Software reliability allocation model of CNC system based on software architecture

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Abstract

In order to guarantee the implementation of reliability target, software reliability allocation model of CNC system was established based on software architecture. Software architecture of CNC system was set up, which decomposed CNC system into the functional units, reliability indexes of the system can be distributed into each component from top to bottom. The relative weight of software element in each level of the architecture was determined with analytic hierarchy process (AHP) method. The software reliability allocation model was built by taking the maximum practicability of CNC system as the target function, the reliability and cost function of component as the constraints. The reliability of each component was calculated through culture algorithm (CA). According to the result, the reliability allocation worked out is reasonable and feasible, and during the development of allocation model, the practicability of CNC system was guaranteed and development cost was also saved effectively.

Keywords: software reliability of CNC system, software architecture, reliability allocation, analytic hierarchy process, cultural algorithm

1 Introduction

This CNC system is the core of the CNC machine tool, whose reliability directly impacts the reliability level of the complete CNC machine tool. The software reliability of CNC system is a significant index for measuring the quality of CNC system. As a result, to improve the software reliability of CNC system is a key to improve the overall performance of the CNC machine tool. Therefore, it is imperative to conduct further studies on the software reliability of CNC system. The CNC system is developing towards high-precision, networking, intelligent and complex trend, with more powerful functions, larger calculated quantity. The software scale expands constantly, and it is getting more difficult to guarantee the software reliability [1]. In order to reach certain reliability target, developers must carry out repeatedly tests with unremitting efforts. However, it is extremely complicate in the software, and each component of the software has different influences on the overall software reliability [2-4]. Consequently, in order to avoid unnecessary valuable resources and costs, it must make a difference between each part of the system.

Reliability allocation means that the stipulated system reliability indexes should be regulated properly among the sub-systems forming the whole system, thus to reach the minimum cost of recourses employed by the system development. The software reliability allocation aims to convert the system reliability index into the reliability index of each sub-system, for guiding the development of sub-system to seek for an optimal design scheme with the resource constraints, thus the system can achieve high reliability [5]. Since the software system is complicated and diversified, each component has distinct influence on the entire software system, and the software developers can only give full considerations during the software development system and assign to each allocation items, software parts till the software units after through comprehension of requirements of the software reliability. So the software developers can be clear about their responsibilities in reliability, carry out reliability analysis and design, and guarantee the implementation of final reliability target.

The hardware reliability allocation technique is mature, but the software reliability allocation is still immature. There have been a series of methods for applying the software reliability allocation already, which mainly includes: Wei Gang has proposed a method of complex software system reliability allocation based on ANP and established reliability allocation model of the complex software system [6]. Kaveh has proposed a dynamic self-adaptive multi-objective particle swarm optimization method to solve binary-state multi-objective reliability redundancy allocation problems [7]. Roberto has corrected the degree of reliability in tandem structure that affects the reliability of the software system components and on this

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basis, proposed the optimal allocation of time test method [8]. Zhou has proposed embedded real-time multi-tasking software reliability allocation model [9]. Kapur has proposed a mathematical model framework with multiple versions of the software [10].

At present, most reliability allocation is based on the test data, and few consider the architecture of software. Therefore, it is difficult to carry out reliability allocation in the early stage of systematic design. The current reliability distribution fails to consider the relationship between the reliability of software system and the reliability of each component. Meanwhile, there are fewer applications of software architecture study in the software reliability of CNC system, lacking a widely accepted model. The architectural model covers overall systematic information, which makes it convenient for comprehending and analysing the system. The architectural model can guarantee the consistency and completeness of system during the reliability allocation process. In this paper, the software architecture of the CNC system is established, the reliability indexes can be allocated to the components properly to satisfy the reliability requirements of the software system.

The remainder of the paper is organized as follows. Section 2 set up the software architecture of CNC system, software reliability allocation model of CNC system is established on the basis of software architecture. Section 3 presents the AHP method to solve the relative weight of software element in each level of the architecture. Section 4 introduced the theoretical culture algorithm to solve the model. Finally, an application example was given in section 5 to verify the method proposed in this paper.

2 Software reliability allocation model of CNC system

The software architecture is the abstraction of overall result in an abstract level, which provides better methods for developers to comprehend the software and to construct bigger and more complicated software system. As the blueprint of software, the software architecture provides an effective approach for people to grasp the overall software structure, which mainly refers to the organizational structure of the software system, the space connections, constraints, as well as the design and evolution principle and criteria. It is a relatively abstract and macroscopic description of the system composition and system structure, indicating the system division and composition. Gerlan & Shaw model generalized the software architecture as [11].

Software Architecture = {components, connectors, constraints}.

The component is the collection of related objects, which implements certain computational logic after implementation. It is related to structure or logic, and can be embedded into different architecture independently for implementing the reuse of components. The adapting piece is a group of objects, providing high-level communication among the components. It connects different components, forming a part of the architecture, generally represented as the frame target or transition target. The constraint refers to the rules of component connection, pointing out the posture and condition of component connection. Generally, it consists of semantic constraints and topology constraints.

According to the software architecture, as well as the hierarchical structure of CNC system and functional unit, software architecture of CNC system was established for the corresponding relationship of each level. The software architecture of CNC system is divided into functional level F, program level P, and component level C, as shown in Figure.1.

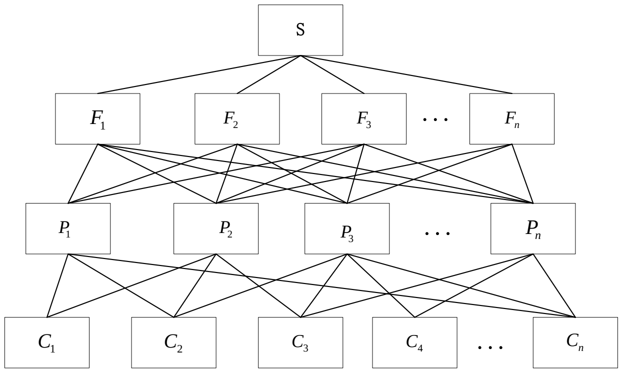

FIGURE 1 Software architecture of CNC system

There is a linear relationship between the software availability and software function, as well as the reliability of these functions [12], which can be defined as:

$$U = \sum_{i=1}^{f} \omega f_i \cdot rf_i \ , \tag{1}$$

$$U = \sum_{i=1}^{p} \omega p_i \cdot rp_i \ , \tag{2}$$

where: ωf_i is the global relative right of function *i*, rf_i is the reliability of function *i*, ωp_i is the global relative right of program *i*, rp_i is the reliability of program *i*.

Suppose all of the components C{c1,c2,c3,…,cn} in software are mutually independent, and then the reliability of program rp_i is the product of the reliability of all components.

$$rp_i = \prod_{j \in c_i} rc_j \ . \tag{3}$$

According to the software architectural characteristics of the CNC system, the reliability index can be allocated to each functional component with the maximum practicability of CNC system as the target, and the reliability and cost of the component as the constraints. Suppose the system has n functional components, remarked as C{c1,c2,c3,…,cn}, the software reliability allocation model of the CNC system is shown as follows:

$$\max[U=\sum_{i=1}^{p}\omega p_i\cdot\prod_{c_j\in c_i} rc_j] \ , \quad (4)$$

$$rc_j \le u_i$$
$$rc_j \ge l_i$$
$$\alpha_j + q_j\cdot rc_j \le \alpha\cdot v_i \ ,$$
$$\sum_{j=1}^{m}\alpha_j + q_j\cdot rc_j \le \Omega$$

where the reliability of component i is rm_i, $0<\omega p_i<1$, $\sum_{i=1}^{n}\omega p_i=1$, and its upper limit is u_i, while its lower limit is l_i. α_j is the general expense at the time of exerting reliability rc_j constraint on the component i, q_j is the adjustable cost expense, α is the deduction of developers profit from 1, v_i is the cost for accomplishing the component i, and Ω is the development cost budget of the numerical control system software.

3 Reliability allocation model AHP analysis

The significance of each component is determined with AHP method, for it can decrease the artificial factor during the weight determination process, thus to guarantee the practicability and relative objectivity of weight. The method of working out weight collection with AHP is shown as follow: according to the architecture of CNC system, the factors of each level are taken as the criteria successively, and significance of all the elements of the next level related shall be compared, and a value of relative significance can be achieved a_{ij}. A judgment matrix can be obtained by comparing each influencing factors, thus n-order matrix can be formed.

$$A=\begin{pmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{pmatrix} , \quad (5)$$

where $a_{ij}>0,\ a_{ji}=\frac{1}{a_{ij}},\ a_{ii}=1,\ i,\ j=1,2,\dots,n$. a_{ij} is selected according to the '1-9' proportion scale improved according to the relative significance [13].

Suppose there are n factors in this level related to a certain index in the previous level, and then the indexes of the previous level above n factors of this level can be the relative significant weight of comparison between the two, namely the weight vector of this level is:

$$W=(w_1,w_2,\dots,w_n)^T \quad 0\le w_i\le 1 (i=1,2,\dots,n) . \quad (6)$$

According to the judgment matrix constructed, sum and product method is adopted for calculating the normalization processing characteristic value w_i and maximum characteristic root $\lambda_{\max}$ of each judgment matrix [14], according to the following equation:

$$w_i=\frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_{k=1}^{n}a_{kj}} \quad (i=1,2,\dots,n) , \quad (7)$$

$$\lambda_{\max}=\frac{1}{n}\sum_{i=1}^{n}\frac{(Aw)_i}{w_i} , \quad (8)$$

where A is the judgment matrix, $(Aw)_i$ is i element of the vector Aw .

By calculating the maximum characteristic root $\lambda_{\max}$ of judgment matrix and characteristic vector W, the relative significance weight of a certain factor towards another factor in previous level. AHP measures the consistency degree of the judgment matrix through calculating the consistency ratio CR, when $CR\le 0.1$, it is in accordance with the consistency, or it is deemed that the judgment is of certain randomness, and it should adjust the element value of the judgment matrix. CR can be calculated according to Equation (9):

$$CR=\frac{CI}{RI} , \quad (9)$$

$$CI=\frac{\lambda_{\max}-n}{n-1} , \quad (10)$$

where CI is consistency index of the judgment matrix, when the judgment matrix is complete consistent, $CI=0$, RI is average random consistency index, $\lambda_{\max}$ is maximum characteristic root of judgment matrix, n is orders of the judgment matrix.

When checking the consistency of each judgment matrix, it should calculate the RI value of the judgment matrix gain according to new scale, and in Table 1, new RI value is given:

TABLE 1 Random consistency index RI

Order	1	2	3	4	5
RI	0	0	0.1690	0.2598	0.3287
Order	6	7	8	9	
RI	0.3694	0.4007	0.4167	0.4370	

4 Culture algorithm

Culture algorithm is a bionic intelligent calculation method simulating the cultural evolution. With the double evolutionary mechanism formed by upper reliability level and bottom population space, the algorithm excavates implicit knowledge reflecting the evolutionary degree and advantageous region from the evolutionary individual in bottom population, and then send feedbacks of the knowledge stored in reliability space to the population evolution process for improving the searching efficiency and improving the performance of algorithm [15]. Culture algorithm simulates the cultural evolution process of human society, with double evolution mechanism on the basis of traditional population-based evolution algorithm [16]. The reliability space is constructed to extract various types of information implied during the evolutionary process, and it is stored in the form of knowledge, which will finally be applied for guiding the evolutionary process. The algorithm flow is shown as follows [17]:

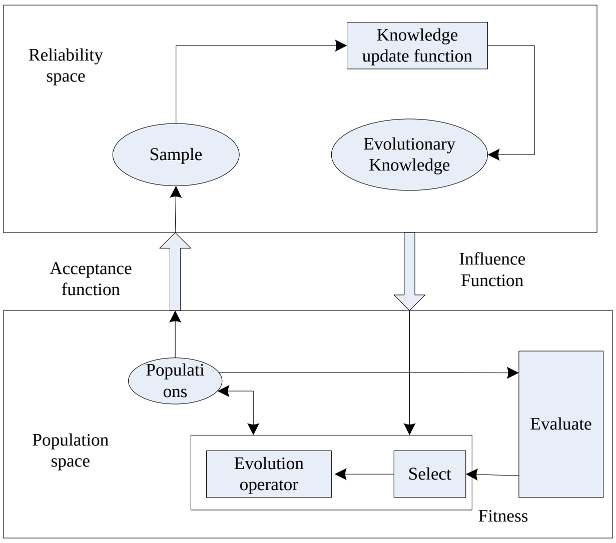

FIGURE 2 Culture algorithm flow

5 Application example

The software architecture of CNC system constructed by taking the maximum practicability of CNC system as the target function is shown as follows:

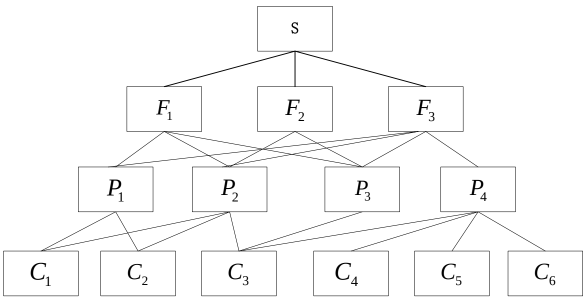

FIGURE 3 Software architecture model of the CNC system

The judgment matrix is constructed by comparing the relative significance of each factor according to the improved 1-9 proportional scale. In the CNC system functional layer, usefulness of the functional importance of F1 F2 F3 CNC system is on scoring pairwise comparison, the judgment matrix U-F as shown in Table 2.

TABLE 2 Evaluation matrix for U-P layer

U	F_1	F_2	F_3
F_1	1	1.22	1.5
F_2	1/1.22	1	1.22
F_3	1/1.5	1/1.22	1

In the CNC system program layer, P1 P2 P3 importance of CNC system functional layer scoring is on scoring pairwise comparison. The judgment matrix F-P as shown in Table 3-5.

TABLE 3 Evaluation matrix for F1-P layer

F_1	P_1	P_2	P_3
P_1	1	1.22	1.22
P_2	1/1.22	1	1
P_3	1/1.22	1	1

TABLE 4 Evaluation matrix for F2-P layer

F_2	P_2	P_3
P_2	1	1.5
P_3	1/1.5	1

TABLE 5 Evaluation matrix for F3-P layer

F_3	P_1	P_2	P_3	P_4
P_1	1	1.22	2.33	1.5
P_2	1/1.22	1	1.86	1.22
P_3	1/2.33	1/1.86	1	1/1.5
P_4	1/1.5	1/1.22	1.5	1

In the CNC system component layer, C1 C2 C3 C4 importance of CNC system program layer scoring is on scoring pairwise comparison. The matrix of P-C judgment as shown in Table 6-8.

TABLE 6 Evaluation matrix for P1-C layer

P_1	C_1	C_2
C_1	1	1.22
C_2	1/1.22	1

TABLE 7 Evaluation matrix for P2-C layer

P_2	C_1	C_2	C_3
C_1	1	1.22	2.33
C_2	1/1.22	1	1.86
C_3	1/2.33	1/1.86	1

P3=1

TABLE 8 Evaluation matrix for P4-C layer

P_4	C_1	C_2	C_3	C_4
C_1	1	1/1.22	1/1.22	1/1.5
C_2	1.22	1	1	1/1.22
C_3	1.22	1	1	1/1.22
C_4	1.5	1.22	1.22	1

The normalization processing characteristic value w_i and maximum characteristic root $\lambda_{\max}$ is calculated according to Equation (7) and Equation (8), the weight vector of each level is obtained, and the single hierarchical arrangement structure is shown in Table 9. The consistency is verified according to Equation (9) and Equation (10) *CR* is smaller or equal to 0.1, and as a result, the judgment matrix constructed is proper and reliable.

According to the above calculation result, the overall weight vector of calculation procedure level and component level towards the target level is calculated, and the consistency has been verified.

WP=(ωp_1 ωp_2 ωp_3 ωp_4)=(0.245 0.397 0.297 0.061),

WC=(ωc_1 ωc_2 ωc_3 ωc_4 ωc_5 ωc_6)=(0.311 0.254 0.386 0.015 0.015 0.019).

TABLE 9 Results of single ordering for hierarchy

H	W	λ_{max}	CI	CR
U-F	[0.4023, 0.3289, 0.2688]	3.0	0	0
F_1-P	[0.3788, 0.3106, 0.3106]	3.0	0	0
F_2-P	[0.6,.04]	2.0	0	0
F_3-P	[0.3436, 0.2792, 0.1497, 0.2275]	4.0001	0	0
P_1-C	[0.5495,0.4505]	2	0	0
P_2-C	[0.4453,0.3618,0.1928]	3.0001	0	0
P_3-C	1	1	0	0
P_4-C	[0.2025, 0.2475, 0.2475, 0.3025]	4.0	0	0

Suppose the software cost is V=1000000, it can be obtained that the component cost vector is V×WC (311 254 386 15 15 19). Let the profit as 50%, and the component 4-6 has no profit, α =1. The development cost of CNC system software is Ω . Substitute the data to Equation (4), it can be obtained that:

$$\max[U = \sum_{i=1}^{p} \omega p_i \cdot \prod_{c_j \in c_i} rc_j]= ,$$

$$0.245(rc_1 rc_2)+0.397(rc_1 rc_2^2 rc_3)+0.297(rc_3^4)+0.061(rc_3^2 rc_4^3 rc_5 rc_6)$$

$$\begin{aligned} & 0.6 \le rc_j \le 1 \quad j = 1,2,\ldots,6 \\ & 95 + 60 rc_1 \le 0.5 \cdot (311) \\ & 70 + 50 rc_2 \le 0.5 \cdot (254) \\ & 85 + 90 rc_3 \le 0.5 \cdot (368) \quad , \\ & 5 + 8 rc_4 \le 15 \\ & 7 + 6 rc_5 \le 15 \\ & 3 + 5 rc_6 \le 19 \end{aligned}$$

$$265 + 60 rc_1 + 50 rc_2 + 90 rc_3 + 8 rc_4 + 6 rc_5 + 5 rc_6 \le 490 .$$

Run the cultural algorithm by Matlab, the result of the first 8 iterations shows in Table 1. Seen from Table 10, the min adaptation function value is steady at 0.9999.

The reliability of the components is:

$[rc_1\ rc_2\ rc_3\ rc_4\ rc_5\ rc_6\ ]$= [0.9758 0.9412 0.6747 0.7026 0.7587 0.8772]

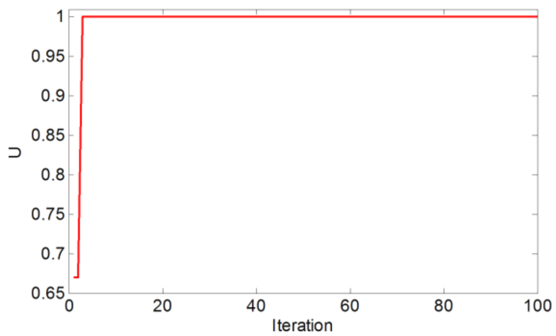

FIGURE 4 Adaptation values and iteration times

TABLE 10 Result of the first 8 iterations

iteration	U
1	0.7490
2	0.7490
3	0.9999
4	0.9999
5	0.9999
6	0.999
7	0.999
8	0.999

Conclusion

The architecture of CNC system software was established in this paper, the software reliability index allocation method of CNC system has been proposed based on software architecture. The reliability index of CNC system has been allocated to the functional units, and the reliability allocation model has been established by taking the system practicability as the target function, and the reliability degree and cost function of functional units as the constraints. The relative weight of each element in the software architecture of CNC system has been calculated with AHP, and the allocation value of each component has been worked out with culture algorithm. The example has shown that this method guarantees that the system reliability index can satisfy the requirements, and meanwhile, it also saves the development cost effectively, improves the validity of allocation method and provide basis for studying the feasibility of its sub-system.

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