FAHP Based Evaluation of real-time operating system performance in Aerospace

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Abstract. The real-time operating system has been gradually applied to China's aerospace industry. Due to the lack of effective evaluation methods for real-time operating system performance, this paper proposes a multi-index comprehensive performance evaluation method--- the Fuzzy Analytic Hierarchy Process, possibility calculation method. This method can comprehensively evaluate and analyse the performance of embedded RTOS, and provide a reliable basis for the selection of embedded operating systems for aerospace systems.

1. Introduction
At present, most of the domestic on-board computers do not use the operating system, mainly using on-board software for single tasks or a small number of tasks, and these on-board software are small in scale and simple in function [1]. In recent years, countries around the world have gradually realized the great role of space technology in the international people's livelihood. The manned spaceflight project entered a period of rapid development. In particular, the commercial space agency represented by SPACE X constantly increased the launch records of the aerospace field. At the same time, the scale, complexity, importance and the proportion of functions undertaken by the aerospace software model have risen sharply. Computer systems in the aerospace industry often require large-scale high-speed data processing or precise control, and each type of spacecraft has different applications and requirements, and the original method can no longer meet the next stage of the aerospace industry. The embedded real-time operating system can effectively solve this problem. Some countries and regions such as Europe and the United States have mass produced and applied real-time operating systems in the aerospace field. It turns out that the choice of RTOS as the basic software in the aerospace field is very successful. RTOS plays an extremely important supporting role in strong real-time and high-reliability applications in missiles, rockets, satellites and warships. The real-time operating system refers to a system that can accept and process at a sufficiently fast rate when external events or data are generated, and the processing result can control the production process or respond quickly to the processing system within a prescribed time, and control all real-time tasks to run in concert [2].

The real-time performance of real-time operating systems is an important factor in operating system evaluation. Although there are many evaluation methods for the comprehensive performance of embedded operating systems, a unified evaluation model has not yet been built. An operability evaluation system for RTOS has not yet been formed in the aerospace field. If the characteristics of the systems are underestimated, it may result in the failure of the flight mission and even endanger the life
of the astronaut. Therefore, according to the new requirements of real-time, reliability and adaptability of aerospace embedded operating system in Chinese space station stage, combining the Fuzzy Analytic Hierarchy Process (FAHP), this paper proposes a mathematical model for aerospace RTOS evaluation to evaluate the RTOS performance from the aspects of real-time, reliability and portability.

2. Performance evaluation index system

As China's manned spaceflight project enters the stage of manned space station, the types, quantities and complexity of loads increase rapidly. In the future construction of spacecraft, strict requirements are imposed on the operating system. Due to the complexity of the operating system requirements in the aerospace industry, it is difficult to predict the performance of an operating system with only few indicators. Therefore, we need to establish a complete operating system performance evaluation index system. Based on the internal quality and external quality models defined in GJB5236-2004 Military Software Quality Metrics and GJB7706-2012 Military Embedded Operating System Evaluation Requirements, combined with the current content of the benchmark suite for RTOS and the multi-threaded high concurrency in the aerospace field, this paper defines the embedded real-time operating system evaluation index system, as shown in Figure 1.

![RTOS Evaluation Index System](image)

- The requirements of RTOS for real-time performance are undoubtedly the most important. Real-time means that when external events or data are generated, it can be accepted and processed at a fast enough speed, and the result can control the external experimental equipment accurately or realize the attitude and orbit control of the aircraft in the specified time;
- Safety means that the source code of the operating system must be transparent to the user, especially the current international cooperation is further deepened, with other organizational or institutional loads participating in the flight task, and the ability to reduce the system loss caused by user misoperation or environmental damage. The particularity of the aerospace field determines that its requirements for system reliability are extremely high.
- In addition, in the design of embedded systems, more and more complex load systems have put forward higher requirements for embedded processors. With the continuous introduction of high performance processors, the portability, extensibility, tailiability and maintainability of the operating system are more stringent.

Therefore, real-time, safety, and portability are selected as the main performance indicators. The real-time indicators are divided into five specific indicators: preemption time, semaphore shuffling time, interrupt response time, deadlock release contact time, and scheduling delay. The safety indicators are based on open source, priority inversion protection and memory protection. Portability is measured by complexity and adaptability. Finally, a three-level embedded operating system evaluation index system will be built.

3. FAHP principle and steps
For the real world, many descriptions or concepts cannot be defined clearly. According to the analysis, observation, and research of such problems, it is difficult to identify the precise rules. In this reason, fuzzy set theory has much advantage to solve these problems [3]. Uncertainty Fuzzy Analytic Hierarchy Process (FAHP) is a multi-objective decision evaluation method that combines qualitative and quantitative analysis. It is a combination of fuzzy mathematics and traditional analytic hierarchy process. Conventional analytical hierarchy process cannot reflect human thinking perfectly. Fuzzy methods have better performance in human language and imprecise human expressions [4]. Its core idea is to use a simple pairwise comparison method to compare and judge the relevant factors in the system, then construct the uncertain fuzzy judgment matrix, and finally carry out comprehensive calculation processing by comparing the comparison judgment results [5]. Theory and practice prove that the FAHP method can effectively avoid subjectivity, blindness, uncertainty and other factors, making the analysis more scientific and in line with human thinking.

3.1 Establish a hierarchical structure model of the evaluation index system

The multi-level structural indicator system can be roughly divided into three layers, namely the target layer, the criterion layer and the indicator layer. The target layer, also called the highest level, mainly describes the purpose of the evaluation and points to the ultimate goal of the problem. The criteria layer affects the achievement of the goal. The indicator layer is a concrete measure for achieving the goal. The factors in the same layer are subordinate to the upper factors or have influence on the upper factors, while at the same time controlling the lower factors or being influenced by the lower factors. The model is shown in Figure 1.

3.2 Structure judgment matrix

The function of the judgment matrix is to compare the relative importance of the same layer elements under the constraints of an element above the previous layer [6]. When using FAHP to construct a judgment matrix, the judgments given are often expressed in the form of interval numbers or fuzzy numbers [7]. Here, we use the method of expert scoring, assuming that a number of experts are invited, the uncertainties in the process of expert consultative method are described by fuzzy variables [8], and use the triangular fuzzy number to construct the judgment matrix.

The triangular fuzzy numbers were proposed by Dutch scholars F.J.M. Van Laarhoven and W. Pedrycz. The triangular fuzzy numbers are directly brought into the comparison judgment matrix to deal with the process of criterion measurement. It can well reflect the understanding of the important relationship between the indicators by subjective evaluators. Let the fuzzy number M on the domain R, the membership function \( \mu_M(x) \) of M can be expressed as (1) for \( R \rightarrow [0,1] \):

\[
\mu_M(x) = \begin{cases} 
\frac{x-l}{m-l} & x \in [l,m] \\
\frac{x-u}{m-u} & x \in [m,u] \\
0 & x \in (\infty,-l] \cup [u,\infty) 
\end{cases} \quad (1)
\]

In the formula (1), \( l \leq m \leq u \), l and u are lower and upper limit of the membership function and m is the median. In general, the triangular fuzzy number M can be written as \((l, m, u)\). In the triangular fuzzy number, l and u represent the fuzzy degree of the judgment. Let \( \delta = u - l \), the larger \( \delta \) is, the higher the degree of ambiguity; on the contrary, the smaller \( \delta \) is, the lower the degree of ambiguity is; the lower \( \delta \) is 0, the judgment is non-blurred.

In terms of integrating expert opinions, there are methods such as mean, maximum value, minimum value, geometric mean, and maximum and minimum mixed weighting processing [9]. Suppose there are a total of \( N \) experts to score, according to the knowledge and experience of experts to assign weights, it is generally believed that the experts have the same knowledge and experience, that is, the weights are the same, and the geometric mean calculation formula (2) is used.
This paper selects the triangular fuzzy number based on the scale method to express the contrast. Considering that the traditional evaluation scale of 1-9 is too cumbersome and according to Saaty's research, the scale of 1-5 is better than 1-9 to some extent. Therefore, this paper uses the evaluation scale of 1-5 instead of the evaluation scale of 1-9. Let $\delta=1$, but if $(0, 1, 2)$ is used, when the expert opinion is integrated using the geometric mean, the left value of the function will be zero. Therefore, this paper uses the equally important fuzzy number $1 = (1/2, 1, 3/2)$. The importance level and assignment under the scale method are shown in Table 1.

| Scale | Definition | Membership Function |
|-------|------------|---------------------|
| 1     | Equally important | $(1/2, 1, 3/2)$ |
| 3     | Strongly more important | $(2, 3, 4)$ |
| 5     | Exceedingly more important | $(4, 5, 6)$ |
| 2,4   | The median of the importance of the above two adjacent judgments | |
|      | reciprocal | The opposite comparison of the above comparison | |

After unifying the scale criterion of the triangular fuzzy number, the fuzzy judgment matrix (3) can be obtained.

$$A = (\bar{a}_{ij})_{m \times n} = \begin{pmatrix} a_{i1} & \cdots & a_{in} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix}$$

Wherein, the triangular fuzzy number $a_{ij}$ represents the relative importance of the factor $A_i$ to the factor $A_j$. $a_{ij} = (l_{ij}, m_{ij}, u_{ij})$ and $l_{ij} = 1/u_{ij}, u_{ij} = 1/l_{ij}, m_{ij} = 1/m_{ij}$.

3.3 Calculate the preliminary comprehensive fuzzy weight value

$$D_i^k = \sum_{j=1}^{n} a_{ij}^k + (\sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij}^k) \quad i=1,2,\ldots,n$$

$D_i^k$ represents the integrated fuzzy value of the element $i$ of the $K$th layer.

3.4 Defuzzification and hierarchical ordering

As the obtained triangular fuzzy weight does not represent the complete accurate state of the required index weight information, a possibility method is adopted for processing, that is, the triangular fuzzy number weights are compared in pairs [10].
Assuming $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$ as two triangular fuzzy numbers, the probability degree of $M_1 \geq M_2$ is defined as formula (5) and (6).

$$V(M_1 \geq M_2) = \mu(d) \begin{cases} 1 & m_1 \geq m_2 \\ \frac{l_2 - u_1}{(m_1 - u_1) - (m_2 - l_2)} & m_1 \leq m_2, u_1 \geq l_2 \\ 0 & \text{otherwise} \end{cases}$$ (5)

Considering that there are often more than two elements in the actual application, it is necessary to compare multiple triangular fuzzy numbers [11]. The probability that a fuzzy number is greater than the other $K$ fuzzy numbers is defined as follow.

$$V(M \geq M_1, M_2, \ldots, M_k) = \min_{i=1,2,\ldots,k} V(M \geq M_i)$$ (6)

Assuming $d(p^i_k) = \min V(S^i_k \geq S_j^k)$, $p^i_k$ is the $i$-th element of the $k$th layer, and the $k$th layer has $n$ elements, then the element weight of the $k$th layer can be expressed as follows:

$$a_k^i = (d(p^i_1), d(p^i_2), \ldots, d(p^i_n))^T$$ (7)

The above weight values are normalized by the formula (10) to obtain the final weight of each indicator.

$$\omega_k^i = \frac{a_k^i}{\sum_{i=1}^{n} d(p^i_1)} \quad i=1,2,\ldots,n$$ (8)

### 3.5 Comprehensive judgment

The product of the weight vector of the evaluation index related to the total target and the weight matrix of the evaluation object related to the evaluation index is a total ranking vector. Each component is a comprehensive score of each evaluation target under the overall goal, and the merits and demerits of each evaluation object are determined by the comprehensive score.

### 4. Application analysis

#### 4.1 Evaluation index system

This paper uses the RTOS performance evaluation system described above. It is divided into three levels: the first layer is the target layer $C$; the second layer is the criterion layer ($C_1 \sim C_3$); the third layer is the index layer ($C_{11} \sim C_{15}, C_{21} \sim C_{23}, C_{31} \sim C_{32}$).

#### 4.2 Structure judgment matrix

Three experts score points by comparing the importance of each indicator. According to the expert scoring, the fuzzy judgment matrix of the criterion layer relative to the target layer is constructed, as shown in Table 2. And formula (2) is used to get the comprehensive fuzzy judgment matrix, as shown in Table 3.

| C  | C1   | C2          | C3          |
|----|------|-------------|-------------|
| C1 | (1,1,1)| (1,2,3)     | (1,2,3)     |
|    |      | (1,1,2)     | (2,3,4)     |
|    |      | (1,2,3)     | (2,3,4)     |
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| C2      | (1/3,1/2,1)   | (1,1,1)     | (1,2,3)   |
|---------|---------------|-------------|-----------|
|         | (1/2,1,1)     |             | (1,2,3)   |
|         | (1/3,1/2,1)   |             | (1,2,3)   |
| C3      | (1/3,1/2,1)   | (1/3,1/2,1) | (1,1,1)   |
|         | (1/3,1/2,1)   | (1/3,1/2,1) | (1,1,1)   |

Table 3. Comprehensive fuzzy judgment matrix

| C   | C1               | C2               | C3               |
|-----|------------------|------------------|------------------|
| C1  | (1,1,1)          | (1,1.58,2,62)    | (1.59,2.62,3.63) |
| C2  | (0.38,0.63,1)    | (1,1,1)          | (1,2,3)          |
| C3  | (0.28,0.38,0.63) | (0.33,0.50,1)    | (1,1,1)          |

4.3 Calculate the preliminary comprehensive fuzzy weight value
According to the matrix obtained in Table 3 and formula (4), the single layer weight can be calculated, as shown in Table 4.

| D   | weight          |
|-----|-----------------|
| Dc1 | (0.34,0.49,0.96)|
| Dc2 | (0.16,0.34,0.66)|
| Dc3 | (0.11,0.18,0.35)|

4.4 Defuzzification and hierarchical ordering
According to the formula (5), (6), (7), the calculation of the probability degree is obtained, the weight is: \( \omega' = (1, 0.7399, 0.2547) \).

After normalization, the result is: \( \omega = (0.5013, 0.3710, 0.1277) \).

The index layer is calculated in the same way as the criterion layer. Due to the limitation of the article length, it will not be described here. Only the results are given, as shown in Table 5.

| target layer | weight   | criterion layer     | \( W_i \) | \( W_{ij} \) |
|--------------|----------|---------------------|-----------|-------------|
| real-time(C1)| 0.5013   | Preemption time     | 0.3138    | 0.1573      |
|              |          | Semaphore shuffling | 0.1812    | 0.0908      |
|              |          | Interrupt response  | 0.4007    | 0.2009      |
|              |          | Context switch      | 0.0920    | 0.0461      |
|              |          | Scheduling delay    | 0.0123    | 0.0062      |
| Reliability(C2)| 0.3710  | Open Source         | 0.5373    | 0.1993      |
|                |          | Priority reversal   | 0.2580    | 0.0957      |
|                |          | Memory protection   | 0.2047    | 0.0760      |
| Portability(C3)| 0.1277  | complexity          | 0.7981    | 0.1010      |
|                |          | Adaptability        | 0.2019    | 0.0258      |

4.5 Comprehensive judgment
In order to verify the rationality and effectiveness of the aerospace embedded real-time operating system evaluation model used in this paper, the real-time performance measured data of the embedded real-time operating system is selected from the reference [12-15], and the relevant indicators are standardized in Table 6. Then, the fuzzy comprehensive analysis method is used to obtain the comprehensive performance evaluation value. The results are shown in Table 7.

| Performance | VxWorks | RTEMS |
|-------------|---------|-------|
| Preemption time | 0.40    | 0.35  |
Semaphore shuffling 0.25 0.10
Interrupt response 0.86 0.81
Context switch 0.81 0.73
Scheduling delay 0.38 0.85
Open Source 0.5 1
Priority reversal 0.84 0.84
Memory protection 0.5 0.5
complexity 0.62 0.75
Adaptability 0.53 0.74

Table 7. Comprehensive performance evaluation value

| OS       | Values |
|----------|--------|
| VxWorks  | 0.82   |
| RTEMS    | 0.75   |

According to the results above, the comprehensive performance of VxWorks is better than RTEMS. In this case, VxWorks is more suitable for manned space control than RTEMS, which is in line with the original expectation. It also verifies the effectiveness of the FAHP method for the evaluation of embedded operating systems in aerospace.

5. Conclusion
Aiming at the problems encountered in the performance evaluation of aerospace operating systems, this paper proposes an operating system performance evaluation method based on triangular fuzzy number analytic hierarchy process. The method fully considers the ambiguity of thinking judgment and the complexity and ambiguity of the evaluation object, at the same time the randomness in the weight determination is avoided. It can scientifically and objectively determine the weight of each indicator in the evaluation index system, and is an evaluation method with strong operability. This method is of great significance for the performance evaluation and program decision of the aerospace industry.

References
[1] Zhu, Y.J., Wang, J.Q., Shi, Z.C., & Yang, M.M. (2013). Discussion on application of embedded operating system in aerospace. Microcontrollers & Embedded Systems, 13(5), 7-10.
[2] Zhou, Y.H. (2013). The Research of Evaluation Index System Based on Embedded Real-Time Operating System. Microcomputer Applications, (12), 7-9.
[3] Geng, Z., Wang, Z., Peng, C., & Han, Y. (2016). A new fuzzy process capability estimation method based on kernel function and FAHP. IEEE Transactions on Engineering Management, 63(2), 177-188.
[4] Rezakhani, S., Naghdi, M., Yousefi, M., & Kia, N. (2015, April). Priority setting in various DG technologies considering the reduction of energy subsidies using FAHP method. In Electrical Power Distribution Networks Conference (EPDC), 2015 20th Conference on (pp. 123-130). IEEE.
[5] Liu, F.H., & Fu, L.P. (2009). Determining the Weights of Evaluation Index of Enterprise's Technological Innovation Capability Based on FAHP. Statistics& Information Forum, 24(2), 24-28.
[6] Ma, Q.H. (2010). Study on Sci-tech Novelty Retrieval Quality Evaluation Base on Fuzzy-AHP (Doctoral dissertation, Nanchang University).
[7] Wang, H.J., Zong, C.F., Guan, X., Xing, R.F., & Liu, L.G. (2011). Method of Determining Weights of Subjective Evaluation Indexes for Car Handling and Stability Based on Fuzzy Analytic Hierarchy Process. Journal of Mechanical Engineering, 47(24), 83-90.
[8] Sun, F., Lu, F., Bi, H., & Yu, C. (2014, June). FAHP based evaluation of IT Outsourcing risk. In Intelligent Control and Automation (WCICA), 2014 11th World Congress on (pp. 602-604). IEEE.
[9] Jin, Y.S. (2017). Research on Software Project Risk Management Based on Fuzzy Analytic Hierarchy Process (Master's thesis, Tianjin Polytechnic University).

[10] Wu, J., Dong, X., Fang, Q., Chen, Z.M., & Zeng, C. (2013). A novel effectiveness Assessment Method of Weapon System Based on Triangular Fuzzy Number Analytic Hierarchy Process. China Mechanical Engineering, 24(11), 1442-1446.

[11] Li, B. (2 osciences (Beijing)).

[12] Dong, J.L., Li Y.F., Yang Q.F., & Zhai, J. (2013). Real-time performance evaluation of embedded operating system in aerospace. COMPUTER ENGINEERING AND DESIGN, 34(1), 114-120.

[13] Yu, F.X. (2006). Comparison and analysis of major embedded real-time operating systems. Computer Applications, 26(4), 761-764.

[14] Ji Z.J., Ma W.L., Chen, H., & Zheng, W.L. (2005). Analysis of Key Techniques Based on Four Embedded Real-Time Operating Systems. Journal of Computer Applications, 22(9), 4-8.

[15] Su, Y.L. (2007). THE COMPARISON & RESEARCH OFFOUR POPULAR RTOS—VXWORKS,QNX,UCLINUX,RTEMS. Computer Applications and Software, 24(8), 196-197.