Collaborative Validation Method for Complex Spaceflight Products Performance Mock-Up

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Abstract

In view of the complex spaceflight products performance mock-up (PMU) validation issues, the validation process of the complex spaceflight products PMU is analyzed, some validation methods are given and a PMU validation tool is proposed and implemented. Firstly, some existing validation methods are introduced based on the analysis of the complex spaceflight products PMU. Then, a framework of the PMU validation tool based on Multi-Agent System (MAS) is proposed, and a new PMU validation tool is designed and implemented. Finally, taking a supersonic aircraft PMU as an example, the effectiveness and practicability of the PMU validation tool is verified. Validation results show that the method and the PMU validation tool can help validating the complex spaceflight products PMU, it is effective and practicable.

Key words: PERFORMANCE MOCK-UP (PMU), MULTI-AGENT SYSTEM (MAS), VALIDATION TOOL, COLLABORATIVE VALIDATION

1. Introduction

The complex spaceflight products digital PMU technology has become a hot research topic in the industry and academia, because its study is challenging and difficult. It's usually consists of hundreds of companies for large complex spaceflight products design that includes feasibility studies, design, manufacture, testing and some other fields. At present, it's not yet mature of quantitative description and modeling theory for the PMU. Complex spaceflight products PMU deals with many subjects and fields widely, facing the ground simulation experimental conditions hard, high target requirements, physical validation difficulties. It's a multi-stage design and whole lifecycle process for development of PMU, including the complete digital information models within the product lifecycle components and devices. And in the research of complex spaceflight products PMU, different subsystem of design modeling, simulation and validation using different tools have different characteristics, the coordination between different systems have different

dependencies, different information models need consistent expression in semantic level.

Performance mock-up (PMU) refers to the cluster of the models describing products completion and performance test in accordance with the design requirements in certain circumstances, taking the three-dimensional geometric and physical models of the products as the foundation. It can effectively shorten the product development cycle, reduce development costs and improve product quality by replacing the real physical mock-up is studied with PMU. However, has a certain credibility is precondition of PMU is able to replace the physical mock-up to analysis and research the product performance. It is meaningless for the research of the real product which the PMU doesn't have a high credibility [1]. Verification, validation and accreditation (VV&A) is an effective means to assure the reliability of PMU. Complex spaceflight products PMU deals with many subjects and fields widely, the verification and accreditation of PMU are similar to general model. Due to the models of complex spaceflight PMU has different levels of data coupling and control coupling; its validation work is numerous. Therefore, the validation of PMU is different from general simulation model validation. It is necessary to research the validation methods and tools of the PMU according to its characteristics.

In this paper, the validation process of the complex spaceflight products PMU is analyzed, some validation methods are given and a PMU validation tool is proposed and implemented. For the characteristics of complex spaceflight products PMU validation, using some existing validation methods based on the analysis of the process of the complex spaceflight products PMU validation and a framework based on multi-agent system, to design and implement a PMU validation tool, and taking a complex spaceflight products PMU as an example, the effectiveness and practicability of the PMU validation tool is verified.

2. Process and the methods for performance mock-up validation

2.1 Establishment of the validation index system of performance mock-up

The validation of PMU includes conceptual model cluster validation and simulation model cluster validation. Conceptual model cluster is mainly refers to the abstract mathematical models which are established based on complex space products of is established (mathematical equations) and related assumptions, etc. Simulation model cluster refers to the computer program that can be run on computer hardware and software supporting platform, described by the computer language. The simulation model is based on mathematical model. Mostly, a computer program is transformed from a mathematical model that does some simplification. Therefore, only after the model of PMU achieving customer satisfaction, its simulation model is validated.

PMU can be divided into multiple subsystem models with the coupling relationship, such as common vehicle PMU can be divided into mechanical subsystem model, hydraulic subsystem model and control subsystem model, etc. And each subsystem model is composed of corresponding sub models. The credibility of sub models can be obtained by Analyzing its main performance parameters and design requirements or test data with the common validation methods. Hereby, we can design a validation index system of prototype mock-up reliability, which is shown in figure 1. Figure 1 is a schematic diagram of a validation index system, and the validation index systems of products PMU are different according to their own composition.

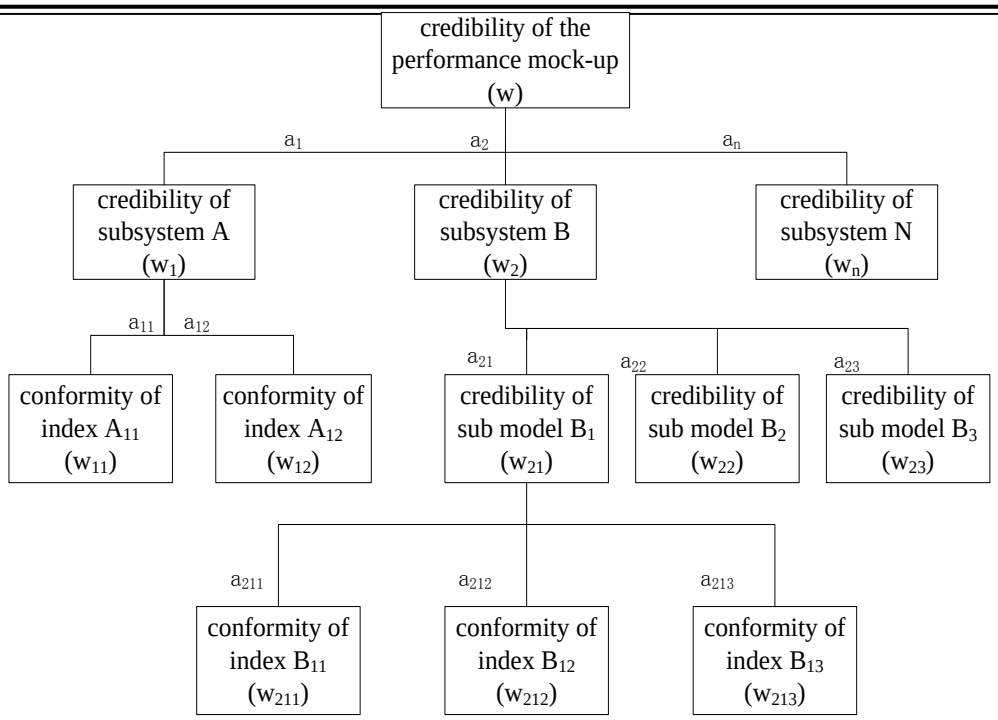

Figure 1. Schematic diagram of PMU validation index system

In figure 1, w_i is the credibility of the subsystem, sub models or the indicators, a_i is the weight at each level to meet the size of the degree of contribution to its superior reliability. For the validation of the cluster of conceptual models, the underlying conformity is given by experts analyzing its model, having some subjectivity. For the validation of the cluster of simulation models, on the premise of the simulation results with the experimental data obtained, numerical analysis method can be used for its consistency test and verify to get the underlying conformity degree. On the basis of the underlying conformity degree and the weights at all levels, the credibility of the PMU can be obtained according to the following formula (1).

$$\begin{cases} w = \sum a_i w_i \\ w_i = \sum a_{ij} w_{ij} \\ w_{ij} = \sum a_{ijk} w_{ijk} \end{cases} \quad (1)$$

Where, a is the weight at each level, w is the credibility or conformity.

2.2 Analysis underlying validation index correspondences for prototype mock-up

For the validation of the cluster of conceptual models, the conformity of each model is obtained either with the expert subjective assignment or with comparing to existing mathematical model by the users, which is easy [2]. Here we emphasis on the calculation of the simulation model validation index conformity.

From the validation index system of the PMU established in figure 1, we can see that as long as the conformity of the underlying index is calculated, the credibility at other levels can be calculated by the formula (1). For the validation of the underlying validation index, its simulation data can be easily get, and its reference data gets difficultly[3]. Therefore, we should be in accordance with the corresponding reference data underlying validation indexes and formulate the corresponding validation strategy. The validation index reference data can be basically divided into the following several sections.

a. There is no reference data, only expert experience. Due to the characteristics of complex space products, sometimes on the physical test to obtain the corresponding performance parameters is almost impossible. Then experts determine the conformity according to the experimental parameters from the expert's experience or directly determine it by observing the simulation results. For example, the offensive and defensive system's simulation of the outer space, this situation can only rely on qualitative knowledge of experts. If the behavior of validation index does not accord with that knowledge, then the

correctness of the sub model is also questionable. In this case, the method of expert subjective assignment is used to evaluate the conformity of the underlying validation index.

b. Only a small amount of reference data. For example, we can get a small amount of related performance parameters through flight tests, or a small amount of reference data from an existing similar test record. Usually, less reference data of performance parameters is static performance parameters. We can use appropriate numerical processing method to compare the simulation results with the reference data to analyze the underlying validation index, usually check whether the results of simulation data with reference data from unified sample.

c. There are more reference data. If there are more static performance parameters, we can choose the method that can handle a large sample of mathematical statistics data and validate the consistency of the data. And if there are more dynamic performance parameters, we can compare the simulation time sequence and the reference time sequence to obtain the conformity of the validation index.

d. There is no reference data, no relevant expert experience. In general, this kind of situation can only in accordance with the requirements of the design performance parameters to continue designing and optimizing each model, it is difficult to determine the conformity.

Now, above different situations of reference data, conformity calculation methods were summarized as table 1.

Table1. Common used model validation method

No reference data	Any reference data			
	Less reference data		More reference data	
	Static parameters	Dynamic parameters	Static parameters	Dynamic parameters
Expert voting Effective test Turing test	Point estimation interval estimation parameter hypothesis test	TIC coefficient spectrum estimation	Bayesian estimation, maximum likelihood estimation	Wavelet analysis, regression analysis

According to the model validation methods summarized in table 1, we can calculate the conformity of the underlying validation index of PMU. Of course, when using the above methods to numerical calculation, the specific methods still need for data preprocessing to make the data can meet the use conditions. Gained from the calculation results of various methods should be to further normalize and then get the conformity of the underlying validation index [4]. Then according to the formula (1), we can calculate the credibility at all levels step by step.

Here we only introduce the TIC coefficient method and its conditions of using, data preprocessing, principle and its process of transformation into conformity, and the process of other method using step is similar to this.

TIC coefficient method is based on the principle of two-time series error norm, which the error norm is based on every moment of the simulation data and the corresponding reference data structure. Therefore, it is necessary to ensure the consistency of two time series. Because the simulation data is more readily available relative to the reference data, and if there are any missing point in the reference data relative to the simulation data, we can give up the simulation data without corresponding to reference data, or by interpolation to complement the lack of reference data points [5].

After dealing with the data, the simulation time series are x_i and t_i^x, reference time series is y_i and t_i^y, t_i^x and t_i^y are one to one correspondence, a total of N points, the coefficient of TIC is:

$$\rho(x,y) = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - y_i)^2}}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}x_i^2} + \sqrt{\frac{1}{N}\sum_{i=1}^{N}y_i^2}} \quad (2)$$

TIC coefficient method is suitable for small samples. When using this method, the data can be segmented, the using steps is as follows:

1) Draw the simulation time sequence and the reference time sequence under the same coordinate system;

2) According to the concerned area or based on the characteristics, curve is divided into n segments;

3) Calculate the coefficient of TIC of each segment;

4) Determine the important degree γ_i of each segement, satisfying $\sum_{i=1}^{n} \gamma_i = 1$, $\rho(x, y)$ represents the TIC coefficient of each segment, the whole period of time sequence TIC coefficient is:

$$\rho(x, y) = \sum_{i=1}^{n} \gamma_i \times \rho_i(x, y) \quad (3)$$

$\rho(x, y) \in [0, 1]$, the accuracy of the method itself is not within the scope of our consideration, making $\rho(x, y)$ as the conformity of underlying validation index.

For the use of other methods, it is also need to analyze the conditions of using the methods, data pretreatment, calculation principle and transformed into conformity, and then we can calculate the conformity.

3. Validation tool for Performance mock-up

Complex aerospace products PMU contains multidisciplinary, wide field, and it relates to the huge amount of data, various knowledge, relying solely on manual validation difficult to quickly and effectively complete the validation of PMU.

Now, validation tools for complex aerospace products PMU are very rare. In this paper, basing on the analysis of characteristics and methods to verify the complex aerospace products PMU, a distributed PMU validation tool is designed and implemented. It can effectively record and deal with the massive experimental data, and quickly, effectively complete the validation PMU.

3.1 Framework of performance mock-up validation tool

PMU for the characteristics of geographically dispersed, different departments, multiple disciplines, validation tools use a centralized two-stage multi agent hierarchical structure, they include system coordination management agent, task node agent. All the tasks of each node agent has the same status and its function is determined by the user, internal knowledge base resources, When necessary, it can cooperate with other task node agent to verify the entire validation tool of all nodes in the Agent before using the system to coordinate the management of Agent registration[6]. System coordination management agent is responsible for the validation tool of task assignment, resource management and task management of the members, at the same time, it is also the Agent of nodes and other nodes Agent to carry out coordination of the intermediary, The system coordination management Agent provides resources and information sharing for other Agent, and it merges and publishes the validation conclusion of the whole validation tools.

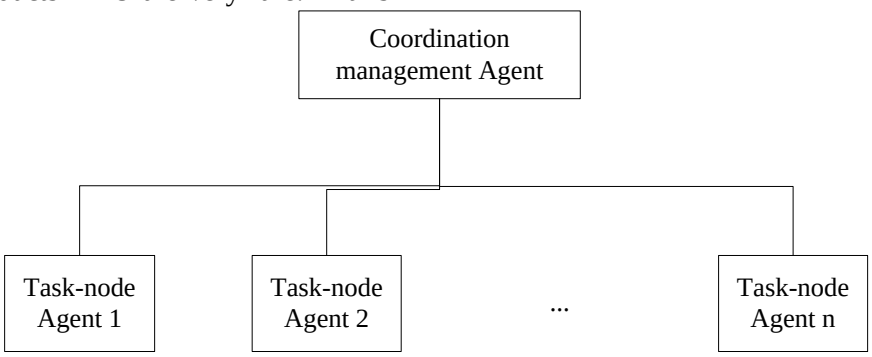

Figure 2. Validation tools in the agent hierarchy

System coordination management Agent and task node Agent have similar structure, in the following, introducing the framework of the task node Agent as the representative. Figure 3 is a single task node Agent internal framework, the key components are described as follows:

(1) Knowledge acquisition Agent gets the test data of PMU or the knowledge of the expert's experience, and converts it into the knowledge and knowledge in the database.

(2) Data record Agent is responsible for obtaining and recording the simulation

results, and what will be provided to the calculation and validation for Agent.

(3) Calculation and validation of Agent according to the definition of good rules, call the appropriate method, the reference data and simulation data will be compared.

(4) Management Agent is responsible for resource management and coordination of various Agent activities, system coordination management Agent is also responsible for the task decomposition and scheduling, management Agent is also responsible for the management of user rights.

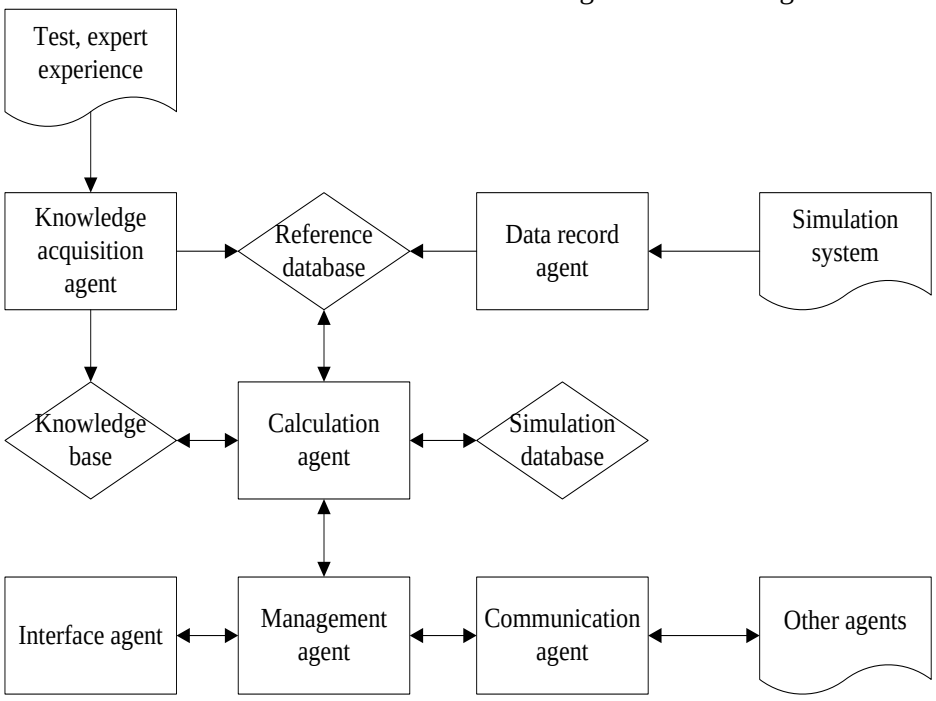

Figure 3. A single task node Agent internal framework

(5) Interface agent and the user dialogue, receiving user instructions and responsible for confirm the data and image display, for the interface between the system management and coordination of the task nodes can be personalized treatment.

(6) Communication Agent is mainly the task node Agent and system coordination management Agent for communication, the communication between the nodes of the communication system can be accomplished through the system coordination management Agent.

(7) Validation method for knowledge base mainly provides the model validation method, that is, the table 1 summarizes the on the model validation methods, the simulation results and data reference databases mainly to verify the provided simulation results and reference data.

The task node Agent in the receiving system Agent through Agent communication coordination and management of the validation task or according to the received user interface Agent to the validation task, the task management Agent analysis and call the calculation Agent, verify the calculation Agent according to calculate the required contents, reference data call simulation data inside the simulation data and reference data in the database and the validation method for the characteristics of data selected from the knowledge base validation method, and then the related calculation results, conformity index required, then the results by the management of Agent reasoning, draw conclusions, the results and conclusions based on Agent interface is displayed to the user or by the communication Agent is returned to the system coordination Agent management, coordination and management of each task node Agent comprehensive results, combined with the conclusion, and the credibility of the final validation conclusion of the prototype performance. Needs to be pointed out is that subsystem validation of all processes are carried out in a single task node agent, the other task agent's information, to the system coordination management agent sends a request, by the system coordination management agent from the other agent to obtain information and return to release, please

ask the agent, thus completing the synergistic interaction between task node agents.

3.2 Process of performance mock-up validation tool

From the internal framework of Agent 3, it can be concluded that the Agent is the core of the whole task node Agent. In order to improve the efficiency of the PMU, this paper designs the different validation process for the concept model and the simulation model. Conceptual model and simulation model are two important steps in the design of the performance model. From Figure 4, it can be seen that the conceptual model mainly uses the qualitative method of expert evaluation.

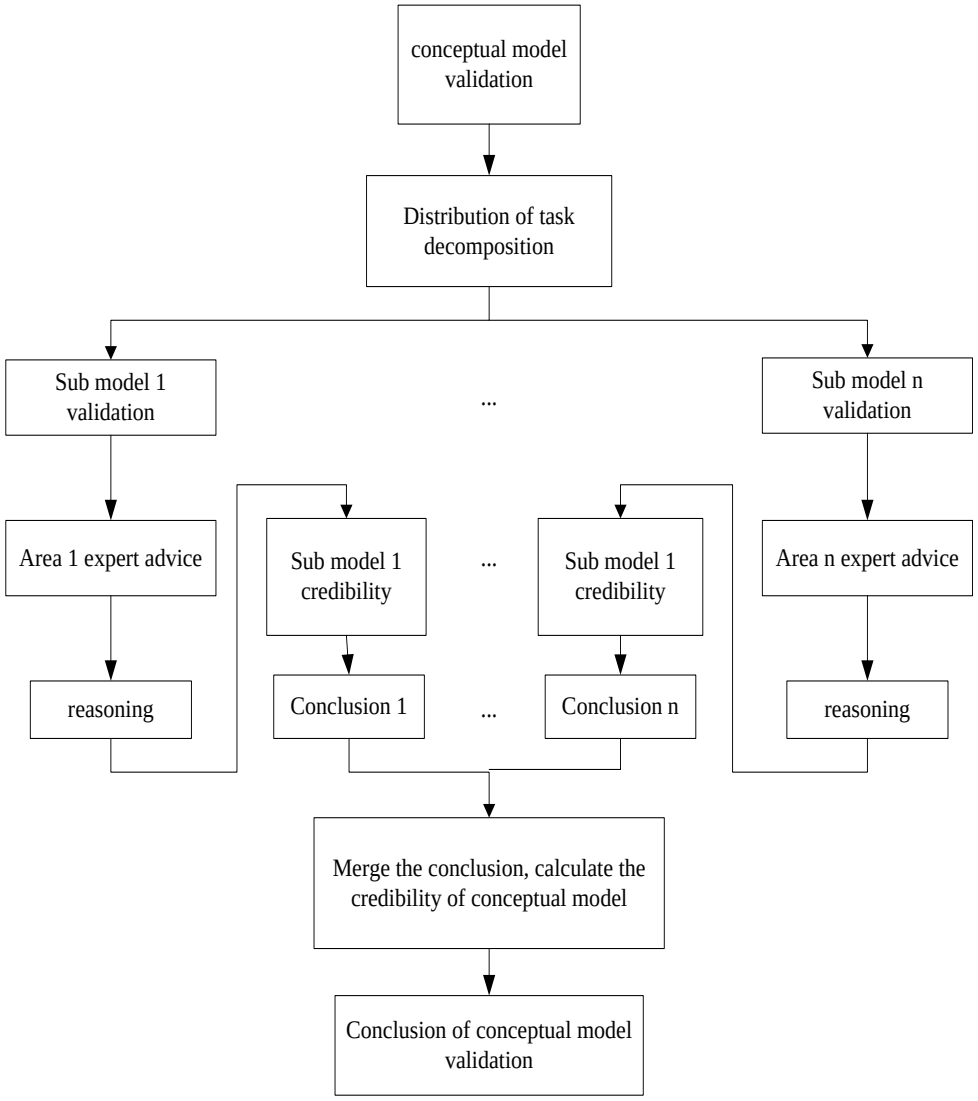

Figure 4. Conceptual model validation process

Different from the concept model, the simulation model is verified by the reference data and can be divided into many cases, figure 5 is the flow chart for the simulation model validation. Static performance parameters and dynamic performance parameters are different in the selection of the validation method, the other places are similar.

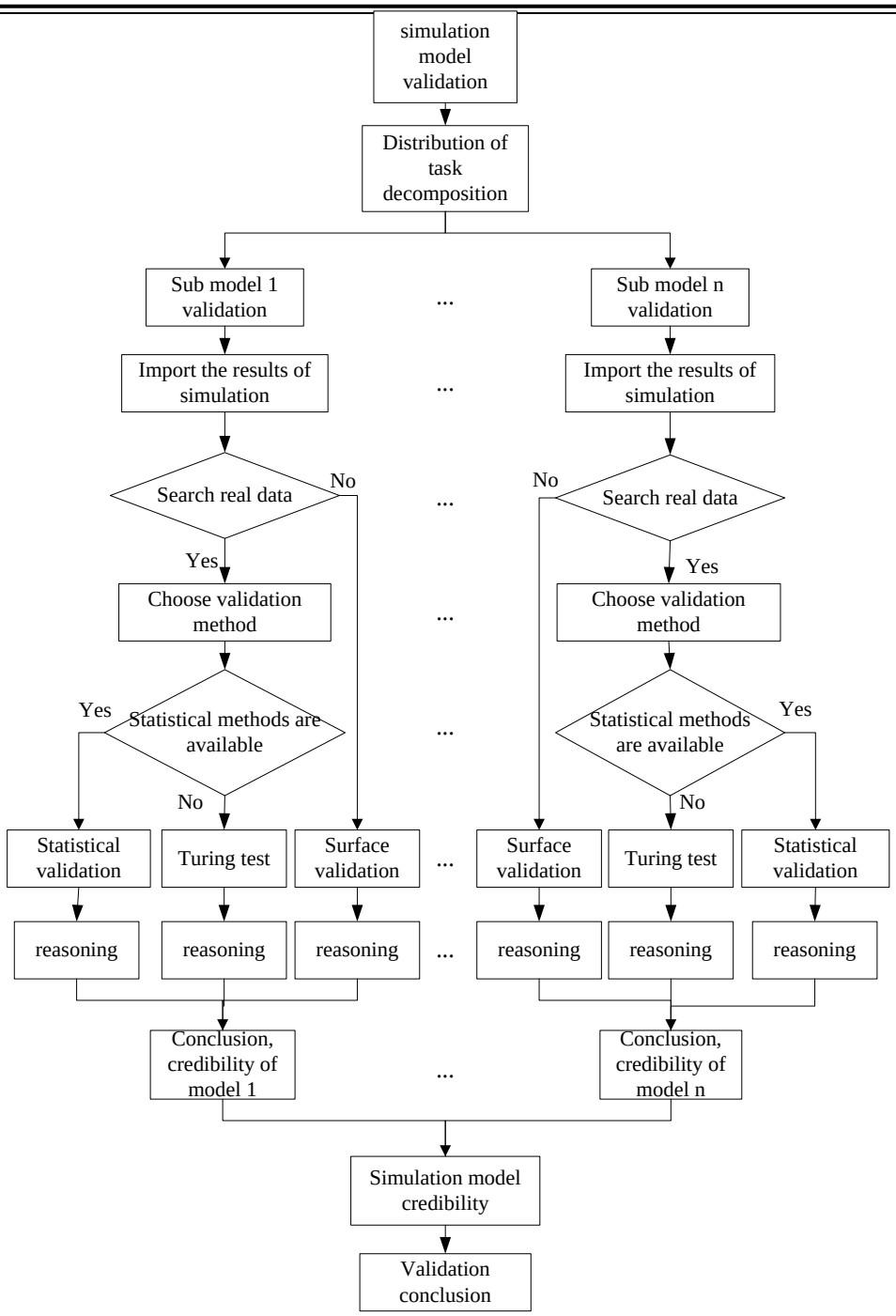

Figure 5. Simulation model validation process

3.3 Realization of the performance mock-up validation tool

Based on the above validation methods and design ideas, the validation tool is realized in the MyEclipse platform, using Java language and Server SQL 2008 database to achieve, the simulation result database and the reference data base are realized by Server SQL 2008. The PMU validation tool contains several function modules: user management module, data management module, knowledge base management module and prototype validation module and so on. The user management includes user rights management and online membership management (online membership management is mainly for the system coordination members and setting function, members of the task did not use the permissions); Data management including simulation results management and reference data management; Knowledge base management includes validation method and reference model, PMU validation includes concept model validation and simulation

model validation. Menu bar provides some basic operations, such as opening, saving, exiting and so on. Some of the specific validation method of using the tool can be viewed by clicking on the right side of the interface.

4. Result analysis of validation--using complex spaceflight products PMU as an example

4.1 Result analysis of PMU validation

Complex spaceflight products PMU is constructed by different design departments and different areas of expertise of the multiple system model, and each system model is composed of multiple sub models with coupling effect. The supersonic aircraft PMU was taken as an example, which is divided into sub-system and sub-model decomposition.

This paper is concerned with the credibility of the complex spaceflight product's control system, so it is necessary to verify PMU's guidance model and attitude control model. Selecting of miss distance as a guidance model to verify the underlying index, yaw attitude control model to verify the underlying index. Table 3 is the miss distance data.

Table 3. Miss distance data.

simulation data	reference data	simulation data	reference data
0.249	0.126	0.280	0.168
0.134	0.123	0.191	0.101
0.187	0.286	0.303	0.122
0.283	0.174	0.122	0.210
0.212	0.241	0.123	0.192
0.119	0.151	0.199	0.178
0.261	0.217	0.192	0.182

Table 4. Yaw angle data (parts).

Time(s)	simulation data(°)	reference data(°)
0.0005	-10.6520	-10.6520
0.0010	-10.6520	-10.6520
0.0015	-10.6520	-10.6520
…	…	…
0.2085	-10.9492	-10.8724
0.2090	-10.9481	-10.8702
0.2095	-10.9464	-10.8690
…	…	…
0.3985	-10.8080	-10.9098
0.3990	-10.8073	-10.9090
0.3995	-10.8066	-10.9083

Because the only validation of complex supersonic aircraft's control system model, using of a computer to carry on offline validation. Start the validation tool, click on the validation tool on the left side of the main interface function button in the validation tool, and select the simulation model button. Firstly, determines the required validation control subsystem model of two sub models: the guidance model and attitude control model; Secondly, gets the degree of the sub models through its underlying validation index of miss distance and yaw Angle data consistency analysis; Once again, the weight of the impact of the reliability of the control system for the distribution of the system is assigned, it is considered that the control system is equally important in the guidance and attitude control, and each of the control points is 0.5. Finally, the reliability of the control system is obtained.

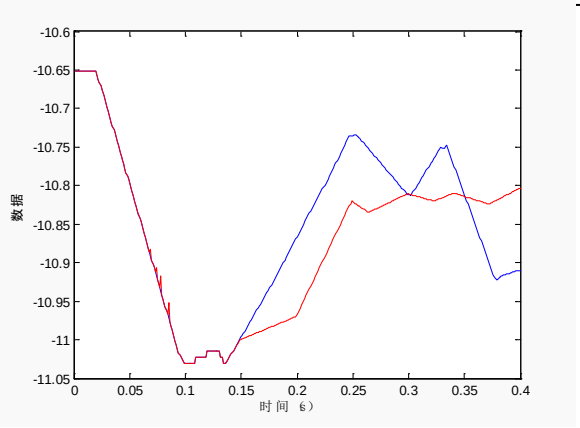

Figure 6. The time-domain plot of yaw angle

Miss distance has less data and it is static performance parameters, selecting interval estimation for its validation, its accuracy was 0.970; yaw angle has more data and it is dynamic performance parameters, selecting TIC section coefficient method to verify it. Figure 7 is the time-domain plot of yaw angle. The conformity was 0.824,which was calculated by using formula (2) and formula (3). Finally, the credibility of the control system was 0.897. According to the validation results, it can be written to verify the conclusion and the test report of the control system is generated.

5. Conclusions

In view of the validation requirements of the complex spaceflight PMU, this paper has analyzed the validation method of PMU, and the blank of the validation method of the complex PMU has been filled. On the basis of this, a set of PMU validation tool has been designed and developed. After testing, the proposed method and validation tool are available, and good results have been obtained. In the future research, it is necessary to refine the validation method and process of the different level of PMU, and thus to improve the validation tool of PMU.

Acknowledgements

This work was partially supported by the defense basic research projects of #A0420131501, and thanks for the help.

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