

Article

Comprehensive Performance Evaluation of Earthquake Search and Rescue Robots Based on Improved FAHP and Radar Chart

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Abstract: To effectively enhance the adaptability of earthquake rescue robots in dynamic environments and complex tasks, there is an urgent need for an evaluation method that quantifies their performance and facilitates the selection of rescue robots with optimal overall capabilities. In this paper, twenty-two evaluation criteria are proposed based on a comprehensive review of existing evaluation criteria for rescue robots across various domains. The evaluation criteria are tested using the test modules developed by the National Earthquake Response support service, obtaining the corresponding values for each criterion. Then, the weights of the criterion layer and comprehensive evaluation index are determined based on the analytical hierarch process and trapezoidal fuzzy number complementary judgment matrix, and a new consistency test method is proposed. The qualitative evaluation and quantitative analysis are effectively combined to overcome the subjective influence of expert decision-making. Additionally, the performance of three earthquake search and rescue robots is comprehensively evaluated and ranked using the improved radar chart method as an empirical example. Finally, the robustness of the ranking results is examined using a weight sensitivity analysis. The results of the sensitivity analysis demonstrate the effectiveness and feasibility of the proposed method, thereby providing valuable insights for developing multi-objective optimization control strategies and structural designs for earthquake search and rescue robots.

Keywords: improve fuzzy analytic hierarchy process (IFAHP); evaluation criteria; comprehensive evaluation; improved radar chart; earthquake search and rescue robots; sensitivity analysis



Citation: Li, L.; Zhao, Z. Comprehensive Performance Evaluation of Earthquake Search and Rescue Robots Based on Improved FAHP and Radar Chart. *Appl. Sci.* **2024**, *14*, 3099. <https://doi.org/10.3390/app14073099>

Academic Editor: José António Correia

Received: 22 February 2024

Revised: 24 March 2024

Accepted: 3 April 2024

Published: 7 April 2024



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1. Introduction

As crucial equipment for earthquake rescue operations, a comprehensive set of multi-dimensional and multi-level performance indexes for earthquake search and rescue robots can effectively serve as the key evaluation criteria to reflect the efficiency and quality of rescue operations [1]. Consequently, evaluating the performance of earthquake search and rescue robots in terms of both quantitative and qualitative measures proves to be a challenging task due to the diversity and complexity of performance indexes.

Numerous theories have been proposed to evaluate the performance of rescue robots. Li, Yutan, et al. [2] have evaluated the walking performance of coal mine rescue robots in terms of various performance indexes, including the maximum trench width, maximum obstacle height, maximum climbing angle, and stair climbing capability. Zhang, Di et al. [3] have assessed the locomotion capabilities of an earthquake search and rescue robot in terms of its performance in flat terrain traversal, climbing steps, rotational movement, ascending slopes, and aerial maneuverability. Zhao, Jing, et al. [4] have evaluated the efficiency of quadruped rescue robots based on their capabilities in survival, locomotion, operation, and environmental interaction. Baek, Jun, et al. [5] have conducted an analysis of the impact factors of mobile rescue robots for human body detection, encompassing communication time and life body identification. However, solely relying on these performance indexes is insufficient for evaluating the performance of earthquake search and rescue robots.

Additionally, there is limited literature available on exploring the hierarchical structure of performance evaluation indexes specifically designed for rescue robots. Therefore, further research is required to develop an evaluation approach for rescue robots.

The selection of an appropriate evaluation method for performance indexes is beneficial for analysts and evaluators in efficiently evaluating alternatives and determining the optimal alternative [6]. When selecting multiple earthquake rescue robots, it is essential to consider the conflicting performance indexes. For instance, during the evaluation of various indexes, certain robots may opt to enhance the mass-volume ratio in order to improve the motion stability of the rescue robot. However, this increase in ratio might have a detrimental impact on obstacle clearance performance when confronted with narrow or low-height rescue environments. Therefore, it is necessary to address this issue by employing a multi-criteria decision-making (MCDM) approach that incorporates various factors [7]. The process of multi-criteria decision-making consists of several stages, including (1) defining objectives, (2) selecting the criteria for measuring those objectives, (3) identifying alternatives, (4) assigning weights to the selected criteria, (5) utilizing a suitable mathematical algorithm to rank the alternatives [8].

Numerous methods have been suggested in existing literature and employed to tackle various MCDM issues [9]. The technique for order preference by similarity to ideal solution (TOPSIS) is a multi-attribute decision-making method based on distance measurement, which calculates the distance between each attribute and the ideal solution, as well as the distance between each attribute and the anti-ideal solution. The relative preference of each attribute is determined by calculating the weighted sum of these two distances, and the optimal alternative can be determined [10]. However, when the information in the environment is incomplete or inaccurate, TOPSIS technology may not fully consider these uncertain factors, resulting in inaccurate decision results. Cluster analysis, a robust method widely employed in MCDM, efficiently uncovers the underlying rules and structures within datasets. By grouping similar alternatives into classes, cluster analysis reduces data dimensionality and facilitates comprehension and processing. Unlike supervised learning techniques, cluster analysis is an unsupervised learning approach primarily aimed at identifying natural clusters or groups when dataset labels are ambiguous or challenging to determine. However, it can only categorize alternatives as either similar or dissimilar without providing information on their relative superiority or importance. Artificial neural networks (ANN) have gained traction in MCDM for addressing complex problems and approximating multi-attribute utility functions by learning the mapping relationship between input and output, but their successful integration requires substantial data support to optimize performance. The analytic hierarchy process (AHP) is extensively utilized in the field of multi-criteria decision-making and has demonstrated its effectiveness in addressing performance decision-making issues of rescue robots [11]. Yutan Li et al. [2] have utilized AHP to evaluate the walking performance of walking mechanism in coal mine rescue robots. Wang, Shipeng et al. [12] have employed AHP to evaluate the technical indexes, performance indexes, and structural indexes for scheme selection during the design and manufacturing process of new water-wading rescue robots. The primary advantages of AHP lie in its ability to simultaneously handle multiple criteria, analyze complex problems hierarchically, and provide a clear and comprehensible model structure. Moreover, the AHP method effectively integrates qualitative and quantitative data, enabling decision-makers to consider both types of information when making decisions and facilitating more comprehensive and accurate evaluations. However, it is important to note that the process of factor comparison often entails inherent uncertainty and subjectivity, as experts may encounter difficulties in establishing a precise scale for comparing two factors. Under such circumstances, employing the classical AHP method may yield decision results that lack accuracy. As an effective approach for handling incomplete or fuzzy information, the fuzzy analytic hierarchy process (FAHP) offers a more comprehensive and scientifically grounded basis for decision-making in the presence of incomplete information and complex causal relationships among variables. The fundamental concept behind FAHP lies in its

consideration of interdependencies between indexes, enabling a clearer understanding of how changes in one index impact others. Consequently, FAHP method has gained widespread application across various domains. For instance, in control engineering, it can optimize control system design; within artificial intelligence [13], it addresses fuzzy logic problems; management science benefits from its ability to tackle complex decision-making challenges [14]; and multi-criteria decision-making relies on FAHP as an indispensable tool.

However, the aforementioned evaluation methods lack a visual mode, which hinders the clear interpretation of the evaluation results. This not only obscures the significance of each index but also complicates the ranking of rescue robots based on their performance. The radar chart method takes into account both the overall strength and coordinated development across various aspects, thereby providing a more comprehensive reflection of an evaluated object's advantages [15]. The most notable feature of radar charts lies in their capacity to visually represent the status of a rescue robot and accurately rank similarly performing rescue robots, thereby facilitating a more comprehensive understanding of their performance [16,17]. However, the weight of each index is fixed and cannot be adjusted according to the actual circumstances in the conventional radar chart. This limitation may result in an underestimation of the pivotal role played by certain indexes during the evaluation process, as well as an overestimation of the significance of other indexes. In conventional radar charts, index values solely impact the shape without influencing evaluation results [18]. Nevertheless, in practical evaluations, index values often become a focal point of attention. Therefore, this paper proposes an improved radar chart that incorporates both index weights and values into its design to ensure more accurate and comprehensive evaluation results.

This paper proposed an improved fuzzy analytic hierarchy process (IFAHP) based on an improved radar chart to evaluate and rank the performance of earthquake search and rescue robots, ultimately facilitating the selection of the search and rescue robot with superior overall performance. Firstly, a comprehensive set of evaluation indexes for search and rescue robots is constructed to address the limitations associated with using a single evaluation index. Subsequently, three types of alternatives for earthquake search and rescue robots are evaluated using performance tests to obtain a comprehensive evaluation set for the corresponding criteria. Additionally, the criterion layer and the weight of each evaluation index are determined using hierarchical analysis and a trapezoidal fuzzy number complementary judgment matrix, and a new consistency test method is proposed, aiming to mitigate the influence of subjective factors on expert decision-making results. Subsequently, the performance indexes of earthquake search and rescue robots are analyzed, followed by a comparative assessment of the overall performance among different types of such robots using an improved radar chart. Finally, the accuracy and effectiveness of the proposed method on three types of earthquake search and rescue robots are verified in practical examples.

The remaining sections of this paper are organized as follows: the related evaluation criteria and hierarchical structure model are shown in Section 2. The content and process of the performance test are described in Section 3. Then, the introduction to the improved fuzzy analytic hierarchy process is given in Section 4. A comprehensive and visual evaluation method for ranking and selection for the performance of earthquake search and rescue robots is presented in Section 5. Finally, the proposed method is illustrated with a case study of the three types of earthquake search and rescue robots in Section 6. A sensitivity analysis of the results is presented in Section 7. The main conclusions, limitations, and future works are summarized in Sections 8 and 9.

2. Evaluation Criteria

The fundamental performance requirements of rescue robots encompass robust survivability to ensure seamless access to rescue sites, versatile mobility for diverse mission execution, precise detection and perception capabilities to enhance rescue efficiency, and rapid communication abilities for enhanced human–robot collaboration and further im-

proved rescue efficiency [19,20]. In the process of conducting a comprehensive literature review on the related concepts of performance evaluation for rescue robots, a series of targeted and practical evaluation criteria from multiple perspectives have been proposed. To enhance the depth and professionalism of our criteria research, we collaborated with an experienced team of experts who possess rich practical experience and excellent theoretical knowledge in the field of rescue robots. These experts have profound expertise in mechanical engineering, automation control, information and communication engineering, as well as disaster prevention and mitigation engineering. Their professional knowledge and unique perspectives provide robust support for our research endeavors. Via extensive collaboration with them, thorough discussions regarding the performance evaluation criteria for rescue robots have been thoroughly discussed.

The evaluation of rescue robots' performance is a comprehensive problem involving multiple factors and levels. The evaluation criteria in this paper are classified into two levels, namely main criteria, and sub-criteria, to facilitate calculation and analysis. The critical factors for assisting rescuers in efficiently searching for survivors at disaster scenes and enhancing rescue efficiency include robust survivability, versatile mobility, precise detection perception capabilities, and rapid communication abilities. Consequently, the main criteria for evaluating rescue robots encompass survivability, mobility, detection perception ability, and communication control ability. The following segment provides concise explanations regarding the interpretations, industry norms, and factors that influence the sub-criteria.

2.1. Survivability

The survivability of rescue robots primarily reflects their reliability, while ensuring an adequate power supply is crucial to sustain uninterrupted rescue operations. The power supply unit is often identified as a limiting factor in the performance of rescue robots, as frequently reported in numerous literature studies [21,22]. The resilience of rescue robots is directly proportional to the operational duration and walking distance when supplied with energy by the power unit [23,24]. Additionally, their continuous ability to initiate and cease operations ensures sustained execution of rescue missions [25]. Therefore, the survivability evaluation criteria are presented in Table 1, providing comprehensive details for analysis.

Table 1. The survivability evaluation criteria.

Main Criteria	Corresponding Criteria	Literature Sources
Survivability	Continuous working time with an independent power supply	[20–23,25]
	Continuous walking distance with an independent power supply	[20–23,26]
	Success rate of continuous start, working, stop	[24,27]

2.2. Mobility

The mobility of rescue robots is paramount for effective disaster relief efforts. Only with robust mobility can they adeptly navigate the complex disaster environment, expeditiously and efficiently execute rescue tasks, and provide timely assistance to trapped personnel. When designing a robot for rescue missions, it is crucial to consider its ability to operate in confined spaces, such as collapsed buildings, caves, or rugged terrains. Factors like debris, uneven terrain, and narrow passageways impose limitations on the physical design of the rescue robot; hence, it must be compact. Consequently, optimizing the size and mass of the rescue robot becomes essential for maneuvering through narrow spaces and overcoming obstacles [28]. To ensure effective operation in these environments, designers need to meticulously evaluate the positioning of the rescue robot's center of gravity [29]. Specifically, when crossing obstacles, maintaining a low center of gravity is imperative to ensure optimal traction capability [30,31]. This precautionary measure prevents tipping over or loss of balance that could hinder task completion. Therefore, designers must thoughtfully consider both structure and weight distribution to achieve an appropriate center of gravity position. In addition to the aforementioned factors, the

continuous advancement and widespread use of re-configurable modular rescue robots have made the mechanical transformation success rate a crucial factor affecting the mobility of such robots. This is because their ability to smoothly adapt and transform into different forms in complex environments directly impacts their task completion success [32,33]. Meanwhile, the rescue robot deployed in disaster sites must possess exceptional climbing, obstacle-crossing, running, and turning capabilities to effectively adapt to diverse terrain environments [34,35]. Moreover, it is imperative for the rescue robot to demonstrate flexible control proficiency and robust load-bearing capacity in order to efficiently transport rescue equipment and materials, promptly reach locations where individuals are trapped, and execute rescue operations [36,37]. Therefore, the mobility evaluation criteria are presented in Table 2, providing comprehensive details for analysis.

Table 2. The mobility evaluation criteria.

Main Criteria	Corresponding Criteria	Literature Sources
Mobility	Mass-to-volume ratio	[29–31,38]
	Unit pressure exerted by the tracked device on the ground	[2,25,39,40]
	Maximum speed of wheel motion	[23,29,34,35,41]
	Minimum turning radius	[42–45]
	Maximum width across trenches	[29,34,35,46,47]
	Maximum height of obstacles to be overcome	[29,34,35,46,48]
	Maximum angle for climbing	[29,34,35,46,49]
	Number of steps climbed per unit time	[29,34,35,46,50]
	Success rate of mechanism transformation	[32,33,51]
	Success rate of path planning	[36,37,52,53]
	Subversive resistance on complex road surfaces	[23,29–31,41]
	Smoothness of walking on complex road surfaces	[30,31,41,54]

2.3. Perception Detection Ability

The significance of rescue robots in rescue operations is self-evident, primarily due to their advanced environmental perception and detection capabilities, as well as their exceptional capacity to efficiently locate and identify victims. In hazardous, unpredictable, and intricate rescue environments, the prompt and accurate identification and localization of victims under harsh conditions while covering extensive search areas within limited timeframes are pivotal factors for evaluating the detection and perception abilities of rescue robots [55–57]. Therefore, the detection perception evaluation criteria are presented in Table 3, providing comprehensive details for analysis.

Table 3. The detection perception evaluation criteria.

Main Criteria	Corresponding Criteria	Literature Sources
Detection perception ability	Probability of life body identification	[55–59]
	Maximum radius for effective search	[55–59]
	Maximum depth for effective search	[55–57,59]

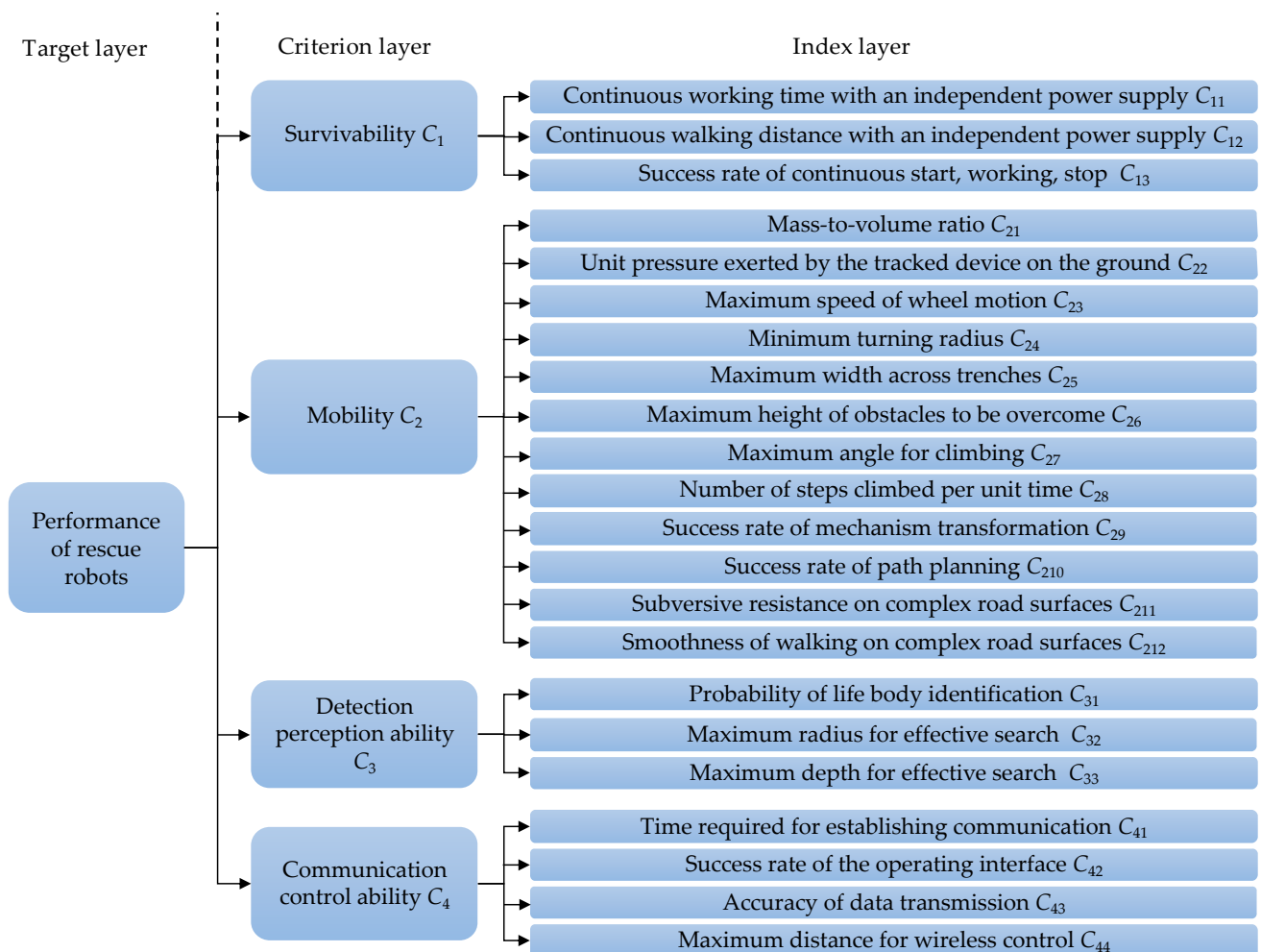
2.4. Communication Control Ability

The communication control ability of rescue robots plays a crucial role in the successful execution of their missions. This ability primarily involves real-time communication between the operator and the rescue robot [60], ensuring precise control by the operator and effective information collection and transmission by the rescue robot to better assist rescue personnel in accomplishing tasks. Key elements of the communication control ability encompass command accuracy and comprehensive signal processing [61]. Therefore, the communication control evaluation criteria are presented in Table 4, providing comprehensive details for analysis.

Table 4. The communication control evaluation criteria.

Main Criteria	Corresponding Criteria	Literature Sources
Communication control ability	Time required for establishing communication	[21,26,60,61]
	Success rate of the operating interface	[58,60–62]
	Accuracy of data transmission	[56,57,60,61]
	Maximum distance for wireless control	[60,61,63]

The corresponding hierarchical structure of these criteria is established based on the above comprehensive analysis and quantification of the evaluation criteria for rescue robots, as illustrated in Figure 1. The hierarchical structure allows for a clear evaluation of the rescue robot's performance on each individual criterion and how these criteria impact the overall performance of rescue robots.

**Figure 1.** The hierarchical structure for the performance of rescue robot.

3. Performance Test

At present, a wide range of rescue robots are available in the market, each with distinct characteristics and functionalities. To comprehensively understand and evaluate their performance, it is essential to have diverse samples for testing and research purposes. Therefore, this paper selects three types of earthquake search and rescue robots developed by the Shenyang Institute of Automation as the subjects of investigation. These three robots are denoted as Sample A, Sample B, and Sample C with their prototypes depicted in Figure 2.

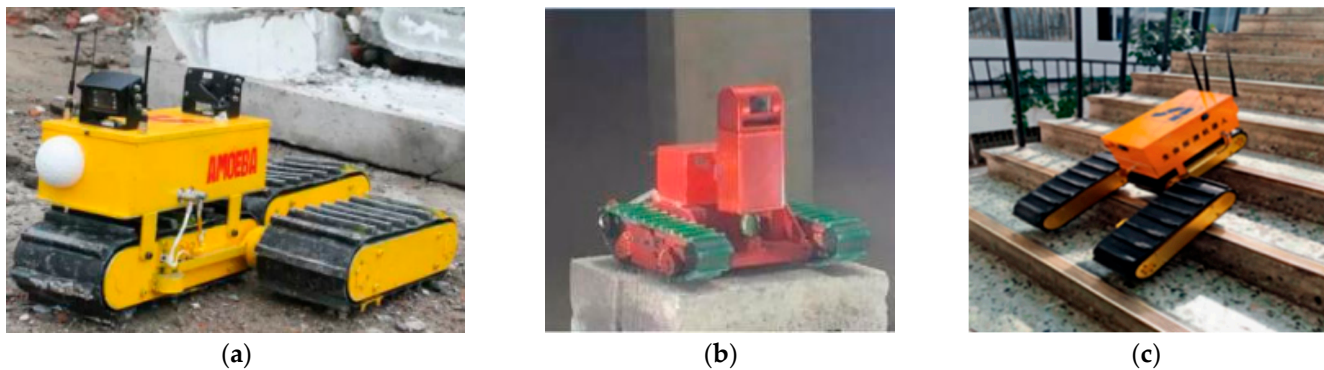


Figure 2. Prototype of the three types of earthquake search and rescue robots: (a) Sample A; (b) Sample B; (c) Sample C.

Each robot exhibits unique design concepts, functional configurations, and practical applications. The related parameters of the three robots are shown in Table 5. Subsequently, a detailed analysis and comparison of these three robots will be conducted.

- Sample A: The robot is designed for exploring ruins and features three independently driven tracks. The position of these tracks can be adjusted to suit various rescue environments and tasks, allowing the robot to transform into linear, triangular, or side-by-side configurations. Meanwhile, the robot can penetrate into the ruins and utilize its own infrared camera and sound sensor to transmit real-time image and voice information from inside the ruins back to the console, enabling rescuers to promptly identify survivors' locations and assess their surrounding environment.
- Sample B: According to the terrain characteristics in rescue environments, the robot's track geometry can be adjusted to enable it to switch between wheeled and tracked motion modes. Meanwhile, the robot is capable of entering hazardous situations and conducting survivor search and environmental detection tasks using its own camera, temperature, and humidity sensor, as well as a toxic and harmful gas sampling device. Additionally, the cloud platform can be deployed vertically alongside the robot into elevator shafts and caves to enhance the rescuer's visibility range.
- Sample C: The mobile mechanism adopts a modular chain structure to ensure its capability to navigate complex terrains. Depending on different rescue environments and tasks, the robot can transform into three distinct configurations: triangular, D-shaped, and side-by-side. Meanwhile, the robot integrates life detection technology with life detection radar, video, and audio information. Additionally, it is capable of penetrating non-metallic materials to effectively detect the vital signs of survivors using this life detection technology.

Table 5. The related parameters of three robots.

Samples	Name	Mass	Volume
Sample A	The deformable robot for searching ruins	20 kg	$520 \times 420 \times 250 \text{ mm}^3$
Sample B	The wheel-track composite exploration robot	15 kg	$360 \times 320 \times 280 \text{ mm}^3$
Sample C	The intelligent life detection robot	25 kg	$520 \times 420 \times 250 \text{ mm}^3$

The performance test of the three types of earthquake rescue robots is conducted to obtain the evaluation criteria's values. In this paper, a series of test modules designed by the national earthquake response support service are used to test the performance of the three types of earthquake rescue robots [64]. The real arrangement of each module is shown in Figure 3. The next section will present the specific content of each module.

1. The dynamic slope test module is a linkage mechanism consisting of a hydraulic lifting platform and a slope device featuring an adjustable continuous slope ranging

from 15° to 16° . Additionally, the module allows for variation in the slope material to assess the climbing ability under different friction conditions.

2. The adjustable cross-cone turning module is designed with a 90° turning angle, allowing for an adjustable cone slope and automatic twisting of the guide frame on both sides to adapt to the cone. The flexibility of turning and lateral balance ability at different speeds can be tested.
3. The adjustable ridge side slope module consists of multiple plates joined together by twisted plates. The slope can be adjusted, and the complexity of the side slope can be modified by altering the direction in which the plates are joined, allowing for testing of both passing ability and balance capability.
4. The complex pavement interspersed construction module consists of a grid and multiple wooden piles. By adjusting the interspersed positions of wooden piles, it is possible to simulate intricate terrains and assess flexibility and passing capacity.
5. The test module of the pipeline consists of torsional splicing techniques. Rotating the entire pipeline simulates complex pipelines and tests their ability to pass through narrow spaces by adjusting the vertical position.
6. The adjustable wave pavement module is constructed by combining multiple plate strands to form a collapsible fan shape. The handle allows for modification of the wave spacing, while one end of the simulated staircase can be elevated to assess the performance on uneven road surfaces and steps.
7. The adjustable slope-crossing module consists of two sets of independent slopes connected face to face, and the spacing can be adjusted according to the need to test the ability to cross the gully.
8. The test module consists of multiple depressions that can be filled with various materials (such as sand and stone columns) to simulate different road conditions.
9. The re-configurable terrain test module consists of a vertical arrangement of hundreds of wooden cubes, forming a rectangular, square matrix. Each individual cube is equipped with an independent lifting and locking device, enabling adjustable height settings. This design allows for the simulation of various complex terrain structures and facilitates the testing of irregular pavement traversal capabilities.

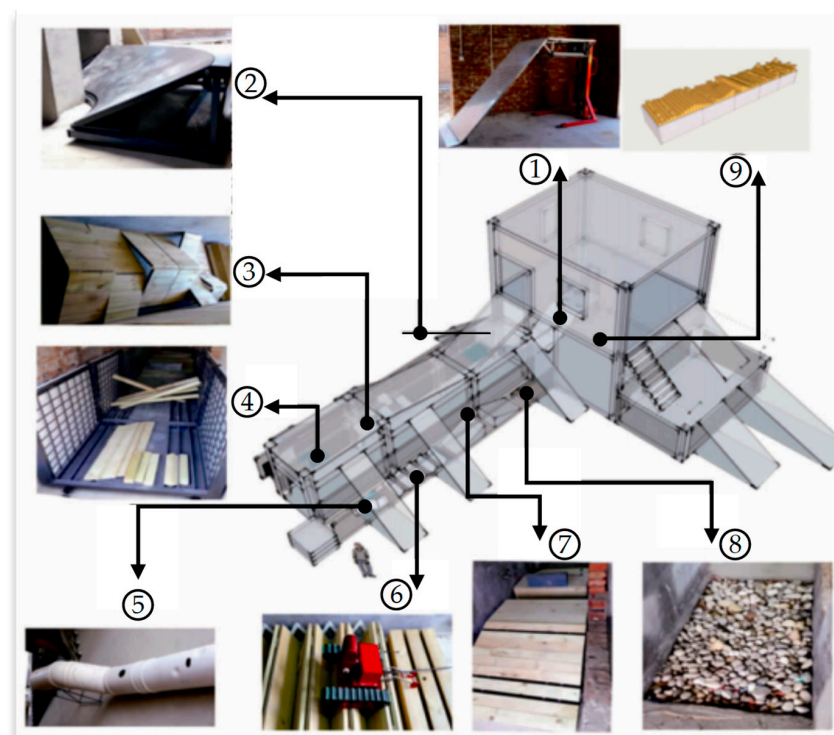


Figure 3. The real arrangement of each module.

The test environment is equipped with real-time monitoring functions. It includes a total of 11 monitoring cameras, a temperature and humidity sensor, six fixed installation wireless nodes, and six randomly scattered wireless nodes. By utilizing the multi-source wireless environment sensing network, remote monitoring of the testing process and environmental information are achieved, as depicted in Figure 4.

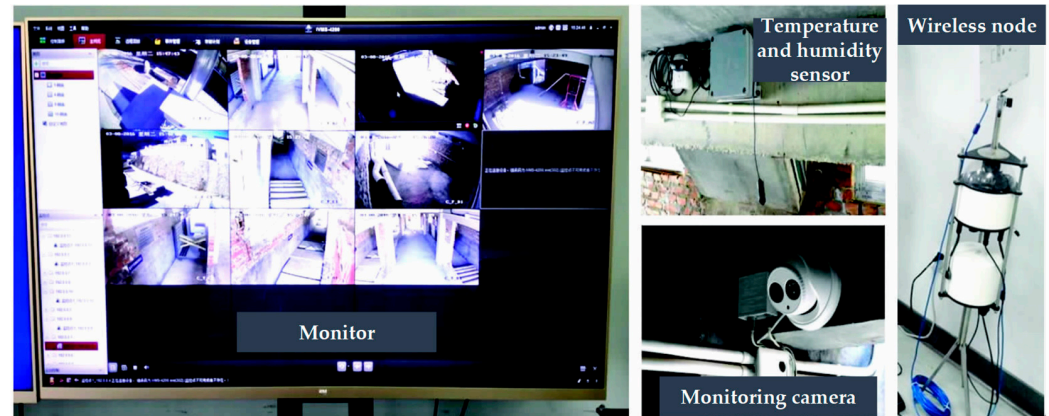


Figure 4. Real-time monitoring and detection hardware.

In this paper, the test standard for each criterion shown in Figure 2 is based on the General specifications of ground robots for search and rescue in ruins (GB/T 37703-2019) [65]. The index test methods are derived from the existing methods [66] used at the national earthquake emergency rescue training base. The performance indexes test results are presented in Table 6. All tests for performance indexes were conducted three times, and the average value was considered as the test result. Additionally, a list of test methods for some important indexes is provided as follows:

1. Testing the values of continuous working time with an independent power supply. When the battery is fully charged, turn on the power switch and operate the robot at low speed (one-third of its maximum speed of wheeled motion) until the robot automatically shuts down due to low power. When the robot starts moving, the stopwatch starts, and when the robot stops moving, the stopwatch stops. The recorded time can be taken as the value of continuous working time with an independent power supply.
2. Testing the values of maximum obstacle height. The initial height of the vertical obstacle is set to be 10 cm, with a width of 5 cm. The measurement is conducted three times. If at least one of the three measurements passes, then the height is increased by 2 cm; if none passes, then the height is reduced by 2 cm. This process is repeated for three measurements. The loop continues until it reaches a point where further increase or reduction is not possible anymore, and the maximum value of height is recorded as the value of maximum obstacle height.
3. Testing the values of walking smoothness on complex road surfaces. The complex bumpy rubble road surface with a length of 50 m is set up. An acceleration sensor is installed on the robot body device in the vertical direction. The robot travels at a uniform speed at 50% of its maximum wheel motion speed. After the movement, the acceleration curves in the vertical direction are output, and the average value of the peak of the curve is represented as a_z is calculated. The value of a_z can be taken as the value of walking smoothness on complex road surfaces.
4. Testing the values of life body identification probability. The organisms are placed at the 70% maximum effective search radius and the 70% maximum effective search depth. Each experiment is conducted five times, and the probability of successful perception can be calculated as the value of life body identification probability.

5. Testing the values of maximum wireless control distance. The initial value of the wireless control distance is set to 10 m. The measurement is conducted three times. If the robot can be successfully controlled at least once out of the three measurements, then the distance is increased by 1 m; if unsuccessful, it is reduced by 1 m. This measurement process is repeated three times. The loop continues until no further increase or reduction is possible, and the maximum value of distance can be recorded as the value of maximum wireless control distance.

Table 6. The specific results for each criterion.

No.	Test Results of the Samples			Normalization Results		
	Sample A	Sample B	Sample C	Sample A	Sample B	Sample C
C ₁₁ (h)	3.13	20	4.35	0.067	0.594	0.105
C ₁₂ (m)	3000	6000	4000	0.222	0.556	0.333
C ₁₃ (%)	100	90	90	1.000	0.875	0.875
C ₂₁ (kg/m ³)	1083	1442	980	0.404	0.917	0.257
C ₂₂ (Pa)	2200	4688	2500	0.960	0.462	0.900
C ₂₃ (m/s)	328	100	350	0.430	1.000	0.375
C ₂₄ (mm)	30	15	20	0.000	0.750	0.500
C ₂₅ (mm)	300	250	300	0.500	0.250	0.500
C ₂₆ (mm)	250	200	200	0.500	0.250	0.250
C ₂₇ (deg)	34	30	32	0.700	0.500	0.600
C ₂₈ (pc)	20	14	18	0.565	0.304	0.478
C ₂₉ (%)	90	100	90	0.857	1.000	0.857
C ₂₁₀ (%)	90	70	80	0.875	0.625	0.750
C ₂₁₁ (mm/s ²)	2	7	3	0.889	0.333	0.778
C ₂₁₂ (mm/s ²)	4	5	6	0.857	0.714	0.571
C ₃₁ (%)	70	70	80	0.500	0.500	0.667
C ₃₂ (m)	18	15	20	0.846	0.615	1.000
C ₃₃ (m)	9	7	12	0.353	0.235	0.529
C ₄₁ (s)	40	60	50	0.250	0.750	0.500
C ₄₂ (%)	90	80	90	0.875	0.750	0.875
C ₄₃ (%)	90	80	90	0.857	0.714	0.857
C ₄₄ (m)	500	600	800	0.167	0.333	0.667

4. Improved Fuzzy Analytic Hierarchy Process (IFAHP)

The AHP method integrates qualitative analysis and quantitative calculation to achieve multi-objective decision-making. It is characterized by its simple structure and strong systematic approach, making it suitable for establishing a hierarchical analysis model to evaluate the performance of earthquake rescue robots. By decomposing the complex problem into objectives, criteria, and indexes at multiple levels and angles, the rationality and systematicness of ranking earthquake rescue robots are ensured. Simultaneously, fuzzy theory is employed to fuzzify the process of weight calculation in order to reduce the influence of subjective factors in expert evaluation. Moreover, an improved fuzzy analytic hierarchy process is utilized for determining the weight calculation of earthquake search and rescue robots, and the conversion between qualitative analysis and quantitative computation is illustrated in Table 7.

It can be seen from Table 7 that the trapezoidal fuzzy complementary judgment matrix can be used to replace the judgment matrix of AHP, and the weight calculation can be fuzzified so as to improve the limitations of subjective decision-making of AHP and ensure the objectivity and rationality of the weight calculation of performance indexes of earthquake rescue robots.

Assuming that the performance evaluation of the earthquake search and rescue robots consists of n ($n > 2$) performance evaluation indexes $y_1, y_2, \dots, y_n$, denoted as set $Y = \{y_i, |i \in N\}$ with $N = \{1, 2, \dots, n\}$. The trapezoidal fuzzy number complementary judgment matrix $\tilde{X} = (\tilde{x}_{ij})_{n \times n}$ is derived, where $\tilde{x}_{ij} = [a_{ij}, b_{ij}, c_{ij}, d_{ij}]$ represents the relative

importance of the index y_i compared to y_j , with $a_{ij} \leq b_{ij} \leq c_{ij} \leq d_{ij}, \forall i, j \in N (i \neq j)$ and satisfying $a_{ii} = b_{ii} = c_{ii} = d_{ii} = 0.5, \forall i \in N, a_{ij} + d_{ji} = 1, b_{ij} + c_{ji} = 1, c_{ij} + b_{ji} = 1, d_{ij} + a_{ji} = 1$.

Table 7. Corresponding table of qualitative analysis and quantitative calculation.

Qualitative Language	Trapezoidal Fuzzy Number
Highly significant	(0.8, 1, 1, 1)
Significant	(0.7, 0.9, 1, 1)
Relatively significant	(0.6, 0.8, 0.8, 1)
Average	(0.3, 0.5, 0.5, 0.7)
Less significant	(0, 0.2, 0.2, 0.4)
Insignificant	(0, 0, 0.1, 0.3)
Highly insignificant	(0, 0, 0, 0.2)

4.1. Establishment of Hierarchical Model

As shown in Figure 1, the hierarchical model of performance evaluation indexes for earthquake search and rescue robots takes the comprehensive performance of earthquake rescue robots as the target layer, while the criteria layer comprises four key aspects: survivability, mobility, detection, and perception ability, and communication and control ability. Each criterion contains multiple specific indexes.

4.2. Improved Method of Consistency Test

Assuming the participation of K experts in the evaluation, the complementary judgment matrix for each expert can be established as $\tilde{X}(\tilde{x}_{ij}^k)_{n \times n}$ based on Table 7, where $\tilde{x}_{ij}^k = [a_{ij}^k, b_{ij}^k, c_{ij}^k, d_{ij}^k]$ represents a trapezoidal fuzzy number, $k \in \{1, 2, \dots, K\}, i, j \in N$.

The kernel and kernel operator are introduced to compute the kernel matrix of the complementary judgment matrix for trapezoidal fuzzy numbers, aiming to test the consistency [67]. The kernel of trapezoidal fuzzy numbers $\tilde{x}_{ij}^k$ is defined as follows.

$$\tilde{x}_{\text{ker},ij}^k = \begin{cases} a_{ij}^k, & \text{when } a_{ij}^k = b_{ij}^k = c_{ij}^k = d_{ij}^k \\ \frac{(c_{ij}^k)^2 + (d_{ij}^k)^2 - (a_{ij}^k)^2 - (b_{ij}^k)^2 + a_{ij}^k c_{ij}^k - a_{ij}^k b_{ij}^k}{3(c_{ij}^k + d_{ij}^k - a_{ij}^k - b_{ij}^k)}, & \text{otherwise} \end{cases} \quad (1)$$

The kernel matrix of $\tilde{X}(\tilde{x}_{ij}^k)_{n \times n}$ can be obtained as $\mathbf{X}_{\text{ker}}^k = (x_{\text{ker},ij}^k)_{n \times n}$.

The process of consistency testing is outlined as follows.

1. The kernel matrix of the k -th expert is obtained as $\mathbf{X}_{\text{ker}}^k$, in accordance with Equation (1).
2. According to Equation (2), the consistency index ρ of $\mathbf{X}_{\text{ker}}^k$ can be determined.

$$\rho = \frac{2}{n(n-1)(n-2)} \sum_{i=1}^{n-1} \sum_{j=i+1}^n \sum_{\substack{f=1 \\ f \neq i,j}}^n \left| \tilde{x}_{\text{ker},ij}^k - (\tilde{x}_{\text{ker},if}^k + \tilde{x}_{\text{ker},jf}^k - \frac{1}{2}) \right| \quad (2)$$

If $\rho < \varepsilon$, then $\tilde{X}^k$ satisfies the consistency criterion and proceed to step 7; otherwise, proceed to the next step. $\varepsilon = 0.2$ can be identified as the critical value of the consistency indexes.

3. The eigenvalue matrix $\mathbf{X}_{\text{ker}^*}^k = (x_{\text{ker}^*,ij}^k)_{n \times n}$ can be calculated for the kernel matrix $\mathbf{X}_{\text{ker}}^k$, denoted as follows.

$$x_{\text{ker}^*,ij}^k = \chi(\varphi_i^k - \varphi_j^k) + 0.5 \quad (3)$$

where the vector $\varphi_i^k = \chi^n / (n - 1) + \sum_{j=1}^n x_{\text{ker},ij}^k / \chi^n$ represents the sorted values, where $\chi \geq (n - 1)/2$.

4. The deviation matrix O can be calculated for the kernel matrix X_{ker}^k , where $O = (o_{ij})_{n \times n} = X_{\text{ker}}^k - X_{\text{ker}^*}^k$, $|o_{st}| = \max\{|o_{ij}| : i < j, i, j \in n\}$.
5. If $o_{st} < 0$, proceed to step 6; if $o_{st} > 0$, appropriately decrease $\tilde{x}_{st}^k$ by a value of α , that is, $\tilde{x}_{st,\text{ker}}^k = \tilde{x}_{st}^k - \alpha$, and correspondingly increase $\tilde{x}_{st}^k$ by the same value, that is, $\tilde{x}_{st,\text{ker}}^k = \tilde{x}_{st}^k + \alpha$. Where α represents the adjustment quantity with $0 < \alpha < 1$.
6. If o_{st} remains less than zero, then appropriately increase $\tilde{x}_{st}^k$, denoted as $\tilde{x}_{st,\text{ker}}^k = \tilde{x}_{st}^k + \alpha$, and correspondingly decrease $\tilde{x}_{st}^k$, denoted as $\tilde{x}_{st,\text{ker}}^k = \tilde{x}_{st}^k - \alpha$.
7. If the consistency requirement is not satisfied, proceed to step 1; otherwise, generate output.

4.3. Weight Calculation

According to Equation (4), the evaluation information from various experts is synthesized.

$$\tilde{x}_{ij} = [a_{ij}, b_{ij}, c_{ij}, d_{ij}] = \left[\frac{1}{K} \sum_{k=1}^K a_{ij}^k, \frac{1}{K} \sum_{k=1}^K b_{ij}^k, \frac{1}{K} \sum_{k=1}^K c_{ij}^k, \frac{1}{K} \sum_{k=1}^K d_{ij}^k \right] \quad (4)$$

and $\tilde{X} = (\tilde{x})_{n \times n}$ can be obtained. Then, the weights between each layer and the fuzzy evaluation values of each indexes y_i can be calculated as follows.

$$\tilde{m}(a_i, b_i, c_i, d_i) = \left[\frac{\sum_{j=1}^n a_{ij}}{\sum_{i=1}^n \sum_{j=1}^n d_{ij}}, \frac{\sum_{j=1}^n b_{ij}}{\sum_{i=1}^n \sum_{j=1}^n c_{ij}}, \frac{\sum_{j=1}^n c_{ij}}{\sum_{i=1}^n \sum_{j=1}^n b_{ij}}, \frac{\sum_{j=1}^n d_{ij}}{\sum_{i=1}^n \sum_{j=1}^n a_{ij}} \right] \quad (5)$$

The fuzzy evaluation value of index y_i is expected as follows.

$$J(\tilde{m}_i) = \frac{a_i + b_i + c_i + d_i}{4} \quad (6)$$

The relative weights of each index are determined by normalizing Equation (7).

$$\omega_i = \frac{J(\tilde{m}_i)}{\sum_{i=1}^n J(\tilde{m}_i)}, i \in N \quad (7)$$

where ω_i represents the relative weight assigned to index y_i .

4.4. Normalization Calculation of Index Values

Each attribute of the evaluation criteria is assigned a performance rating, which reflects their respective characteristics. It is a frequent occurrence for performance evaluations to utilize diverse units of measurement for various criteria, thus necessitating the quantification and standardization of these criteria in order to facilitate comparability. The method of linear scale transformation takes into account the maximum and minimum performance ratings for attributes when performing the calculations. This approach offers the benefit of ensuring that the scale measurement falls exclusively within the range of 0 to 1 for every attribute [68]. In general, the evaluation criteria can be categorized into two types: those that emphasize greater and superior relative value (referred to as benefit type) and those that focus on the opposite (referred to as cost type).

For the performance criteria of the three types of earthquake search and rescue robots in this paper, the criteria C_{11} , C_{12} , C_{13} , C_{21} , C_{23} , C_{25} , C_{26} , C_{27} , C_{28} , C_{29} , C_{210} , C_{12} , C_{31} , C_{32} , C_{33} , C_{41} , C_{42} , and C_{43} are benefit type criteria. The criteria C_{22} , C_{24} , C_{211} , C_{212} , and C_{41} are cost type criteria. To ensure ease of plotting and subsequent data processing,

Equation (8) is employed to normalize the benefit type criteria, while Equation (9) is utilized for normalizing the cost type criteria.

$$x_{ij}^* = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}} \quad (8)$$

$$x_{ij}^* = \frac{x_j^{\max} - x_{ij}}{x_j^{\max} - x_j^{\min}} \quad (9)$$

where $x_j^{\max}$ and $x_j^{\min}$ are the maximum and minimum performance ratings for attributes $C_j (j = 1, 2, \dots, n)$ among the alternatives, respectively.

The specific results of the three types of earthquake search and rescue robots (Sample A, Sample B, and Sample C) after testing and normalization are presented in Table 6.

5. Improved Radar Chart

The conventional radar chart method is founded upon the unit circle, where the radial line extending from the center to the circumference serves as the axis of evaluation corresponding to each criterion. The normalized evaluation criteria are plotted on their corresponding axes, and the points marked on these axes are connected in sequence to form a closed polygon. This process yields the radar chart of the evaluated object, as shown in Figure 5a. However, due to the variation in index order, which results in the connection of marker points and leads to polygons of varying shapes, the conventional radar chart method fails to yield a unique final evaluation outcome. Therefore, This paper introduces an improved radar chart method, as illustrated in Figure 5b, to address this issue. The analysis procedure of the improved radar chart method encompasses the subsequent steps.

1. The unit circle, centered at O , is partitioned into n sectors according to a selected set of criteria, where each sector represents the domain corresponding to its respective criterion. By utilizing the equation $\alpha_i = 2\pi\omega_i$, the weights (ω_i) assigned to evaluation criterion X_i are subsequently transformed into central angles (α_i).
2. The axis can be set as sector radius, and the corresponding criterion axis is labeled with the normalized quantitative value of each criterion.
3. The radius (r_i) is considered as the calibration value, while the determination of the central angle (α_i) depends on the weight assigned. This weight is utilized for drawing a circular arc, as depicted in Figure 5b.
4. The evaluation result is derived from the criterion of eigenvectors utilizing the dimensions of both area and perimeter in the improved radar chart [69].

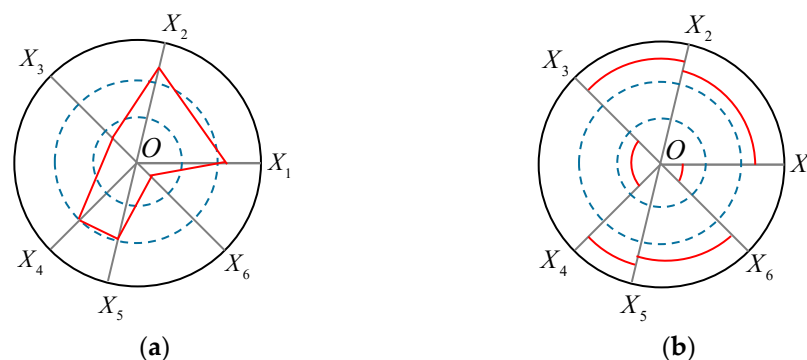


Figure 5. Radar chart: (a) Traditional radar chart; (b) Improved radar chart.

By utilizing the improved radar chart, the values for area S_i and perimeter L_i can be derived, which represent the overall strengths of the evaluated object and the balance between different evaluation criteria. The evaluation object is considered better when the area in the radar chart is larger. In cases where the area remains constant, a larger perimeter

indicates a more balanced set of criteria. The area and perimeter of the radar chart are defined as follows.

$$\begin{cases} S_i = \sum_{j=1}^n \frac{\pi \omega_j r_j^2}{n} \\ L_i = \sum_{j=1}^n \frac{2\pi \omega_j r_j}{n} \end{cases} \quad j = 1, 2, \dots, n \quad (10)$$

where S_i denotes the overall merits of subject being evaluated, L_i signifies the balance achieved among different criteria for evaluation, n represents the number of criteria.

Utilizing the established eigenvectors S_i and L_i , the evaluation vector v_i can be defined as follows.

$$\begin{cases} v_{i1} = S_i / S_{\max} \\ v_{i2} = L_i / (2\pi \sqrt{S_i / \pi}) \end{cases} \quad (11)$$

where $v_{i1} \in [0, 1]$ is the area evaluation value. The magnitude of the value is directly proportional to the degree of comprehensiveness in evaluating the object. Similarly, $v_{i2} \in [0, 1]$ is the perimeter evaluation value. The magnitude of the value reflects a higher level of equilibrium in the fluctuations of the evaluation object's criterion. As a result, the evaluation vector takes into account both the extent of change in the object being evaluated and the level of balance for each criterion.

The geometric average method is adopted to construct the evaluation function. The larger the value is, the better the comprehensive performance is. The formulation of the evaluation function is shown as follows.

$$f(v_{i1}, v_{i2}) = \sqrt{v_{i1} v_{i2}} \quad (12)$$

where $f(v_{i1}, v_{i2})$ represents the comprehensive performance value.

6. Application

Three evaluators who are decision-makers in the field of rescue robots have meticulously chosen, each with distinct backgrounds and extensive experience. The first evaluator has a Ph.D. degree and boasts more than two decades of research proficiency in robot motion control and drive. The second decision maker is an engineer specializing in earthquake rescue robot exploration and rescue technology, who has made significant contributions to the development of testing and evaluation processes. The third decision maker is a member of an earthquake emergency rescue team, possessing extensive knowledge about the practical application scenarios for earthquake rescue robots. According to Table 7, the $\tilde{X}$ value of the criterion layer relative to the target layer was determined by each decision maker. The consistency indexes were calculated as $\rho_1 = 0.1667$, $\rho_2 = 0.0417$, and $\rho_3 = 0.1333$, all falling below the predefined threshold ε .

$$\tilde{X} = \begin{bmatrix} (0.5, 0.5, 0.5, 0.5) & (0.5, 0.7, 0.8, 0.9) & (0.8, 1, 1, 1) \\ (0.1, 0.2, 0.3, 0.5) & (0.5, 0.5, 0.5, 0.5) & (0.5, 0.7, 0.7, 0.9) \\ (0, 0, 0, 0.2) & (0.1, 0.3, 0.3, 0.5) & (0.5, 0.5, 0.5, 0.5) \end{bmatrix}$$

According to Equations (4)–(7), The corresponding weights for the performance of earthquake search and rescue robots can be further obtained $W_A = \{0.2080, 0.2570, 0.2690, 0.2660\}^T$. The results highlight that detection perception capability is recognized as a crucial factor influencing the selection of earthquake search and rescue robots based on their performance. According to the same principle, the relative weight of each index with respect to each criterion can be derived, as illustrated in Table 8.

The findings indicate that the probability of life body identification C_{31} has the most significant impact on the performance of earthquake search and rescue robots, followed by the Success rate of the operating interface C_{42} and Continuous working time with an independent power supply C_{11} . This is because efficiently locating survivors in earthquake debris is the primary function of earthquake search and rescue robots, and the duration of their operation significantly affects search and rescue effectiveness. Ensuring accurate communication data between the robot and operator serves as a crucial guarantee for

successful survivor detection by the earthquake search and rescue robot. However, while enhancing the overall performance of earthquake search and rescue robots, the Mass-to-volume ratio C_{21} , Unit pressure exerted by the tracked device on the ground C_{22} , and Subversive resistance on complex road surface C_{211} are less significant. Additionally, the survivability of the earthquake search and rescue robot is significantly impacted by Continuous working time with an independent power supply C_{11} . The mobility of the earthquake search and rescue robot is significantly impacted by the Maximum width across trenches C_{25} , Maximum height of obstacles to be overcome C_{26} , Maximum angle for climbing C_{27} , Number of steps climbed per unit time C_{28} and Success rate of mechanism transformation C_{29} . The detection perception ability of the earthquake search and rescue robot is significantly impacted by the Probability of life body identification C_{31} . The Communication control ability of the earthquake search and rescue robot is significantly impacted by the Success rate of the operating interface C_{42} .

Table 8. Weights and consistency ratios for each criterion.

Main Criterion	Sub-Criterion	Weight	
		C_i	C_{ij}
C_1	C_{11}	0.2080	0.5753
	C_{12}		0.2740
	C_{13}		0.1507
C_2	C_{21}	0.2570	0.0105
	C_{22}		0.0210
	C_{23}		0.0829
	C_{24}		0.0804
	C_{25}		0.1590
	C_{26}		0.1741
	C_{27}		0.1300
	C_{28}		0.1043
	C_{29}		0.1013
	C_{210}		0.0444
	C_{211}		0.0338
	C_{212}		0.0583
C_3	C_{31}	0.2690	0.6000
	C_{32}		0.2000
	C_{33}		0.2000
C_4	C_{41}	0.2660	0.0664
	C_{42}		0.4839
	C_{43}		0.1768
	C_{44}		0.2730

The data presented in Tables 6 and 8 have been incorporated into the improved radar chart, as depicted in Figure 6a. The findings demonstrate that Sample C offers a viable solution for enhancing the capability of earthquake search and rescue robots to effectively penetrate debris and locate survivors while aiding rescuers in establishing access routes. By utilizing Sample C, the associated risks with search and rescue operations can be mitigated, thereby leading to improved overall efficiency of rescue efforts. The overall evaluation results for both Sample A and Sample B are strikingly alike; however, Sample B demonstrates a higher level of proportionality across all criteria compared to Sample A. After that, by applying Equation (12), the colored sections within the improved radar chart are analyzed to determine their area and perimeter, resulting in the extraction of evaluation results for each respective section.

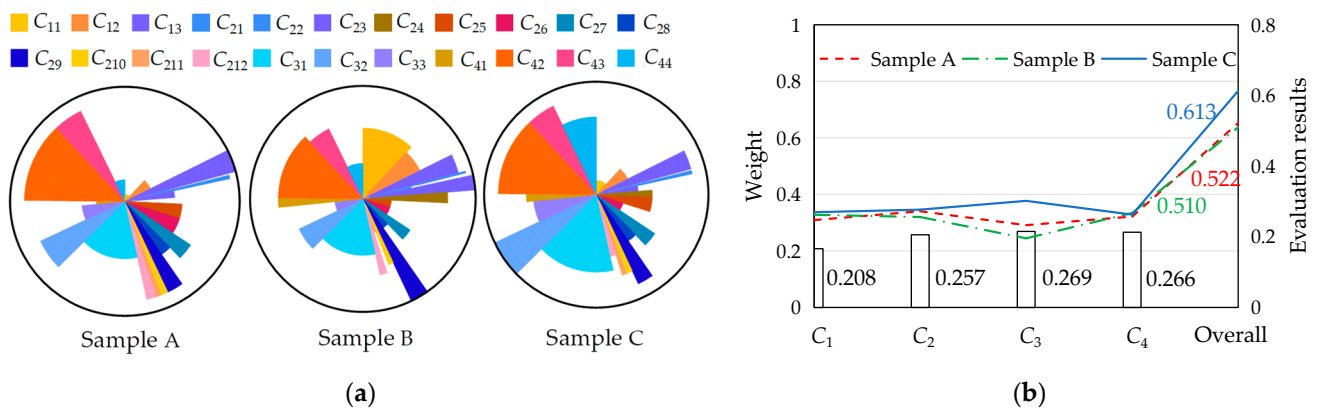


Figure 6. Performance graphic of three types of earthquake search and rescue robots: (a) Improved radar chart; (b) Evaluation results.

The order of performance ranking for the three earthquake search and rescue robots is as follows: Sample C (the evaluation result is 0.613) outperforms Sample A (the evaluation result is 0.522), which in turn outperforms Sample B (the evaluation result is 0.510), as depicted in Figure 6b. The height of a rectangle represents the weight assigned to each criterion, with weights of 0.208 for survivability, 0.257 for mobility, 0.269 for Detection perception ability, and 0.266 for Communication control ability. It is clear that Sample B surpasses in Survivability and Communication control ability but falls behind in Mobility and Detection perception ability. Sample B demonstrates lower walking performance values, including Minimum turning radius C₂₄, Maximum width across trenches C₂₅, Maximum height of obstacles to be overcome C₂₆, Maximum angle for climbing C₂₇, and Number of steps climbed per unit time C₂₈, which are deemed important factors by experts. Consequently, this results in the comparatively inferior performance of sample B among the three earthquake search and rescue robots.

7. Sensitivity Analysis

The weights of criteria may continuously fluctuate throughout the entire project ranking process, potentially impacting the final rankings. Conducting sensitivity analysis facilitates a better understanding of the significance and priority of each criterion, ensuring that crucial factors are adequately considered during the project ranking process. In the case of selecting earthquake search and rescue robots, it is imperative to perform sensitivity analysis to assess their robustness and reliability. This analysis aids in comprehending potential outcomes under different circumstances and facilitates necessary measures to ensure that selected earthquake search and rescue robots remain competent in any situation.

In this paper, the perturbation method is adopted to conduct sensitivity analysis on index weight; that is, after the index weight in the decision is slightly perturbed, the change of scheme ordering under the same decision framework is observed. Assuming that the weight of the initial index C_j is ω_j , the index weight after disturbance changes to $\omega'_j = t\omega_j$, where $0 < \omega'_j < 1$ and $0 < t < 1/\omega_j$. Simultaneously, the weights of other indexes undergo adjustments as $\omega'_k = d\omega_k, k \neq j, k = 1, 2, \dots, m$. The adjusted weights satisfy the following conditions.

$$\omega'_j + \sum_{k \neq j, k=1}^m \omega'_k = 1 \quad (13)$$

Equation (13) can be transformed into $d = (1 - t\omega_j)/(1 - \omega_j)$. Therefore, for each index weight ω_j , when different t is taken, m index weights can be disturbed, and m groups of index weights after disturbance can also be obtained.

According to the variation of Equation (13), different values of t correspond to distinct index weight ω_j . The four criteria weights are individually perturbed, resulting in the derivation of four new criteria weights. It is important to note that when adjusting the

weight of an individual criterion, it is necessary to normalize all criteria weights to maintain consistency in the weighted scheme. The detailed data can be found in Table 9.

Table 9. Weight range for each criterion.

No.	Weight Range				Evaluation Results		
	C ₁	C ₂	C ₃	C ₄	Sample A	Sample B	Sample C
1	0.179 (−0.029)	0.282 (+0.025)	0.293 (+0.024)	0.246 (−0.0200)	0.511	0.512	0.620
2	0.181 (−0.027)	0.297 (+0.040)	0.27 (+0.001)	0.252 (−0.0140)	0.513	0.514	0.619
3	0.237 (+0.029)	0.237 (−0.020)	0.19 (−0.079)	0.336 (+0.070)	0.515	0.516	0.618
4	0.218 (+0.010)	0.208 (−0.049)	0.318 (+0.049)	0.294 (+0.028)	0.518	0.519	0.615

The impact of weight changes on the sample grades can be observed in Figure 7. Sample A is evaluated as the third grade, and Sample B is evaluated as the second grade when the weight of the Survivability criterion decreases from its initial value of 0.208 in Figure 7a to 0.179 or below or when the weight of the Mobility criterion increases from its initial value of 0.257 in Figure 7b to 0.297 or above, or when the weight of Detection perception ability criterion decreases from its initial value of 0.269 in Figure 7c to 0.19 or below, or when the weight of Communication control ability criterion increases from its initial value of 0.266 in Figure 7d to 0.294 or above.

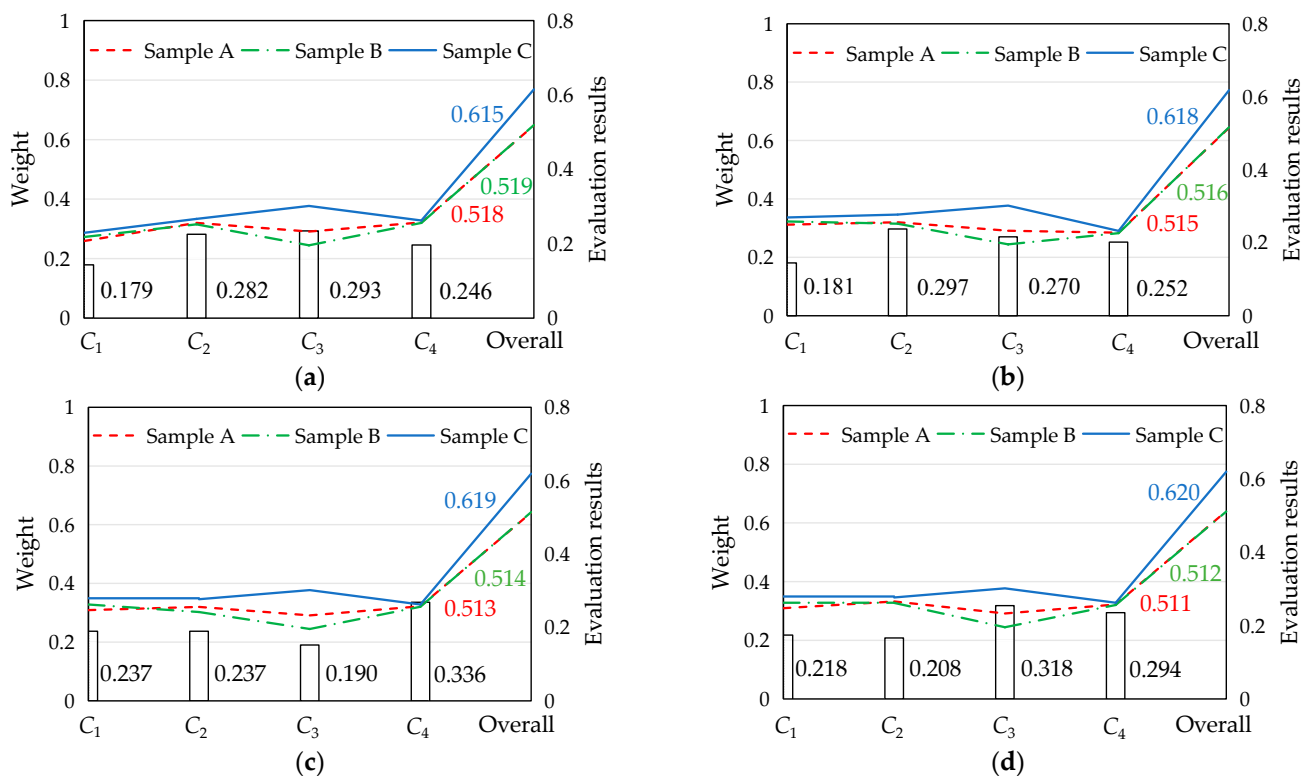


Figure 7. Findings of weight sensitivity analysis: (a) Sensitivity findings regarding the criterion of "Survivability"; (b) Sensitivity findings regarding the criterion of "Mobility"; (c) Sensitivity findings regarding the criterion of "Detection perception ability"; (d) Sensitivity findings regarding the criterion of "Communication control ability".

Sample C consistently maintains a leading position in the performance evaluation of earthquake search and rescue robots, demonstrating its resilience against changes in other criterion weights. This finding suggests that the performance evaluation system for these robots is relatively insensitive to variations in criterion weights, indicating a certain level of

stability and reliability. However, the sensitivity analysis reveals that ranking results are more responsive to changes in the weights assigned to detection perception ability while being less sensitive to alterations in survivability weights. This discovery implies that detection perception ability plays a crucial role in determining the performance ranking of earthquake search and rescue robots, aligning with our expectations as these robots need exceptional perception abilities to swiftly identify and locate trapped individuals within complex environments. Therefore, when formulating performance evaluation criteria for such robots, criteria related to detection perception ability should be thoroughly considered as they significantly enhance actual rescue effectiveness. Simultaneously, it is important to strike a balance among various criterion weights and avoid overemphasizing one aspect at the expense of neglecting other vital performances; this approach ensures better fulfillment of earthquake search and rescue robot requirements during real-life scenarios.

8. Conclusions

Considering the rapid advancements in earthquake search and rescue robot development across various research institutions worldwide, this paper proposes a novel evaluation method for comprehensively analyzing the performance of earthquake search and rescue robots. By horizontally comparing and evaluating the overall performance of multiple earthquake search and rescue robots, the one with superior comprehensive capabilities can be identified.

- (1) The evaluation criteria for the indexes of rescue robots are identified, resulting in the establishment of a comprehensive and hierarchical structure of earthquake search and rescue robots. This structure considers four aspects, namely survival ability, motion ability, detection perception ability, and communication control ability.
- (2) The weights of the criterion layer and comprehensive evaluation index are determined based on the analytical hierarchy process and trapezoidal fuzzy number complementary judgment matrix, and a new consistency test method is proposed. Qualitative evaluation and quantitative analysis are effectively combined to overcome the subjective influence of expert decision-making. The performance of earthquake search and rescue robots is comprehensively evaluated and ranked using an improved radar chart method. Furthermore, sensitivity analysis is conducted to examine how changes in the weights of the main criteria affect the ranking results.
- (3) An in-depth case analysis using three types of earthquake search and rescue robots is presented as examples. The results demonstrate that the evaluation criteria are not only practical but also effectively measure and evaluate the performance and effectiveness of earthquake search and rescue robots. Furthermore, the proposed evaluation method has been validated using practical application, providing valuable insights for optimizing control strategies and structural designs of rescue robots.

9. Recommendations and Future Work

- (1) Evaluating the performance of rescue robots is a highly intricate and time-consuming task that encompasses a vast array of knowledge. Not all potential criteria that could be incorporated into the model were considered in the proposed approach. These criteria may include safety performance criteria and economic performance criteria in relation to the overall performance of rescue robots. Additionally, the inclusion of a new criterion has the potential to alter the ranking of the alternatives.
- (2) The establishment of a scientific and rational evaluation index system is pivotal for the performance assessment of seismic search and rescue robots, as it directly impacts the accuracy and reliability of the evaluation results. Hence, future research should focus on selecting key indexes while eliminating redundant ones to establish a more comprehensive evaluation index system.
- (3) The performance test environment test methods of the index were based on the existing methods of the national earthquake emergency rescue training base. In the

future, it is necessary to propose new index test methods according to the requirements of each index.

Author Contributions: Conceptualization, L.L. and Z.Z.; methodology, L.L.; software, L.L.; validation, L.L.; formal analysis, L.L.; investigation, L.L.; resources, Z.Z.; data curation, L.L.; writing—original draft preparation, L.L.; writing—review and editing, Z.Z.; visualization, L.L.; supervision, Z.Z.; project administration, Z.Z.; funding acquisition, Z.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (Grant No. 12002032).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors thank the National Earthquake Emergency Rescue Training Base for providing the testing site, as well as to the esteemed members of the expert group.

Conflicts of Interest: The authors declare no conflict of interest.

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