Research on a multi-attribute comprehensive evaluation system for unmanned ground vehicles

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Abstract. To promote the development of unmanned ground vehicles, it is very necessary to establish a scientific and reasonable evaluation system for unmanned ground vehicles. This paper analyses the structure and operation of unmanned ground vehicles, and also proposes a multi-attribute comprehensive evaluation system for unmanned ground vehicles. Based on six aspects including environment perception, communication command, behavioural decision-making, human-computer interaction, weapon system and mobile platform, a new evaluation indicator system is established. In the quantitative process of qualitative indicators, Z-number theory is introduced to better describe the uncertainty degree of judgment and reasoning in human's understanding of complex things. In order to make the indicator weights more scientific, the combined weighting model with analytic hierarchy process and information entropy is adopted for weight analysis, which not only takes into account the influence of evaluation experts on weights, but also reduces the subjective arbitrariness of weights. The least-squares grey relational analysis method is used to analyse the correlation between the comparison series and the reference series, and a comprehensive quantitative evaluation result of the unmanned ground vehicles is obtained. The evaluation examples of unmanned ground vehicles show that the proposed evaluation system can quantitatively evaluate the overall technical performance of unmanned ground vehicles. This evaluation system has high reference value for the evaluation of other complex weapons.

1. Introduction
The rapid progress in automatic control, microelectronics, computers, materials, communications and other fields has promoted the rapid development of ordnance science and technology, produced many new weapons and equipment, and accelerated the update of weapons and equipment in all countries around the world. As a new type of land-based weaponry, unmanned ground vehicles can change its mission load according to operational requirements, and assist or replace soldiers to complete tasks such as reconnaissance, alerting, search and rescue, transportation, and precision strikes. Since the 1980s, the United States, Britain, France, Germany, Russia, Japan, South Korea and other countries have successively launched their own research programs, and carried out the development of unmanned ground vehicles for military applications [1].
From the off-road challenge [2,3] in 2004-2005 and the urban challenge [4] in 2007 organized by DARPA for unmanned ground vehicles, it can be found that the pre-established evaluation system can well stimulate the research enthusiasm of the research team, thus accelerating the rapid development of unmanned ground vehicles. How to evaluate the performance level of unmanned ground vehicles is an extremely complicated problem, and it is also a key technology in the integration process of unmanned ground vehicles. Therefore, many researchers have carried out a series of studies. Sun et al. [5] established an evaluation indicator system for intelligent behavior of unmanned ground vehicles, and used the fuzzy synthesis method and analytic hierarchy process to successfully solve the evaluation problem of the unmanned ground vehicles in the "Future Challenge 2011". Zhao et al. [6] established another intelligent behavior evaluation indicator system by taking into account typical driving conditions, obstacle avoidance and intersections, and then applied entropy-cost function method to comprehensively evaluate unmanned ground vehicles. Zhang et al. [7] proposed a more perfect intelligent behavior evaluation system for unmanned ground vehicles in order to provide the standards for the study of intelligent behavior. Then, the comprehensive evaluation method based on analytic hierarchy process was used to convert the performance of unmanned ground vehicles into scores, realizing the purpose of comparison and ranking of multiple vehicles. In addition, there are research literatures on the evaluation of the survivability [8], the evaluation of turning performance [9], and the evaluation of navigation capabilities for unmanned ground vehicles [10]. However, there are relatively few literatures on the multi-attribute comprehensive evaluation of unmanned ground vehicles.

Therefore, this paper proposes a multi-attribute comprehensive evaluation system for unmanned ground vehicles to realize the quantification of comprehensive performance. Section 2 analyses the structure and operation of unmanned ground vehicles, and then establishes a comprehensive performance evaluation indicator system that includes environmental perception, communication command, behavioral decision-making, human-computer interaction, weapon system and mobile platform. Section 3 details the calculation model for comprehensive performance evaluation, which includes the quantification algorithm of qualitative indicator based on Z-number theory, a combined weighting model, and the least-squares grey correlation analysis model. The evaluation examples of unmanned ground vehicles show that the calculation model can quantitatively evaluate the overall technical performance of unmanned ground vehicles in Section 4. Finally, conclusions are presented in Section 5.

2. Comprehensive evaluation indicator system of unmanned ground vehicles

Unmanned ground vehicle should have three major functions. First, it must have mobility. Second, it must have autonomy, that is, it has some functions similar to a human driver. Finally, it has a certain combat capability, that is, it can complete some combat mission by equipping with specific payload. In order to realize the above three functions, unmanned ground vehicles must have necessary functional modules, and these necessary functional modules will directly reflect the overall effectiveness of unmanned ground vehicles. According to the structure and operation of unmanned ground vehicles, it can be roughly divided into environment perception module, communication command module, behavioral decision-making module, human-computer interaction module, weapon system and mobile platform. If the vehicles make a correct tactical behavior, it should be jointly affected by these modules. The structure and operation of ground unmanned vehicles are shown in figure 1.
The environment perception module integrates research results including machine vision, GPS, radar recognition, and multi-modal information fusion. This module uses different sensors to capture useful information, and then reasonably combines and distributes them to obtain a more accurate and reliable description of the environment.

b. The communication command module uses communication technologies such as radio and smart antennas to transmit environmental information to the console for necessary human intervention, which overcomes the shortcomings of intelligent decision-making. A strong communication command module is not only the guarantee of information exchange between unmanned ground vehicles and console, but also the basis for coordinated operations of multiple vehicles on the battlefield in the future.

c. The behavior decision-making module uses technologies such as artificial intelligence, neural networks, and databases to analyze the surrounding environment, and then makes intelligent decisions about the vehicle's motion planning and weapon tactical behavior.

d. The human-computer interaction module mainly refers to the control-display device that located in the ground control station for battlefield information collection and remote control.

e. The weapon system carries a variety of weapons depending on the mission, such as small-caliber weapons such as machine guns, large-caliber weapons such as rockets, and non-lethal weapon.

f. The mobile platform not only has the basic driving ability such as turning, accelerating and braking, but also should have a certain climbing ability, obstacle avoidance ability, wading ability, soft passing ability, load capacity and endurance ability.

Based on the above analyses, a comprehensive performance evaluation indicator system is established, as shown in figure 2.
Comprehensive performance evaluation indicator system for unmanned ground vehicles

Environmental perception $C_1$, Communication command $C_2$, Behavior decision-making $C_3$, Human-computer interaction $C_4$, Weapon system $C_5$, Mobile platform $C_6$

Detection and identification of static obstacles $u_1$, Behavioral understanding of dynamic obstacles $u_2$, Accuracy of 3D terrain modeling $u_3$, Position accuracy $u_4$, Latency of obstacle avoidance $u_5$, Efficiency of obstacle avoidance $u_6$, Tactical ability $u_7$, Availability $u_8$, Customer satisfaction $u_9$, Theoretical lethality index $u_{10}$, Goodness-of-fit index $u_{11}$, Pedestal performance $u_{12}$, High speed performance $u_{13}$, Gradeability $u_{14}$, Wade ability $u_{15}$, Climbing obstacle capability $u_{16}$, Soft ground passability $u_{17}$, Load capacity $u_{18}$, Endurance ability $u_{19}$, Interactivity efficiency $u_{20}$, Customer satisfaction $u_{21}$, Theoretical lethality index $u_{22}$, Goodness-of-fit index $u_{23}$, Pedestal performance $u_{24}$.

**Figure 2.** Comprehensive performance evaluation indicator system for unmanned ground vehicles.

In the above indicator system, $u_1$, $u_2$, $u_3$, $u_{10}$, $u_{11}$, $u_{12}$ and $u_{13}$ are qualitative indicators, expressed as $U_X = \{u_1, u_2, u_3, u_{10}, u_{11}, u_{12}, u_{13}\}$. The other indicators are quantitative indicators, expressed as $U_I$. Each quantitative indicator is represented by a performance parameter or an equation, as shown in table 1.

**Table 1. Implications of quantitative indicators.**

| Indicator | Implication | Unit | Indicator | Implication | Unit |
|-----------|-------------|------|-----------|-------------|------|
| $u_4$     | The distance between the virtual location and the real location | m    | $u_{17}$  | Maximum travel speed | $Km/h$ |
| $u_5$     | Latency in non-interference communication | $ms$ | $u_{18}$  | Minimum turning radius | m |
| $u_6$     | Frame loss rate under interference conditions | /    | $u_{19}$  | Maximum gradeability | / |
| $u_7$     | Recovery time | $min$ | $u_{20}$  | Fording depth | m |
| $u_8$     | Number of collisions in obstacle avoidance test | /    | $u_{21}$  | Maximum height of surmountable obstacle | m |
| $u_9$     | The shortest passage time in obstacle avoidance test | s    | $u_{22}$  | Minimum passage time | s |
| $u_{14}$  | The launching speed × targets number × failure rate × range factor × accuracy × reliability | /    | $u_{23}$  | Maximum load weight | $Kg$ |
| $u_{15}$  | Firing dispersion $R_{50}$ | $cm$ | $u_{24}$  | Maximum working time | $h$ |
| $u_{16}$  | Angular velocity | $rad/s$ |

3. Calculation model for comprehensive performance evaluation

The calculation model includes the quantification algorithm of qualitative indicator based on $Z$-number theory, a combined weighting model, and the least-squares grey correlation analysis model.
3.1. *Quantitative method of qualitative indicators based on Z-number theory*

In the past, evaluation experts usually used 1–9 to measure the value of qualitative indicators. In fact, it is very difficult in giving an accurate value to describe the quantification of qualitative indicators in the fuzzy environment. Professor Zadeh proposed the concept of Z-number in 2011 [11]. A Z-number consists of a pair of fuzzy numbers, expressed as \(Z = (\tilde{A}, \tilde{B})\), where \(\tilde{A}\) is a fuzzy number describing the attributes of objective things, and \(\tilde{B}\) is another fuzzy number describing the reliability of \(\tilde{A}\). Therefore, in this paper, Z-number theory is introduced in the quantification process of qualitative indicators. In this process, experts are not required to give a specific number, but to give an interval value and indicate how reliable the interval is. Obviously, the introduction of Z-number theory makes the quantification process more consistent with human thinking habits in fuzzy environment.

The core idea of the quantitative method of qualitative indicators based on Z-number theory is to regard the expert's judgment and the reliability of the judgment as two fuzzy numbers \(\tilde{A}\) and \(\tilde{B}\), respectively. For a certain qualitative indicator, \(n\) experts are invited to score it, and \(n\) pairs of Z-numbers are obtained, which are expressed as \(Z_i = (A_i, B_i)\), where \(i = 1, 2, \ldots, n\). First, the two fuzzy numbers \(\tilde{A}\) and \(\tilde{B}\) in the \(n\) pairs of Z-numbers are regarded as independent generalized fuzzy numbers, and sorted by a sorting algorithm based on the centroid point, spread, and Minkowski degree [12]. Thus, \((\text{Score}_{\tilde{A}_i}, \text{Score}_{\tilde{B}_i})\) was obtained, where \(\text{Score}_{\tilde{A}_i}\) is the ranking score of \(\tilde{A}_i\) in \(\tilde{A}_1, \tilde{A}_2, \ldots, \tilde{A}_n\) and \(\text{Score}_{\tilde{B}_i}\) is the ranking score of \(\tilde{B}_1, \tilde{B}_2, \ldots, \tilde{B}_n\). Finally, \((\text{Score}_{\tilde{A}_i}, \text{Score}_{\tilde{B}_i})\) are sorted again according to a certain algorithm to obtain \(n\) Z-number sorting values. That is, the score of each expert for the qualitative indicator is obtained. By calculating the average value of \(n\) Z-number sorting values, the experts’ final quantization value for the qualitative indicator is obtained.

**3.1.1. The establishment rule of Z-number.** The forms of generalized fuzzy numbers are \((a_{i1}, a_{i2}, a_{i3}, a_{i4}; \mu_{iL}, \mu_{iR})\), \(-1 < a_{i1} < a_{i2} < a_{i3} < a_{i4} < 1\), \(\mu_{iL} \in [0, 1]\), \(\mu_{iR} \in [0, 1]\), where \(\mu_{iL}\) is the left height of the generalized fuzzy number, \(\mu_{iR}\) is the right height of the generalized fuzzy number [13].

In order to improve availability, the judgment rules of advantages and disadvantages are as follows: “0–0.2 is very poor; 0.2–0.4 is poor; 0.4–0.6 is general; 0.6–0.8 is good; 0.8–1.0 is excellent.” The expert gives an interval \([a_{i1}, a_{i4}]\) based on his own judgment, and establishes a generalized trapezoid fuzzy number \(\tilde{A}_i\) by equation (1).

\[
\begin{align*}
    a_{i2} &= a_{i1} + 0.25 \times (a_{i4} - a_{i1}) \\
    a_{i3} &= a_{i4} - 0.25 \times (a_{i4} - a_{i1}) \\
    \mu_{iL} &= \mu_{iR} = 1
\end{align*}
\]

The reliability degree \(\tilde{B}_i\) of the judgment interval is artificially divided into five levels, and each level is expressed in the form of a triangular fuzzy number, as shown in table 2.

**Table 2. Grade table of judgment interval reliability.**

| Judgment interval reliability | Doubtful | General certain | Certain | Very certain | Absolutely certain |
|------------------------------|----------|-----------------|---------|--------------|-------------------|
| \(\tilde{B}_i\)              | 0.2,0.3,0.3,0.4;1,1 | 0.4,0.5,0.5,0.6;1,1 | 0.6,0.7,0.7,0.8;1,1 | 0.8,0.9,0.9,1.0;1,1 | 1.1,1.1,1.1 |

**3.1.2. Calculate the position of the centroid point.** Taking the fuzzy number \(\tilde{A}_i\) as an example, the calculation equation for the position of its centroid point is as follows:

\[
\{\}
\]
\[
\begin{align*}
\chi_{A_i} &= \frac{\int_{a_{i1}}^{a_{i2}} (xf_{A_i}^L) dx + \int_{a_{i2}}^{a_{i3}} f_{A_i}^T x dx + \int_{a_{i3}}^{a_{i4}} (xf_{A_i}^R) dx}{\int_{a_{i1}}^{a_{i2}} (f_{A_i}^L) dx + \int_{a_{i2}}^{a_{i3}} f_{A_i}^T dx + \int_{a_{i3}}^{a_{i4}} (f_{A_i}^R) dx} \\
y_{A_i} &= \frac{\int_{0}^{\mu_i} (y g_{A_i}^R - y g_{A_i}^L) dy + \int_{\mu_i}^{\mu_{2i}} (y g_{A_i}^L - y g_{A_i}^R) dy}{\int_{0}^{\mu_i} (g_{A_i}^R - g_{A_i}^L) dy + \int_{\mu_i}^{\mu_{2i}} (g_{A_i}^L - g_{A_i}^R) dy}
\end{align*}
\]

If \( A_i \) is a real number, it can be expressed as \( A_i = (a_i, a_i, a_i, a_i, \mu_i, \mu_i) \), and the calculation equation for the position of its centroid point is as follows:

\[
\begin{align*}
\chi_{A_i} &= a_i \\
y_{A_i} &= \mu_i
\end{align*}
\]

where \( \chi_{A_i} \) is the abscissa of the centroid point of \( A_i \), \( y_{A_i} \) is the ordinate of the centroid point of \( A_i \), \( f_{A_i}^L, f_{A_i}^T, f_{A_i}^R \) are the piecewise membership function of \( A_i \), and \( g_{A_i}^L, g_{A_i}^T, g_{A_i}^R \) are the inverse functions of \( f_{A_i}^L, f_{A_i}^T, f_{A_i}^R \) respectively.

3.1.3. Calculate the spread of generalized fuzzy number. Similarly, taking the fuzzy number \( A_i \) as an example, the calculation equation of its spread is as follows:

\[
STD_{A_i} = \sqrt{\frac{3}{2} \left( \sum_{j=1}^{4} (a_{ij} - \bar{x}_{A_i})^2 \right)^{\frac{1}{2}}}
\]

where \( STD_{A_i} \) is the spread of \( A_i \), and \( \bar{x}_{A_i} = \frac{1}{4} (a_{i1} + a_{i2} + a_{i3} + a_{i4}) \).

3.1.4. Calculate the Minkowski degree of generalized fuzzy number. Similarly, taking the fuzzy number \( A_i \) as an example, the calculation equation of Minkowski degree at \( P = 2 \) is as follows:

\[
d_{p=2}(A_i) = 2 \times \left[ \frac{1}{\beta - \alpha} \int_{a}^{\beta} |A_i(x) - A_i(0.5(x))|^P dx \right]^{\frac{1}{P}} = 2 \times \left[ \frac{1}{\beta - \alpha} \left( \int_{a_{i1}}^{a_{i2}} |0.5 - |f_{A_i}^T - 0.5| | dx + \int_{a_{i2}}^{a_{i3}} |0.5 - |f_{A_i}^R - 0.5| | dx \right) \right]^{\frac{1}{P}}
\]

where \( d_{p=2}(A_i) \) is the Minkowski degree of \( A_i \) at \( P = 2 \). Normally, \( \alpha = -1, \beta = 1 \).

3.1.5. Calculate the Score \( A_i \) and Score \( B_i \). According to the \( (x_{A_i}, y_{A_i}) \), \( STD_{A_i} \), and \( d_{p=2}(A_i) \), the score of \( A_i \) is obtained by equation (6).

\[
Score_{A_i} = \frac{\mu(x_{A_i}) \cdot \left| x_{A_i} \right| + \sqrt{2} \omega_1 (x_{A_i}^2 + y_{A_i}^2)^{\frac{1}{2}}}{1 + 2 \omega_1 + \omega_2 STD_{A_i} + \omega_3 d_{p=2}(A_i)}
\]

Similarly, the score of \( B_i \) is obtained by equation (7).

\[
Score_{B_i} = \frac{\mu(x_{B_i}) \cdot \left| x_{B_i} \right| + \sqrt{2} \omega_1 (x_{B_i}^2 + y_{B_i}^2)^{\frac{1}{2}}}{1 + 2 \omega_1 + \omega_2 STD_{B_i} + \omega_3 d_{p=2}(B_i)}
\]
where \( \mu(x_{A_i}) \), \( \mu(x_{B_i}) \) are the sign coefficients of the centroid abscissa. If \( x_{A_i} \in [0,1] \), then \( \mu(x_{A_i}) = 1 \). If \( x_{A_i} \in [-1,0) \), then \( \mu(x_{A_i}) = -1 \). Normally, \( \omega_1 = 0.1 \), \( \omega_2 = 0.1 \), \( \omega_3 = 0.8 \).

### 3.1.6. Calculate the difference of the distance from \((\text{Score}\bar{A}_i, \text{Score}\bar{B}_i)\) to the reference points.

It is known that the equation (8) is correct.

\[
|x_{A_i}| + \sqrt{2}\omega_1(x_{A_i}^2 + y_{A_i}^2)^{\frac{1}{2}} \leq 1 + 2\omega_1 \leq 1 + 2\omega_1 + \omega_2\text{STD}_{A_i} + \omega_3d_{p=2}(\bar{A}_i) \quad (8)
\]

Therefore, the equation (9) is also inferred to be correct.

\[
-1 \leq \text{Score}\bar{A}_i = \frac{\mu(x_{A_i}) \cdot |x_{A_i}| + \sqrt{2}\omega_1(x_{A_i}^2 + y_{A_i}^2)^{\frac{1}{2}}}{1 + 2\omega_1 + \omega_2\text{STD}_{A_i} + \omega_3d_{p=2}(\bar{A}_i)} \leq 1 \quad (9)
\]

Similarly, \(-1 \leq \text{Score}\bar{B}_i \leq 1\).

If \((\text{Score}\bar{A}_i, \text{Score}\bar{B}_i) = (1,1)\), then \(Z_i = (\bar{A}_i, \bar{B}_i)\) should have the highest priority in Z-number sorting. Conversely, if \((\text{Score}\bar{A}_i, \text{Score}\bar{B}_i) = (-1,-1)\), then \(Z_i = (\bar{A}_i, \bar{B}_i)\) should have the lowest priority in Z-number sorting. Therefore, \((-1,-1)\) and \((1,1)\) are selected as reference points.

The difference of the distance from \((\text{Score}\bar{A}_i, \text{Score}\bar{B}_i)\) to the reference points is obtained by equation (10).

\[
\text{DS} = [(\text{Score}\bar{A}_i + 1)^2 + (\text{Score}\bar{B}_i + 1)^2]^{\frac{1}{2}} - [(\text{Score}\bar{A}_i - 1)^2 + (\text{Score}\bar{B}_i - 1)^2]^{\frac{1}{2}} \quad (10)
\]

where \(\text{DS}\) is the difference of the distance from \((\text{Score}\bar{A}_i, \text{Score}\bar{B}_i)\) to \((-1,-1)\) and \((1,1)\).

### 3.1.7. Calculate the quantified value of a qualitative indicator.

The purpose of introducing Z-number theory is to describe the fuzzy attributes of things, therefore the reliability of the judgment interval is important information but not decisive information. That is, \(\bar{A}_i\) is more important than \(\bar{B}_i\). In order to ensure that \(\bar{A}_i\) has sufficient weight, equation (11) is used to calculate a single Z-number comprehensive score.

\[
\text{Score}\bar{Z}_i = \text{Score}\bar{A}_i + \text{DS} \quad (11)
\]

where \(\text{Score}\bar{Z}_i\) is the quantitative score of a qualitative indicator by the \(i\)th expert.

The final quantified value \(\text{Score}(u)\) of a qualitative indicator is obtained by equation (12).

\[
\text{Score}(u) = \frac{1}{n} \sum_{i=1}^{n} \text{Score}\bar{Z}_i \quad (12)
\]

### 3.2. Combined weighting model

According to the different data sources, weight calculation methods can be divided into subjective weighting method and objective weighting method. The subjective weighting method can better reflect the background conditions and the intention of the evaluator. However, the weight obtained by this method has a large subjective arbitrariness. The objective weighting method makes the weights more objective, but it is prone to some unreasonable phenomena, such as the weight of important indicators is too small. In order to make the indicator weights more scientific, the combined weighting model with analytic hierarchy process (AHP) and information entropy (IE) is adopted for weight analysis, which not only takes into account the influence of evaluation experts on weights, but also reduces the subjective arbitrariness of weights.

#### 3.2.1. Calculating weights by AHP

First, the nine-level scale method is used to confirm importance degrees, as shown in Table 3.
Table 3. Definition of importance.

| Scale number | Meaning                                    | Scale number | Meaning                                    |
|--------------|--------------------------------------------|--------------|--------------------------------------------|
| 1            | Both are equally important                 | 1            | Both are equally important                 |
| 3            | Left is weakly more important than top     | 5            | Left is moderately less important than top |
| 5            | Left is moderately more important than top  | 7            | Left is strongly less important than top   |
| 7            | Left is absolutely more important than top  | 9            | Left is absolutely less important than top |
| 2, 4, 6, 8   | Between the median of the above two adjacent judgments | 2, 4, 6, 8   | Between the median of the above two adjacent judgments |

Pairwise comparison is made between the sub-indicators that belong to a same parent indicator, and the results are shown in table 4.

Table 4. Relationship between indicators.

| Indicator 1 | Indicator 2 | … | Indicator k |
|-------------|-------------|---|-------------|
| a_{11}      | a_{12}      | … | a_{1k}      |
| a_{21}      | a_{22}      | … | a_{2k}      |
| …           | …           | … | …           |
| a_{k1}      | a_{k2}      | … | a_{kk}      |

According to the results in table 4, \( A = [a_{ij}]_{k \times k} \).

The matrix \( A \) is normalized by columns using equation (13).

\[
\bar{a}_{ij} = \frac{a_{ij}}{\sum_{i=1}^{k} a_{ij}}
\]  

Then, \( G_i \) is obtained by equation (14).

\[
G_i = \sum_{j=1}^{k} \bar{a}_{ij}
\]

The weight vector \( W_{AHP} \) is obtained by equation (15).

\[
W_{AHP} = \frac{G_i}{\sum_{i=1}^{k} G_i}
\]

Finally, it is judged by equation (16) whether \( W_{AHP} \) be accepted. If \( c < 0.1 \), then \( W_{AHP} \) is accepted.

\[
c = \frac{\gamma_{\text{max}} - k}{C.R \cdot (k - 1)}
\]

where \( \gamma_{\text{max}} \) is the largest eigenvalue of \( A \), and \( C.R \) is obtained from table 5.

Table 5. The rules of \( C.R \) value.

| k  | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| C.R| 0.58| 0.90| 1.12| 1.24| 1.32| 1.41| 1.45| 1.49| 1.51|

3.2.2. Calculate weights by IE. It is assumed that there are \( n \) unmanned ground vehicles, and they are combined into a set, which is expressed as \( X = \{x_1, x_2, \ldots, x_i, \ldots, x_n\} \). Similarly, all the basic indicators in the evaluation indicator system of unmanned ground vehicles are combined into another set, which is expressed as \( U = \{u_1, u_2, \ldots, u_i, \ldots, u_m\} \). The original data matrix composed of \( X \) and \( U \) is expressed as \( R = [r_{ij}]_{n \times m} \), as shown in table 6.
Table 6. The form of the original data matrix $R$.

|      | $u_1$ | $u_2$ | ... | $u_m$ |
|------|-------|-------|-----|-------|
| $x_1$ | $r_{11}$ | $r_{12}$ | ... | $r_{1m}$ |
| $x_2$ | $r_{21}$ | $r_{22}$ | ... | $r_{2m}$ |
| ... | ... | ... | ... | ... |
| $x_n$ | $r_{n1}$ | $r_{n2}$ | ... | $r_{nm}$ |

The original data matrix $R$ is normalized by column, and the normalized decision matrix $\bar{R}$ is obtained, which is expressed as $\bar{R} = [\bar{r}_{ij}]_{n \times m}$.

$$\overline{r}_{ij} = \frac{r_{ij}}{\sum_{i=1}^{n} r_{ij}}$$ (17)

The information entropy of an indicator $u_j$ is calculated by equation (18).

$$E_j = -\frac{1}{\ln n} \sum_{i=1}^{n} \overline{r}_{ij} \ln \overline{r}_{ij}$$ (18)

Where, if $\overline{r}_{ij} = 0$, we specify $\overline{r}_{ij} \ln \overline{r}_{ij} = 0$.

The weight of $u_j$ based on information entropy is calculated by equation (19).

$$w_{IE_j} = \frac{1 - E_j}{\sum_{i=1}^{m} (1 - E_i)}$$ (19)

3.2.3. Combination weighting method of AHP–IE. The combined weight based on AHP–IE is calculated by equation (20).

$$W_{AHP–IE} = \rho W_{AHP} + (1 - \rho) W_{IE}$$ (20)

where $\rho$ is the preference factor, which reflects whether the evaluator wants the combination weight to be biased towards the AHP subjective weights or the IE objective weights.

3.3. The least-squares grey relational analysis method

The unmanned ground vehicle is a typical grey system. The application of the least-squares grey relational analysis method can not only independently evaluate some capabilities of ground unmanned vehicles, but also comprehensively evaluate unmanned ground vehicles [14].

Since the units of each evaluation indicator are different, the original data $R$ must be standardized. If $R_{ij}$ is the benefit indicator, then $\bar{R}_{ij}$ is obtained by equation (21). If $R_{ij}$ is the cost indicator, then $\bar{R}_{ij}$ is obtained by equation (22).

$$\bar{R}_{ij} = \frac{R_{ij} - \min R_j}{\max R_j - \min R_j}$$ (21)

$$\bar{R}_{ij} = \frac{\max R_j - R_{ij}}{\max R_j - \min R_j}$$ (22)

where $\bar{R}_{ij}$ is the normalized value of the original value $R_{ij}$, $\max R_j$ is the maximum value in row $j$ of matrix $R$; $\min R_j$ is the minimum value in row $j$ of matrix $R$.

The reference vector $C^+$ and $C^-$ are obtained by equation (23).

$$\begin{cases} C^+_i = \max_j \bar{R}_{ij} \\ C^-_i = \min_j \bar{R}_{ij} \end{cases}$$ (23)

The grey relational coefficient between $\bar{R}_i$ and the reference vector is calculated by equation (24).

$$\begin{cases} \delta^+_{ij} = \frac{\min \min_j |C^+ - \bar{R}_{ij}| + \mu \cdot \max_j \max_j |C^+ - \bar{R}_{ij}|}{|C^+ - \bar{R}_{ij}| + \mu \cdot \max_i \max_j |C^+ - \bar{R}_{ij}|} \\ \delta^-_{ij} = \frac{\min \min_j |C^- - \bar{R}_{ij}| + \mu \cdot \max_j \max_j |C^- - \bar{R}_{ij}|}{|C^- - \bar{R}_{ij}| + \mu \cdot \max_i \max_j |C^- - \bar{R}_{ij}|} \end{cases}$$ (24)
where $\delta^+_{ij}$ is the $j$th element in the grey relational coefficient vector between $R_i$ and $C^+$. $\delta^-_{ij}$ is the $j$th element in the grey relational coefficient vector between $R_i$ and $C^-$. $\bar{R}_i$ is the decision information vector of the $i$th unmanned ground vehicle. Normally, $\mu = 0.5$.

The correlation degree of $\bar{R}_i$ are calculated by equation (25).

$$
\begin{align*}
\gamma^+_i &= \delta^+_i \cdot W_{AHP-IE}^T \\
\gamma^-_i &= \delta^-_i \cdot W_{AHP-IE}^T
\end{align*}
$$

(25)

where $\gamma^+_i$ and $\gamma^-_i$ is the degrees of positive and negative correlation of $\bar{R}_i$, respectively.

The final evaluation score of the $i$th unmanned ground vehicle is obtained by equation (26).

$$
E_i = \frac{1}{1 + (\frac{\gamma^-_i}{\gamma^+_i})^2}
$$

(26)

where $E_i$ is the final evaluation score of the $i$th unmanned ground vehicle.

4. Example simulation
Based on the evaluation indicator system established in this paper, the above model is used to quantitatively evaluate the six unmanned ground vehicles.

4.1. Quantification of qualitative indicators
It is known that the seven indicators $u_1$, $u_2$, $u_3$, $u_{10}$, $u_{11}$, $u_{12}$, and $u_{13}$ are qualitative indicators. Ten experts are invited to evaluate each qualitative indicator, and then the Z-number theory is used to quantify the experts’ judgment. In the following, the process is illustrated by quantifying the qualitative indicator $u_4$ of the second unmanned ground vehicle. The expert’s judgment results are shown in table 7.

| Name      | Judgment interval | Reliability of the judgment | Name      | Judgment interval | Reliability of the judgment |
|-----------|-------------------|-----------------------------|-----------|-------------------|-----------------------------|
| Expert 1  | [0.6-0.8]          | Certain                     | Expert 6  | [0.7-0.9]        | Certain                     |
| Expert 2  | [0.4-0.6]          | General certain             | Expert 7  | [0.7-0.9]        | Certain                     |
| Expert 3  | [0.5-0.7]          | Very certain                | Expert 8  | [0.5-0.7]        | General certain             |
| Expert 4  | [0.6-0.8]          | Very certain                | Expert 9  | [0.8-1.0]        | Doubtful                    |
| Expert 5  | [0.4-0.6]          | Certain                     | Expert 10 | [0.6-0.8]        | Certain                     |

According to equation (1) and table 2, the data in table 7 is converted to $\bar{A}_i$ and $\bar{B}_i$. The results are shown in table 8.

| $i$ | $\bar{A}_i$ | $\bar{B}_i$ |
|-----|-------------|-------------|
| 1   | (0.6,0.75,0.8;1,1) | (0.6,0.7,0.8;1,1) |
| 2   | (0.4,0.5,0.6;1,1)  | (0.4,0.5,0.5;1,1)  |
| 3   | (0.5,0.55,0.6;1,1) | (0.8,0.9,0.9;1,1)  |
| 4   | (0.6,0.65,0.7;1,1) | (0.8,0.9,0.9;1,1)  |
| 5   | (0.4,0.5,0.6;1,1)  | (0.6,0.7,0.8;1,1)  |

$\text{Score} \bar{A}_i$, $\text{Score} \bar{B}_i$, and $\text{Score} Z_i$ are obtained by the equations (2-12), and are shown in table 9.

| $i$ | $\text{Score} \bar{A}_i$ | $\text{Score} \bar{B}_i$ | $\text{Score} Z_i$ |
|-----|-----------------|-----------------|-----------------|
| 1   | 0.6227          | 0.5979          | 0.6806          |
| 2   | 0.4531          | 0.4320          | 0.5195          |
| 3   | 0.5376          | 0.7648          | 0.7010          |
| 4   | 0.6227          | 0.7648          | 0.7463          |
| 5   | 0.4531          | 0.5979          | 0.5894          |

$\text{Score} \bar{A}_i$, $\text{Score} \bar{B}_i$, and $\text{Score} Z_i$.
According to equation (12), $\text{Score}(u_4) = 0.6542$. That is, the comprehensive score of the indicator $u_4$ of the second unmanned ground vehicle is 0.6542.

### 4.2. Acquisition of the original data matrix $R$

The qualitative indicators were quantified according to the above method, and the quantitative indicators were obtained through experiments. The original data matrix $R$ is shown in Table 10.

**Table 10.** Data for all indicators of the six unmanned ground vehicles.

| Type       | $u_1$ | $u_2$ | $u_3$ | $u_4$ | $u_5$ | $u_6$ | $u_7$ | $u_8$ | $u_9$ | $u_{10}$ | $u_{11}$ | $u_{12}$ |
|------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|----------|----------|----------|
| Vehicle 1  | 0     | 0     | 3     | 205   | 0.22  | 4     | 12    | 210   | 0     | 0.567    | 0.532    |          |
| Vehicle 2  | 0.654 | 0.627 | 0.725 | 4     | 210   | 0.25  | 4     | 12    | 210   | 0.567    | 0.532    |          |
| Vehicle 3  | 0.573 | 0.504 | 0.578 | 5     | 215   | 0.25  | 4     | 6     | 160   | 0.567    | 0.501    | 0.487    |
| Vehicle 4  | 0.511 | 0.446 | 0.493 | 5     | 215   | 0.52  | 8     | 12    | 210   | 0.544    | 0.481    | 0.436    |
| Vehicle 5  | 0.599 | 0.586 | 0.634 | 4     | 210   | 0.25  | 4     | 6     | 154   | 0.601    | 0.617    | 0.586    |
| Vehicle 6  | 0.586 | 0.586 | 0.631 | 4     | 205   | 0.22  | 3     | 6     | 154   | 0.601    | 0.648    | 0.617    |

| Type       | $u_{13}$ | $u_{14}$ | $u_{15}$ | $u_{16}$ | $u_{17}$ | $u_{18}$ | $u_{19}$ | $u_{20}$ | $u_{21}$ | $u_{22}$ | $u_{23}$ | $u_{24}$ |
|------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Vehicle 1  | 0.532     | 0.879     | 4.6       | 0.70      | 50        | 1.2       | 40        | 0.8       | 0.5       | 160       | 200       | 8         |
| Vehicle 2  | 0.544     | 0.755     | 5.5       | 0.87      | 30        | 1.5       | 35        | 0.5       | 0.4       | 180       | 150       | 6         |
| Vehicle 3  | 0.525     | 1.030     | 3.6       | 0.87      | 30        | 1.5       | 35        | 0.5       | 0.4       | 180       | 150       | 6         |
| Vehicle 4  | 0.521     | 0.879     | 8.9       | 0.87      | 30        | 1.5       | 35        | 0.5       | 0.4       | 190       | 150       | 6         |
| Vehicle 5  | 0.544     | 0.755     | 5.5       | 0.87      | 30        | 1.5       | 35        | 0.5       | 0.4       | 180       | 150       | 6         |
| Vehicle 6  | 0.599     | 0.755     | 5.5       | 0.87      | 30        | 1.5       | 35        | 0.5       | 0.4       | 180       | 150       | 6         |

### 4.3. Calculation of combined weights

First, according to the requirements of AHP, we analyze the degree of importance between sub-indicators that belong to the same parent indicator, and then the acceptable $W_{AHP}$ is obtained by the equations (13-17). Secondly, using $R$ from Table 10 and the equations (17-19), $W_{IE}$ is calculated. Finally, the combined weight $W_{AHP-IE}$ based on AHP-IE is calculated by equation (20).

Since the experts consulted in this paper are authoritative in this field, $W_{AHP}$ can reflect the actual situation of unmanned ground vehicles. Therefore, we hope that the $W_{AHP-IE}$ is close to the $W_{AHP}$, and the $W_{IE}$ plays a supporting role to reduce the subjective arbitrariness of experts. To sum up, the preference factor $\rho = 0.8$. $W_{AHP}$, $W_{IE}$ and $W_{AHP-IE}$ are shown in Table 11.

**Table 11.** Weight data of $W_{AHP}$, $W_{IE}$ and $W_{AHP-IE}$.

| Type       | $u_1$ | $u_2$ | $u_3$ | $u_4$ | $u_5$ | $u_6$ | $u_7$ | $u_8$ | $u_9$ | $u_{10}$ | $u_{11}$ | $u_{12}$ |
|------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|----------|----------|----------|
| $W_{AHP}$  | 0.0780 | 0.0780 | 0.0780 | 0.0390 | 0.0252 | 0.0830 | 0.0458 | 0.0910 | 0.0910 | 0.0830   | 0.0458   |          |
| $W_{IE}$   | 0.1580 | 0.1618 | 0.1622 | 0.0119 | 0.0002 | 0.0502 | 0.0475 | 0.1088 | 0.0142 | 0.1572   | 0.0051   | 0.0059   |
| $W_{AHP-IE}$ | 0.0940 | 0.0948 | 0.0948 | 0.0336 | 0.0202 | 0.0764 | 0.0461 | 0.0946 | 0.0756 | 0.1042   | 0.0674   | 0.0378   |

| Type       | $u_{13}$ | $u_{14}$ | $u_{15}$ | $u_{16}$ | $u_{17}$ | $u_{18}$ | $u_{19}$ | $u_{20}$ | $u_{21}$ | $u_{22}$ | $u_{23}$ | $u_{24}$ |
|------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| $W_{AHP}$  | 0.0252   | 0.0485   | 0.0268   | 0.0147   | 0.0034   | 0.0034   | 0.0062   | 0.0111   | 0.0111   | 0.0034   | 0.0062   |          |
| $W_{IE}$   | 0.0010   | 0.0254   | 0.0338   | 0.0025   | 0.0191   | 0.0027   | 0.0011   | 0.0059   | 0.0052   | 0.0011   | 0.0055   | 0.0055   |
| $W_{AHP-IE}$ | 0.0204   | 0.0439   | 0.0282   | 0.0123   | 0.0065   | 0.0033   | 0.0052   | 0.0121   | 0.0095   | 0.0091   | 0.0038   | 0.0061   |

### 4.4. Quantitative evaluation based on the least-squares grey correlation method for unmanned ground vehicles

In the evaluation indicator system, the indicators $u_1$, $u_2$, $u_3$, $u_{10}$, $u_{11}$, $u_{12}$, $u_{13}$, $u_{14}$, $u_{16}$, $u_{17}$, $u_{19}$, $u_{20}$, $u_{21}$, $u_{23}$ and $u_{24}$ are the benefit indicator. The indicators $u_4$, $u_5$, $u_6$, $u_7$, $u_8$, $u_9$, $u_{15}$, $u_{16}$ and $u_{22}$ are the cost indicator.

The original data sub-matrix $R_{C_i}$ ($i = 1,2,3,4,5,6$) for each capability was obtained from Table 10, and the capability scores of $C_1$, $C_2$, $C_3$, $C_4$, $C_5$, and $C_6$ for the six unmanned ground vehicles were calculated respectively by the equations (21-26), as shown in figure 3.
The original data matrix $R = (R_{C1}, R_{C2}, R_{C3}, R_{C4}, R_{C5}, R_{C6})$ is obtained from table 10. Similarly, the score vector $E$ of the comprehensive evaluation for the six unmanned ground vehicles is calculated by equation (21-26).

$$E = (0.1673, 0.4388, 0.3216, 0.1586, 0.3708, 0.4115)$$

4.5. Result

The elements in the score vector $E$ are sorted in descending order, and the ranking of the advantages and disadvantages for the evaluated unmanned ground vehicles can be obtained:

Vehicle 2 > Vehicle 6 > Vehicle 5 > Vehicle 3 > Vehicle 1 > Vehicle 4

Therefore, Vehicle 2 is the best unmanned ground vehicle. Combined with figure 3 for further analysis, the following results are obtained:

a. By comparing Vehicle 2 and Vehicle 5, it can be found that the environment perception module and behavior decision-making module have a significant impact on the vehicle performance, and improving the vehicle's environment perception capability and behavior decision-making capability is conducive to the overall performance of the vehicles.

b. By comparing Vehicle 5 and Vehicle 6, it can be found that the communication command capability and human-computer interaction capability of unmanned ground vehicles have a certain influence on the actual combat effect. Under the condition that the research institution considers the cost of technology research and development, the limited funds can be given priority to the development of stronger communication command equipment and human-computer interaction equipment, which can quickly improve the comprehensive performance level of unmanned ground vehicles in a short period of time.

c. Although Vehicle 1 has strong mobile platform and communication command capability, it has poor environmental perception capability and behavior decision-making capability. Although Vehicle 3 is equipped with very strong weapons, other capabilities are obviously inadequate. Vehicle 4's each capability is relatively low and need to be strengthened in all aspects. Therefore, Vehicle 1, Vehicle 3 and Vehicle 4 have very low comprehensive score.

5. Conclusion

From the research, it can be concluded that:

a. The comprehensive performance evaluation indicator system for unmanned ground vehicles includes six aspects: environment perception, communication command, behavior decision-making, human-computer interaction, weapon system and mobile platform, which
comprehensively and meticulously reflects the overall technical level of unmanned ground vehicles. In addition, the sub-indicators of each aspect are represented by the parameters that have physical significance to improve the usability of the indicator system.

b. This paper proposes to use two fuzzy numbers (\( \tilde{A}_i \) and \( \tilde{B}_i \) in \( Z \)-number theory) to describe the uncertainty degree of judgment and reasoning in human's understanding of complex things, which not only contains more decision-making information, but also conforms to human thinking habits. The above example show that this method overcomes the shortcomings of the traditional nine-level scale method and can well solve the quantification problem of qualitative indicators.

c. The simulation results show that the calculation model proposed in this paper can not only quantify the comprehensive performance level of unmanned ground vehicles, but also well analyze the influence of each sub-capability on the comprehensive performance of unmanned ground vehicles, and provide a reference for the future improvement of unmanned ground vehicles.

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