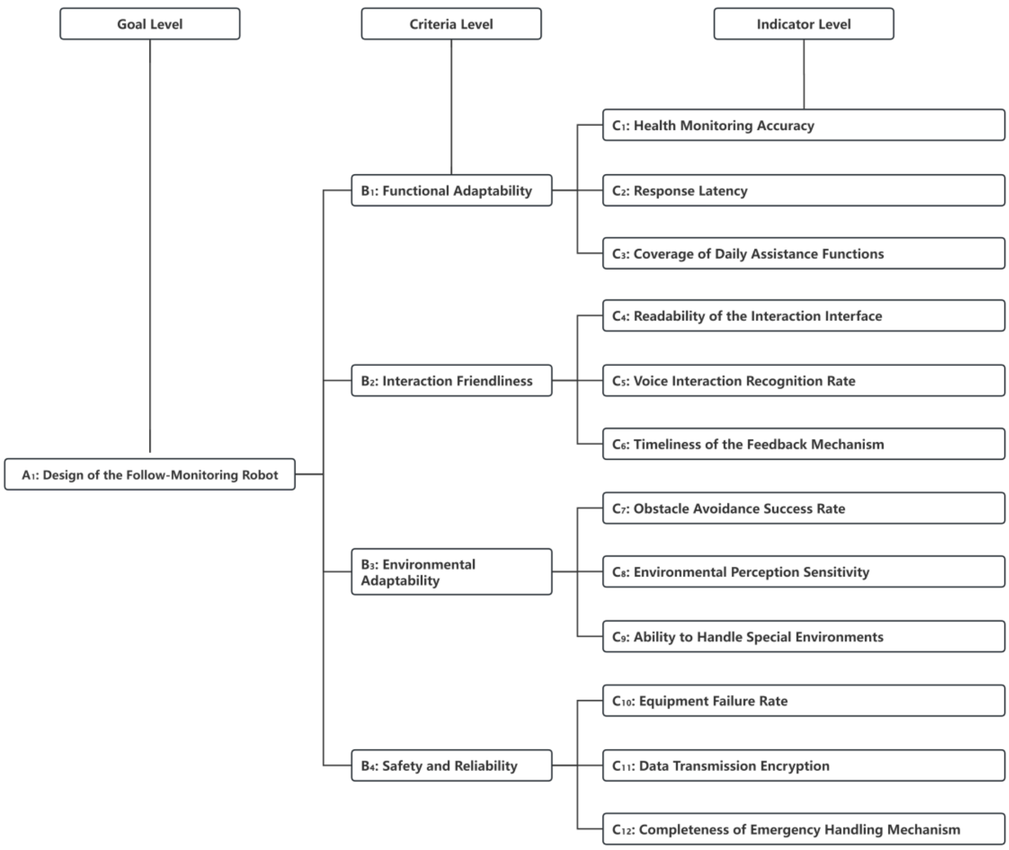

Figure 2. Hierarchical structure model of the follow-up monitoring robot.

2.3. Construction of the judgment matrix and weight calculation

In the process of constructing the judgment matrix and calculating the demand weights, a multi-level judgment matrix was established to quantitatively compare the relative importance of the design elements of the follow-monitoring robot. The “1–9 scale method” was used to compare factors at both the criteria level and indicator level.

A total of 12 experts were invited to participate in the evaluation, including 2 professionals from robot manufacturing and sales, 3 industrial design faculty members, and 7 graduate students in industrial design engineering. The arithmetic mean and accumulation method were applied to calculate the weights at each level, and the results are presented in **Table 1** and **Table 2**. After constructing the judgment matrix, the formula is expressed as follows in Equation (1).

$$W_i = \frac{1}{n}\sum_{j=1}^{n} \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} \left(i = 1,2,\cdots, \ n\right) \tag{1}$$

Table 1. Judgment matrix and weights of the criteria level for the design of the follow-monitoring robot

A	B_1	B_2	B_3	B_4	Weight
B_1	1.00	3.00	2.00	4.00	0.4658
B_2	0.33	1.00	0.50	2.00	0.1611
B_3	0.50	2.00	1.00	3.00	0.2771
B_4	0.25	0.50	0.33	1.00	0.0960

Table 2. Judgment matrix and weights of the indicator level for the design of the follow-monitoring robot

A	C_1	C_2	C_3	Weight
C_1	1.00	3.00	5.00	0.6479
C_2	0.33	1.00	2.00	0.2299
C_3	0.20	0.50	1.00	0.1222

To reduce the subjectivity of expert scoring and ensure the validity of the weighting coefficients, a consistency test was conducted on the model. The maximum eigenvalue (λ_{max}) and the consistency index (CI) were calculated as follows:

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{2}$$

Specifically, after calculating the weights of each judgment matrix, the Consistency Ratio (CR) was used for validation. The Random Index (RI) was obtained from the reference table, and the Consistency Ratio (CR) was calculated as follows:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{3}$$

When the CR value is less than 0.1, it indicates that the matrix has satisfactory consistency; if the CR value is greater than or equal to 0.1, the corresponding judgment matrix needs to be adjusted. The value of the average Random Consistency Index (RI) is obtained from reference tables. The results of the consistency test are shown in **Table 3**.

Table 3. Results of the consistency test

Factor	λ_{max}	CI	RI	CR
A	4.05	0.0167	0.89	0.0188
B_1	3.02	0.0100	0.52	0.0192
B_2	4.10	0.0333	0.89	0.0374
B_3	4.08	0.0267	0.89	0.0299
B_4	4.03	0.0100	0.89	0.0112

According to **Table 3**, the CR values of the matrices are 0.0188, 0.0192, 0.0374, 0.0299, and 0.0112, all of which are less than 0.1. Therefore, all judgment matrices pass the consistency test, and the results are considered valid. Based on this outcome, the indicator weights of each influencing factor can be further integrated to obtain the overall goal weights of the design factors, providing a scientific basis for the design of the follow-monitoring robot.

3. Results and discussion

3.1. Weight results and analysis

Based on the analysis, the influencing factors at both the criterion and indicator levels for the design of the follow-and-monitor robot need to be comprehensively ranked individually to determine the priority of indicators that serve as the core foundation for industrial design practice, as shown in **Table 4**.

Table 4. Overall objective weight ranking

Goal level	Criteria level		Indicator level		Composite weight	Ranking
	Criterion	Weight	Indicator	Weight		
Design of the follow-monitoring robot	Functional adaptability	0.4658	Health monitoring accuracy	0.6479	0.3020	1
			Response latency	0.2299	0.1068	3
			Coverage of daily assistance functions	0.1222	0.0569	10
	Interaction friendliness	0.1611	Readability of the interaction interface	0.5390	0.0866	5
			Voice interaction recognition rate	0.2973	0.0479	9
			Timeliness of the feedback mechanism	0.1638	0.0264	12
	Environmental adaptability	0.2771	Obstacle avoidance success rate	0.4826	0.1337	2
			Environmental perception sensitivity	0.3274	0.0907	4
			Ability to handle special environments	0.1900	0.0526	11
	Safety and reliability	0.0960	Equipment failure rate	0.5263	0.0505	7
			Data transmission encryption	0.2837	0.0272	13
			Completeness of emergency handling mechanism	0.1900	0.0182	14

The weight analysis results indicate that functional adaptability (0.4658) holds the highest proportion among all criteria, establishing it as the pivotal factor in the design. Priority should be given to ensuring the stability and accuracy of core modules, such as health monitoring and follow control. Environmental adaptability (0.2771) ranks second, requiring integration with residential spatial characteristics to enable smooth robot movement across different rooms and furniture arrangements. Although interaction friendliness (0.1611) carries a relatively lower weight, interface layout, font size, and information presentation remain crucial in influencing the user experience of elderly individuals. Safety and reliability (0.0960), while comparatively smaller in weight, are essential for long-term product operation and data protection, thus still warranting sufficient attention.

3.2. Design optimization process

Advanced sensors and algorithms are employed to achieve real-time health tracking, safety monitoring, and health assessments. The follow distance and speed can be adjusted according to the elderly user's mobility, with real-time alerts for environmental hazards. Health monitoring integrates physiological indicators to provide personalized recommendations, while supporting customizable functions to accommodate individual differences, avoiding both redundancy and insufficiency.

The robot's environmental perception is enhanced to detect obstacles, stairs, and other potential risks. Optimized obstacle-avoidance algorithms ensure flexible navigation during following, and testing confirms adaptability to various home lighting and floor conditions, guaranteeing stable operation. The design focuses on the characteristics of elderly users, simplifying operational procedures to support independent use. The interface features large fonts and high-contrast design, with multi-modal feedback through sound, flashing lights, and haptics. Emotional design elements are incorporated to enhance interaction experience and user acceptance [9].

High-quality components are selected to reduce failure rates, encryption technologies ensure data security, and an emergency mechanism is established, allowing immediate activation in case of equipment malfunction or if the elderly user encounters an emergency.

3.3. Design practice

During the design process of the follow-and-monitor robot, we first conducted demand research and analysis, then constructed an Analytic Hierarchy Process model to determine the weight distribution of requirements. Based on the weight proportions of each element, design concepts for the robot were developed from the perspectives of functional adaptability, interaction friendliness, environmental adaptability, and safety reliability. These concepts were subsequently visualized using tools such as hand-drawn sketches and 3D modeling, with the final solutions presented in **Figure 3** and **Figure 4**.

Figure 3. Design sketch proposal of the follow-and-monitor robot.

Figure 4. Design rendering of the follow-and-monitor robot.

The follow-and-monitor robot developed in this study is grounded in the practical needs of elderly users, with optimizations spanning four key aspects: functionality, interaction, environment, and safety. The robot integrates health monitoring and autonomous follow capabilities, enabling stable navigation and obstacle avoidance in indoor environments. Its interface is designed to be clear and intuitive, with simplified operations for ease of use by older adults. Structurally, it incorporates anti-tip and emergency stop mechanisms to ensure operational safety. The overall design balances practicality and reliability, providing convenient and safe daily living assistance for the elderly.

4. Discussion

From the perspective of the alignment between weight results and design practice, the AHP model effectively resolved the issue of "ambiguous design priorities": quantitative analysis clearly identified "functional adaptability as the core," directing 60% of R&D resources toward health monitoring and follow functions, thereby avoiding "diffusing efforts evenly." Consistency checks verified the scientific validity of the weight data, eliminating expert subjective bias. The ranking of indicator layers refined design directions, making technical implementation more targeted.

The study found differences in elderly users' perceptions of emergency functions, with some failing to fully recognize their importance. While safety is a critical design element, its acceptance and trust among elderly users still need improvement. This phenomenon highlights a contradiction between user perceptions and actual needs. The relatively lower weight of safety-related indicators does not imply that such functions are unnecessary; rather, it reflects some elderly users' insufficient awareness of risks. Therefore, emergency functions should be retained in the design, and efforts should be made to enhance users' understanding and willingness to use safety features through illustrated manuals and voice guidance during initial use [10].

In terms of technical implementation and cost control, a balance must also be struck. For instance, while the "response delay" indicator carried a high weight, upgrading to high-end processors would increase costs by approximately 30% [11]. By optimizing algorithms to eliminate redundant recognition candidates, delays were controlled within 1.5 seconds, meeting performance requirements without excessively raising the product price [12]. This strategy achieved a rational balance between demand and cost, while ensuring the product's long-term operational stability and user trust.

5. Conclusion

Based on AHP, this study constructs and validates a design optimization model for a follow-and-monitor robot for elderly users. The findings indicate that functional adaptability is the primary factor influencing the design. During the design process, priority should be given to ensuring the stability and precision of core functional modules, such as health monitoring and following control, to meet the basic usage needs of elderly users. Environmental adaptability also plays a key role in enhancing system reliability, as the robot must be capable of efficient navigation and obstacle avoidance in home environments. Interaction friendliness significantly impacts user experience; thus, the design should optimize interface layout, simplify operational logic, and enhance information readability to improve intuitiveness and comfort of use. Although safety and reliability have a relatively lower weight, they remain irreplaceable in ensuring long-term stable operation of the device and strengthening user trust.

This study provides data-driven support and methodological guidance for the design of intelligent elderly care robots, while also offering insights for industrial design practices. Future research could incorporate emotion recognition, adaptive learning, and personalized interaction to make the robots more intelligent and better suited for home-based elderly care.

Disclosure statement

The authors declare no conflict of interest.

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