Research on Evaluation of Linux in Aerospace Based on Improved FAHP

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Abstract: The evaluation and selection of embedded operating system are very important for manned spaceflight engineering. Considering the fuzziness and hierarchy of the evaluation process, a fuzzy analytic hierarchy process (FAHP) based on variation coefficient method and Criteria Importance Through Intercriteria Correlation (CRITIC) method is proposed to be applied to comprehensive evaluation of real-time Linux in space embedded system. The evaluation system, evaluation set and Gaussian distribution membership function are constructed, and the weight values of each criterion and index are determined by variation coefficient method and CRITIC method. The measured data are used for quantitative indexes such as real-time performance, and the expert scoring method is used for qualitative indexes such as reliability and compatibility, and verifies the validity of the model through simulation. The results show that the improved FAHP can quickly and intuitively judge the performance characteristics of Linux system and its derivatives, and provide a method for scientific and effective evaluation of space embedded operating system.

1. Introduction
In recent years, many countries all over the world have recognized the enormous role of manned space technology and deep space exploration technology in national defense security and national production, and a large number of spacecrafts for various purposes have emerged. In particular, the commercial aerospace group represented by SPACE X is constantly creating new records one after another in the history of human space launch. In 2011 and 2016, China launched the TianGong I and TianGong II Space Laboratory. At present, the manned space station is under development, and the scale and complexity of the spacecraft and its internal loads have reached unprecedented scale. Therefore, embedded real-time Linux is gradually being used in aerospace control systems due to its open source, rich interface and good real-time performance. In January 2014, JAXA, a Japanese aerospace research and development organization, transferred the solar observation satellite "Sunrise" and the satellite control function of the observation satellite GEOTAIL to the Linux platform [1]. In fact, embedded Linux real-time solutions include Xenomai, RTAI, and Preempt-RT. However, the real-time performance of Linux system based on the three real-time patches mentioned above and what new features the three patches will bring to the Linux kernel are all urgent problems to be solved. In addition to real-time performance, reliability and portability of Linux system are important for spacecraft applications. How to use scientific methods to evaluate real-time Linux scientifically and systematically, and choose the most suitable real-time Linux system as the next generation spacecraft load control system according to different application scenarios is an urgent problem to be solved. Therefore, according to the new requirements of China's space station stage for real-time, reliability and compatibility of aerospace
embedded operating systems, it is of great practical significance to carry out the evaluation of aerospace embedded real-time Linux.

At present, there are many comprehensive evaluation methods, such as Analytic Hierarchy Process (AHP) [2-3], Artificial Neural Network [4], and Fuzzy Analytic Hierarchy Process (FAHP). The AHP method is easily restricted by the evaluator's cultural background and it is very difficult to test whether the judgment matrix is consistent, and the standard CR < 0.1 lacks the scientific basis for testing whether the judgment matrix has consistency [5]. At the same time, the biggest problem of AHP is that when a certain level of evaluation indicators reaches four or more, the consistency of thinking is difficult to guarantee. The artificial neural network method cannot be applied to the comprehensive evaluation system of the operating system due to the complexity of the evaluation index of the operating system and the slow convergence speed of the operating system. While the standard FAHP method solves the problems of the AHP method, which does not consider the correlation between the evaluation indicators, so there are still some limitations in some special applications.

The evaluation of aerospace embedded real-time Linux is an integrated multi-factor evaluation. Therefore, this paper proposes a fuzzy hierarchical analysis method based on Gaussian distribution function scale to improve membership function to establish aerospace embedded real-time Linux evaluation system. At the same time, the combination of the coefficient of variation method and the CRITIC method improves the problem that the entropy method cannot effectively measure the correlation between indicators. In this paper, the evaluation model of the improved fuzzy AHP method is given, and the effectiveness and feasibility of the method are verified by an example.

2. Improve FAHP's judging method

Fuzzy Analytic Hierarchy Process (FAHP) and Computational Process Analytic Hierarchy Process (AHP) are a systematic analysis method combining qualitative and quantitative methods proposed by Professor T. L. Saaty of American Operations Research in the 1970s [6]. FAHP is a method of adding fuzzy set theory to traditional analytic hierarchy process. It describes the evaluation in interval form under the premise of thinking ambiguity, and becomes the scientific basis and theoretical method for solving the problem with uncertainty [7-8].

The literature [9-10] used the improved FAHP method to study the credibility of the railway train operation control system and the automatic ticket gate capacity system. Literature [11] only made a simple assessment of the embedded operating system in the aerospace field from a real-time perspective. The literature [12] describes the content of the operating system's evaluation system only in terms of functionality, efficiency, reliability, ease of use, maintainability and portability. At present, no systematic, comprehensive and scientific evaluation of the embedded real-time Linux system in the aerospace field has been found.

2.1. Establishment of the evaluation system

In the control system of the manned space field, considering the complexity of the operating system requirements, it is difficult to make a systematic, scientific and comprehensive evaluation of the aerospace embedded operating system with only real-time indicators. Therefore, it is necessary to establish a complete evaluation system. This paper combines the quality model and basic measurement and test points of military software products defined by GJB5236-2004 Military Software Quality Metrics and GJB7706-2012 Military Embedded Operating System Evaluation Requirements. At the same time, combined with the special requirements of the embedded real-time operating system in the aerospace field, the evaluation index of aerospace embedded real-time Linux was customized.

Following the principles of objectivity, measurability, completeness, independence, consistency and simplicity of the selection evaluation indicators [13], combined with the special requirements of real-time, reliability and compatibility in the manned space field, this paper selects the following indicators to comprehensively evaluate the aerospace embedded real-time Linux operating system, as shown in Table 1.
| Target layer | Criterion layer | Indicator layer |
|--------------|----------------|-----------------|
| Linux efficiency U | Real-time U1 | Interrupt delay time U11 |
| | | Task preemption time U12 |
| | | Task switching time U13 |
| | | Semaphore shuffling time U14 |
| Reliability U2 | | Kernel stability U21 |
| | | Mean Time Between Failure U22 |
| | | System fault tolerance rate U23 |
| Compatibility U3 | | Hardware compatibility U31 |
| | | Software compatibility U32 |

It can be seen from Table 1 that the evaluation system can be divided into three levels, namely the target layer, the criterion layer and the indicator layer. The criteria layer is divided into real-time U1, reliability U2, and compatibility U3. The index layer is further divided into real-time indicators such as interrupt delay time U11, task preemption time U12, task switching time U13, and semaphore shuffling time U14; reliability indexes such as kernel stability U21, Mean Time Between Failure (MTBF) U22, and system fault tolerance rate U23; And compatibility indicators such as hardware compatibility U31 and software compatibility U32.

This article refers to the real-time performance test indicators of industry-recognized real-time operating systems such as Rhealstone and Hartstone. The real-time indicator is further refined into four indicators: interrupt delay time U11, task preemption time U12, task switching time U13, and semaphore shuffling time U14. This paper removes the two indicators of deadlock release time and system throughput rate in the Rhealstone method. Because of the real-time solution based on real-time patches such as Xenomai, RTAI, and Preempt-RT, priority inheritance has been used to avoid the problem of priority inversion [9]. At the same time, for aerospace embedded real-time systems, the importance of real-time is much greater than the overall throughput of the system. Therefore, this article has removed these two indicators.

Reliability is embodied in three aspects: kernel stability U21, Mean Time Between Failure U22, and fault tolerance U23. A real-time dual-core mechanism based on Xenomai, RTAI real-time patches treats a system as consisting of two parts: a real-time part and a non-real-time part. The real-time microkernel has a higher priority than the standard Linux kernel and is primarily responsible for the processing of real-time tasks. Non-real-time tasks are handled by standard Linux. The standard Linux kernel runs while the real-time microkernel does not have real-time tasks to process. They can communicate through pipes or shared memory. Since the Linux real-time solution based on Xenomai and RTAI real-time patches is a dual-core architecture, once any kernel fails or crashes, Linux will reset, unexpected reset of the Linux may lead to the loss of important data, etc. For any kernel, the probability of a crash during work is obeying the Poisson distribution. The probability of failure does not occur: \( p_1 = p(x=0) = e^{-\lambda} \), then for a dual-core system, the probability of no failure is, \( p_2 = p(x_1=0) * p(x_2=0) = e^{-\lambda_1} * e^{-\lambda_2} = e^{-\lambda_1+\lambda_2} \). Here, let’s assume \( \lambda_1 = \lambda_2 = \lambda \), then \( p_1 > p_2 \). Therefore, it is not difficult to conclude that the stability of single-core system is higher than that of dual-core system. In summary, the real-time Linux dual-core architecture has a lower average failure time and fault tolerance than the single-core Linux operating system.

Compatibility refers to the hardware compatibility U31 and software compatibility U32 of the real-time system. With the increasing complexity of each load system in spacecraft, and considering the
requirement of updating software when spacecraft is in orbit in the next ten or twenty years, the selection of embedded hardware platform is relatively novel. Therefore, hardware compatibility and software compatibility (including applications, third-party software, and databases) of embedded real-time Linux have become a factor that cannot be ignored.

2.2. Evaluation sets and evaluation criteria
The evaluation set is a collection of evaluation results obtained after comprehensive evaluation of the aerospace embedded real-time Linux system, and the result can be expressed as \( V=\{v_1, v_2, v_3, \ldots \} \). In this paper, the evaluation grades are divided into five levels: “excellent”, “good”, “medium”, “poor” and “very poor”. Here, the method of measuring data is used for quantitative indicators such as real-time indicators, and the evaluation method of expert scoring is used for qualitative indicators such as reliability and compatibility, and the fuzzy judgment matrix is constructed accordingly.

2.3. Determination of membership function
The membership function is one of the important means to characterize the degree of blurring of fuzzy sets. In the embedded real-time Linux evaluation process, due to the differences in the knowledge background of the evaluators, it is difficult to avoid the influence of subjective factors, and the assessment of the accuracy and objectivity of the results of the aerospace embedded real-time Linux is very high. However, the traditional 1-9 standardization method often shows inconsistencies between the measured results and the thinking judgment [14]. Therefore, in order to meet the consistency requirements as much as possible, and to minimize the influence of subjective factors, a Gaussian distribution function with 0-1 scale is proposed as the membership function to generate the fuzzy judgment matrix. The index is as shown in Equation 1:

\[
R(x|\mu_j, \sigma_j) = \exp\left[-\frac{(x - \mu)^2}{\sigma^2}\right] \quad (1)
\]

Where \( \mu_j, \sigma_j \) are the distribution parameters of the \( j \)-th rank. The values of \( \mu_j \) and \( \sigma_j \) can be obtained from historical experience, as shown in Table 2.

| Rank         | Excellent | Good      | Medium    | Poor      | Very poor |
|--------------|-----------|-----------|-----------|-----------|-----------|
| [\mu_j, \sigma_j] | [0.9,0.2] | [0.7,0.2] | [0.5,0.2] | [0.3,0.2] | [0.1,0.2] |

2.4. Determination of indicator weight coefficient
The core of the FAHP method is how to determine the weight of each indicator. The Entropy weight method has been widely used to calculate the weight of each indicator of comprehensive evaluation, but it does not consider the consistency between the indicators [15]. Assigning different weight values to individual indicators will directly affect the final evaluation results. At the current stage, the methods for determining the weight of indicators mainly include subjective weighting method and objective weighting method [4]. The biggest feature of the former is that it has great uncertainty and the result lacks credibility. For the latter, the commonly used methods are weighted statistical method, factor analysis weight method, entropy weight method, CRITIC method and so on. The first three do not consider the correlation between indicators, and there is a certain degree of correlation between the indicators of the real-time Linux operating system. For example, the task preemption time includes the task switching time. The CRITIC method assigns weights based on the amount of information and correlation between indicators. Because the magnitude and dimension of the indicators are not the same, the CRITIC method calculates the variability of each index according to the standard deviation, which leads to the natural defects of the standard CRITIC method on this issue. In summary, in order to improve the objectivity of the FAHP method, this paper uses the combination of the coefficient of variation method and the CRITIC method to determine the weight between indicators. Not only fully consider the information volume of indicators and the correlation between indicators, but also make up for the lack of variability of indicators using standard deviation [4].

In this paper, the coefficient of variation is determined by the coefficient of variation method and the CRITIC method. The specific steps are as follows:
Construct the original predictor matrix:
\[ X = \{x_{ij}\}, \quad i \in \{1, 2, \ldots, n\}, \quad j \in \{1, 2, \ldots, m\} \]  
(2)

It can be seen from Table 1 that the physical meaning and magnitude of each indicator are not the same, so each indicator must be standardized before evaluation. In this paper, the elements of matrix X are preprocessed by Max-Min standardization method:

\[ x'_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \]  
(3-a)
\[ x'_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \]  
(3-b)

For the i-th indicator, the higher the j-th index, the better, the standardization using the 3-a formula. On the other hand, if the j-th index is as low as possible for the i-th index, the 3-b formula is used for standardization.

The internal variability of the evaluation index, that is, the sample standard deviation is:

\[ \sigma_j = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_{ij} - \bar{x}_j)^2} \]  
(4)

\( \bar{x}_j \) is the expected value of the indicator j, \( \bar{x}_j = \frac{1}{n} \sum_{i=1}^{n} x_{ij} \).

According to the definition of the coefficient of variation method, the degree of variation of the j-th index is

\[ v_j = \frac{\sigma_j}{\bar{x}_j} \quad (j=1, 2, \ldots, n) \]  
(5)

And because the correlation coefficient of the i-th and j-th items of the indicator is \( R(x_i, x_j) = \{r_{ij}\} \),

\[ r_{ij} = \frac{\text{Cov}(x_i, x_j)}{\sqrt{\text{Var}(x_i)\text{Var}(x_j)}} = \frac{\sum(x_i - \bar{x}_i)(x_j - \bar{x}_j)}{\sqrt{\sum(x_i - \bar{x}_i)^2 \sum(x_j - \bar{x}_j)^2}} \]  
(6)

\( \text{Cov}(x_i, x_j) \) is the covariance of the indicators i and j, \( \text{Var}(x_i) \) is the variance of the indicator i, the coefficient of degree of independence of each index can be obtained from equation (6).

\[ r_{ij} = \sum_{i=1}^{n}(1 - r_{ij}) \]  
(7)

\( r_{ij} \) is the correlation coefficient between the i-th and j-th items of the indicator.

Then, according to equations (5) and (7), the information quantity of the index j and the comprehensive quantization coefficient of the degree of irrelevance are obtained as:

\[ C_j = v_j r_j = \frac{\sigma_j}{\bar{x}_j} \sum_{i=1}^{n}(1 - r_{ij}) \]  
(8)

In summary, according to formula (8), the weight value of each indicator can be calculated:

\[ \omega_j = \frac{C_j}{\sum_{j=1}^{m} C_j} \]  
(9)

3. Engineering case analysis

3.1. Evaluation steps

The basic flow of the evaluation model of the aerospace embedded real-time Linux operating system based on improved FAHP presented in this paper is as follows:

1) Analyze the relationship between the evaluation indexes of aerospace embedded real-time Linux, and establish an evaluation index system and evaluation set of aerospace embedded real-time Linux;

2) For the criteria and indicators established in step 1, respectively determine the membership function that matches it;

3) Using the coefficient of variation method and the CRITIC method to jointly determine the weight values of each criterion and indicator;

4) For the membership function established in step 2, the quantitative indicators and the qualitative indicators are evaluated by means of measured data and expert scoring methods, and the best solution is selected according to the evaluation results;
3.2. Evaluation process and results analysis

First, because the selected U1, U2, and U3 criteria have different weights for aerospace embedded real-time Linux, the three criteria of U1, U2, and U3 are weighted by expert scoring methods. The results are as follows.

\[ RU = \begin{bmatrix} 0.5 & 0.7 & 0.8 \\ 0.3 & 0.5 & 0.7 \\ 0.2 & 0.3 & 0.5 \end{bmatrix} \]

Then, the matrix \( RU \) can obtain the weight value \( WU \) of the U1, U2, and U3 criteria by Equations 3 to 9, as shown below.

\[ WU = [0.5899, 0.2633, 0.1468] \]

The real-time indicators U11, U12, U13, and U14 are scored by experts, and the fuzzy evaluation matrix \( RU1 \) is as follows:

\[ RU1 = \begin{bmatrix} 0.5 & 0.7 & 0.7 & 0.8 \\ 0.3 & 0.5 & 0.6 & 0.6 \\ 0.3 & 0.4 & 0.5 & 0.55 \\ 0.2 & 0.4 & 0.45 & 0.5 \end{bmatrix} \]

The weight values of the real-time indicators of U11, U12, U13, and U14 can be obtained by Formula 3~Formula 9, as follows:

\[ WU1 = [0.424, 0.2409, 0.2222, 0.1129] \]

For the qualitative indicators such as reliability indicators U21, U22 and U23 and portability U31 and U32, the weights are calculated by expert scoring. The fuzzy evaluation matrices \( RU2 \) and \( RU3 \) are as follows.

\[ RU2 = \begin{bmatrix} 0.5 & 0.65 & 0.75 \\ 0.35 & 0.5 & 0.6 \\ 0.25 & 0.4 & 0.5 \end{bmatrix} \]

\[ RU3 = \begin{bmatrix} 0.5 & 0.7 \\ 0.3 & 0.5 \end{bmatrix} \]

The weight values of \( WU2 \) and \( WU3 \), which are obtained by using Equations 3 to 9 for reliability and portability, are:

\[ WU2 = [0.434, 0.308, 0.258] \]

\[ WU3 = [0.6, 0.4] \]

In order to verify the validity of the evaluation model of the aerospace embedded Linux operating system based on the improved FAHP proposed in this paper, the four real-time indicators are preprocessed and then evaluated. The measured values are not listed separately in the space, and the preprocessed data is shown in Table 3.

| Index          | U1  | U1  | U1  | U1  |
|----------------|-----|-----|-----|-----|
| Linux std.     | 0.4 | 0.5 | 0.5 | 0.5 |
| Linux+Preempt-RT | 0.5 | 0.6 | 0.5 | 0.5 |
| Linux+Xenomai  | 0.7 | 0.6 | 0.6 | 0.5 |
| Linux+RTAI     | 0.8 | 0.6 | 0.6 | 0.5 |

According to Table 3, the fuzzy evaluation matrix \( BI \) of the real-time index can be obtained,

\[ BI = \begin{bmatrix} 0.4 & 0.5 & 0.5 & 0.5 \\ 0.5 & 0.6 & 0.5 & 0.5 \\ 0.7 & 0.6 & 0.6 & 0.6 \\ 0.8 & 0.6 & 0.6 & 0.6 \end{bmatrix} \]

Next, expert scoring is used to score the standard Linux, Preempt-RT based patches, Xenomai patches and RTAI patches based on the reliability and compatibility criteria, and the fuzzy judgment
matrices $B_2$ and $B_3$ are obtained.

\[
B_2 = \begin{bmatrix}
0.8 & 0.7 & 0.7 \\
0.7 & 0.6 & 0.6 \\
0.5 & 0.4 & 0.5 \\
0.5 & 0.4 & 0.4 \\
0.7 & 0.8 & 0.7 \\
0.4 & 0.4 & 0.4 \\
0.3 & 0.4 & 0.3 \\
\end{bmatrix}
\]

\[
B_3 = \begin{bmatrix}
0.7 & 0.8 \\
0.7 & 0.4 \\
0.4 & 0.4 \\
0.3 & 0.4 \\
\end{bmatrix}
\]

According to $V = B_i W_{\mu_i}^T$ ($i = 1, 2, 3$), the evaluation results of the standard Linux, Preempt-RT based patches, Xenomai patches and RTAI patches can be obtained as follows:

\[
V_1 = [0.4576, 0.52409, 0.6424, 0.6848] \\
V_2 = [0.7434, 0.6434, 0.4692, 0.4434] \\
V_3 = [0.74, 0.7, 0.4, 0.3] \\
V = V_1 * 0.5899 + V_2 * 0.2633 + V_3 * 0.1468 = [0.57430746, 0.581327911, 0.56121212, 0.56475074]
\]

The four values of vector $V_1$, $V_2$, $V_3$, and $V$ correspond to real-time, reliability, compatibility, and final evaluation results of standard Linux, Preempt-RT based patches, Xenomai patches, and RTAI patches based on real-time Linux.

In summary, based on the evaluation results of the improved FAHP comprehensive assessment program, the overall evaluation results of the above four mainstream embedded Linux are: The Linux system based on Xenomai patch and RTAI patch has the best real-time performance, but the reliability and compatibility are slightly lower. The reliability and compatibility of standard Linux systems are good but the real-time performance is too poor; Linux based on Preempt-RT patch has better real-time performance, reliability and compatibility. The final evaluation result of the real-time Linux system based on Preempt-RT patch is better than the other three, so it can be determined that the real-time Linux system based on Preempt-RT patch is the first choice for the current stage manned space application system load control system.

4. Conclusion

Aimed at the practical problems of embedded real-time Linux operating system evaluation in manned space engineering application system, this paper proposes and establishes a FAHP comprehensive evaluation system based on the variation coefficient method and CRITIC method. This method not only quantitatively solves the qualitative indicators such as the reliability and compatibility of embedded real-time Linux, but also adopts the measured data scheme for quantitative indicators such as real-time performance. It greatly reduces the subjective impact of relying on expert scoring, and greatly simplifies the computational complexity through the use of MATLAB calculations, providing a more intuitive and convenient reference for the development and selection of manned space applications. It also provides a new way of thinking for the evaluation and selection of embedded operating systems in the aerospace and other engineering fields.

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