Modeling and Collaborative Simulation Model Library for Performance Prototype

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Abstract
In order to realize the effective accumulation and reuse of simulation models, using database and Meta model sharing technology, a reusable simulation model for performance prototype is established. Then the hierarchical framework of collaborative simulation model for spacecraft performance is analyzed, the simulation model is divided into the top level system simulation model, the main model and the Meta model, and the performance prototype collaborative simulation life cycle data sharing technology is presented. Experimental results show that these models can be constructed to provide simulation model libraries, such as Matlab/Simulink simulation tool in the field, can effectively achieve the performance prototype collaborative simulation lifecycle data sharing.

Key words: Performance Prototype, Collaborative Simulation, Model Library, Model Sharing.

1. INTRODUCTION

Performance prototype collaborative design environment supporting multidisciplinary collaborative modeling and simulation function hierarchy model involves a large number of various types of meta data model and unified management needs(Fan Miaomiao,2010). Where Meta model information management is the key to build a multi discipline collaborative modeling and simulation platform system for aerospace product performance prototype, and the construction of performance prototype simulation library is an important part of the system(Xu Heng,2012). In the simulation of performance prototype, because it involves a multidisciplinary modeling and simulation, integration between different models, data exchanging and sharing, involving such as conceptual model, functional model, simulation model, optimization model and management model are needed in a unified model database sharing and collaborative simulation and reuse (Chi, 2010). By sharing technology model can extend multi-disciplinary simulation model, modification, integration and collaborative management.

Meanwhile, since the constructed model libraries are generally available as a standalone simulation unit encapsulates meta-model input / output interface, you can achieve transmission parameters, data manipulation and problem-solving capabilities. Meta model detailed definition of the semantic model, model integration and interoperability between the information described can achieve a better simulation, simulation model fitting and evaluation and verification (Zhang and Zuo, 2010). So the model has the relative independence, and it can realize the multi subject parallel simulation. The model base can be unified management of multi subject domain Meta model.

Although scholars for performance prototype distributed modeling and simulation in the field have done a lot of research, but is currently in the study of complex aerospace products life cycle of integrated design and management of the problems are still apparent. In particular the study of quantitative description and definition of digital prototype performance prototype, collaborative modeling and simulation methods are rare(Vazquez and Carlos,2015), currently the digital prototype technology research focus mainly on prototype structure modeling and virtual assembly and other fields, relatively few of complex spaceflight system level function and performance of the integrated verification(Grogan and Paul, 2015), in digital, using digital environment, virtual verification and other products, it still needs the further research.

In this paper, a prototype of the Winged-cone performance prototype of the hypersonic concept aircraft is designed as an example, around performance prototype simulation model base management structure, and management aspects of the model library shared technology life cycle, building and object interface model simulation model libraries and the like, to explore the performance of prototype collaborative simulation model libraries construction method.

2. DEFINITION OF PERFORMANCE PROTOTYPE SIMULATION MODEL

Performance prototype contains the complete digital information model of parts and equipment in the whole life cycle of products, should reflect the actual characteristics of the specified products, can be integrated analysis, optimization (Hiraishi and Kunihiko, 2015). Complex spacecraft performance prototype integrated modeling needs analytic hierarchy qualitative and quantitative systematic decomposition, for example, the literature (Guo,
2013) uses analytic hierarchy process to quantify the key technologies of hypersonic cruise missile. In this paper, the hierarchical analysis method is used to decompose the subsystem and the performance parameters of the digital performance prototype of complex aerospace products. Based on the above analysis, this paper takes the model of the hypersonic vehicle as an example, and uses the eight tuple to represent the Meta model of a performance prototype:

\[ P_{DMU} = \{\text{identification, mapping, parameters, parts_library, simulation_model, model_state, model_format, maturity}\} \]

(1)

According to the formula (1), the definition of the model of the performance of the hypersonic vehicle is defined, and the detailed analysis of the detailed content of each member in the eight tuple is analyzed in detail.

(1) **identification**: Showing identification element model, each element has a unique model identifier;

(2) **mapping**: It represents coordinates and positioning; use coordinates to describe hypersonic vehicle state coordinate origin in the center of gravity of the moving object (Li, 2013):

1) \( O_{x,y,z} \) is ground coordinate shaft, its axis parallel to the respective axes relative to the earth is fixedly connected to the inertial coordinate interpretation shafting \( O_{x,y,z}' \), then \( O_{x,y,z}' \) straight up;

2) \( O_{x,y,z} \) is the trajectory coordinate system, its \( O_{x} \) axis pointing moving object with respect to inertial velocity vector interpretation shaft \( O_{x,y,z}' \) direction, \( O_{y} \) axis is in the vertical plane, when the horizontal movement of the object on the \( O_{x} \) direction, and its direction is upward, the direction angle of \( O_{x,y,z} \) relative to \( O_{x,y,z}' \) is determined by the Euler angle \( \theta \) and \( \psi \) (\( |\theta| \leq \pi/2, |\psi| \leq \pi \)).

3) \( O_{xyz} \) is the body coordinate system, which is relatively fixed on the research object, \( O_{xy} \) plane is usually fixed in the plane of the plane of symmetry, relative to the \( O_{xyz} \) direction angle is determined by \( \vartheta \), \( \gamma \), \( \varphi \) angle (\( |\vartheta| \leq \pi/2, |\gamma| \leq \pi, |\varphi| \leq \pi \)).

4) \( O_{x,y,z}, \) is the speed coordinate system, it was off along the \( O_{x} \) axis direction airspeed vector, and \( O_{y} \) plane is located in the \( O_{x,y,z} \) plane, and when the \( O_{x} \) and \( O_{x,y,z} \) axes coincide, it also coincides with the \( O_{y} \) axis; \( O_{x,y,z} \) relative to the direction angle of \( O_{x,y,z}' \) determined by the Euler angle \( \vartheta, \gamma, \varphi \) (\( |\vartheta| \leq \pi/2, |\gamma| \leq \pi, |\varphi| \leq \pi \)); and the direction angle of \( O_{xyz} \) is determined by \( \alpha, \beta \) (\(|\alpha| \leq \pi, |\beta| \leq \pi/2\)), when it is calm, coincidence between \( O_{x} \) and \( O_{x,y,z} \) axis, \( \varphi_{z} = \psi \), \( \vartheta_{z} = \theta \).

Direction cosine matrix can be used to achieve from one axis to another axis system transformation. \( A^{x,y,z} \rightarrow x_{1},y_{1},z_{1} \) represent \( O_{x,y,z} \) from \( O_{x_{1},y_{1},z_{1}} \) axis system to transform matrix, at this time, \( A^{x,y,z} \rightarrow x_{1},y_{1},z_{1} = (A^{x_{1},y_{1},z_{1}} \rightarrow x,y,z)^{-1} \) \((A^{x_{1},y_{1},z_{1}} \rightarrow x,y,z) \).

For the coordinate transformation matrix system may be expressed by the following methods:

\[ A^{x,y,z} \rightarrow x_{1},y_{1},z_{1} (\vartheta,\gamma,\varphi) = \begin{bmatrix} \cos \varphi \cos \vartheta & \sin \varphi \cos \vartheta \cos \gamma & -\sin \varphi \cos \vartheta \sin \gamma \\ \sin \varphi \cos \gamma + \cos \varphi \sin \vartheta \sin \gamma & -\sin \varphi \sin \gamma & \cos \varphi \cos \gamma \end{bmatrix} \]

(2)

\[ A^{x_{1},y_{1},z_{1}} \rightarrow x,y,z (\vartheta_{1},\gamma_{1},\varphi_{1}) = \begin{bmatrix} \cos \varphi_{1} \cos \vartheta_{1} & \sin \varphi_{1} \cos \vartheta_{1} \cos \gamma_{1} & -\sin \varphi_{1} \cos \vartheta_{1} \sin \gamma_{1} \\ \sin \varphi_{1} \cos \gamma_{1} + \cos \varphi_{1} \sin \vartheta_{1} \sin \gamma_{1} & -\sin \varphi_{1} \sin \gamma_{1} & \cos \varphi_{1} \cos \gamma_{1} \end{bmatrix} \]

(3)
(3) parameters: Used to represent the performance parameters describe the main list, by bulk library to store performance parameters;

(4) parts_library: It used to represent the model involved common parts library, through the library to describe all parts of the body parts of the conceptual model and its characteristic relations products;

(5) simulation_model: To establish the performance simulation model, establishment of hypersonic vehicle performance of the prototype model of superb is through its aerodynamic shape, structure, propulsion and control, performance/ballistics, gas dynamic thermal/thermal and cooling mathematical model; the superb hypersonic vehicle flight simulation system is set up. Mainly including the aerodynamic system model, configuration system model, propulsion system model, control system model, performance/trajectory model, and aerodynamic thermal / thermal model and cooling system model (Bilimoria and Schmidt, 1995). Newton’s second law can be used to represent the dynamic equation of hypersonic vehicle:

\[ F = \frac{d}{dt}(mV)_{x} \quad \overrightarrow{M} = \frac{d\overrightarrow{H}}{dt}|_{x} \]

In formula (6), \( F \) represents the vector sum of all external forces acting on the aircraft, \( m \) is the quality of the aircraft, \( \bar{F} \) represents the velocity vector of an aircraft, \( \overrightarrow{M} \) is the vector of all the torques acting on the aircraft, \( \overrightarrow{H} \) represents all the moment of momentum.

In order to facilitate multidisciplinary optimization and Simulation of performance of the prototype, the model to the NASA for study for hypersonic aircraft concepts Winged-cone based, the general of the performance calculation formula (Bolender and Doman, 2007):

\[ \overline{V} = \frac{T \cos \alpha - D}{m} g \sin \gamma \]
\[ \overline{g} = \frac{L + T \sin \alpha}{mV} \frac{g \cos \gamma}{V} \]
\[ \bar{q} = M_{y} / I_{y} \]
\[ \bar{a} = q - \overline{g} \]
\[ \overrightarrow{H} = V \sin \gamma \]

Where, \[ L = \frac{1}{2} \rho V^{2} s C_{L}, D = \frac{1}{2} \rho V^{2} s C_{D}, \]
\[ M_{y} = \frac{1}{2} \rho V^{2} \bar{s} (C_{u}(\alpha) + C_{u}(\delta_{r}) + C_{u}(q)) \]
\[ \rho = 1.2266 e^{-37315.2} \]
\[ g = 9.8 \left( \frac{635676}{635676 + \rho} \right)^{2}, C_{L} = 0.6203 \alpha \]
\[ C_{D} = 0.6450 \alpha^{2} + 0.0043378 \alpha + 0.003772 M_{y} I_{y}, C_{D} C_{m} \]
\[ C_{m}(\alpha) = -0.035 \alpha^{2} + 0.036617 \alpha + 5.3261 \times 10^{-6} \]
\[ C_{u}(\delta_{r}) = 0.0292 (\delta_{r} - \alpha) \]

In the above formula, \( \gamma \) is the trajectory angle, \( \alpha \) is an attack solution, \( \rho \) is for atmospheric density, is pitching moment, is the moment of inertia of pitch angle. is a drag coefficient, is the lift coefficient.

The engine dynamic model of a hypersonic vehicle is shown in the following:

\[ \overrightarrow{b} = k_{1} \overrightarrow{b} + k_{2} b + k_{3} \overrightarrow{b}_{com} \]
\[ C_t = \begin{cases} 
0.02576 \beta & \text{if } \beta < 1 \\
0.0224 + 0.00336 \beta & \text{if } \beta > 1 
\end{cases} \quad (13) \]

\[ T = \frac{1}{2} \rho V^2 s C_t \quad (14) \]

\[ m = 136820(1 + \Delta m) \text{kg} \quad (15) \]

\[ I_s = 9.49(1 + \Delta I) \times 10^6 \text{ kg m}^2 \quad (16) \]

\[ S = 334.73(1 + \Delta S) \text{m}^2 \quad (17) \]

\[ \bar{\varepsilon} = 24.38(1 + \Delta \varepsilon) \text{m} \quad (18) \]

\[ \rho = 1.25(1 + \Delta \rho) \times 10^{-2} \text{ kg/m}^3 \quad (19) \]

Where, \( |\Delta n| \leq 0.03, |\Delta| \leq 0.02, |\Delta S| \leq 0.03 \), \( |\Delta \varepsilon| \leq 0.02, |\Delta \rho| \leq 0.03 \), the control parameters for the engine throttle threshold \( \beta_{\text{com}} \) and elevator angle \( \delta_e \); the input is the flight speed \( V \) and the flight altitude \( h \).

(6) \textit{model state}: Represents the state of the model, which represents the specific state of the current model, such as revision, activation, and deactivation;

(7) \textit{model format}: Used to represent the format of the model, such as the format of the model to express (including UML, ontology description and Meta model, etc.);

(8) \textit{maturity}: It represents the technical maturity of the performance of the prototype, in the 1990s, the United States NASA proposed technological maturity (technology readiness level, TRL) concept. Technology maturity is a systematic, objective technical evaluation system, based on various stages of development or maturity of the key nodes of a particular technology assessment, technology maturity will be divided into nine, as is shown in Figure 1.

By constructing the performance prototype model can be parameterized simulation model shows that the performance of the prototype of the product from prototype has the ability to diversify.

According to the above definition, digital performance hardware is built specifically for the process shown in Figure 2.

The large complex aerospace products in supersonic flight weapons are as an example. The supersonic flight performance digital prototype weapon subsystem model and performance parameters are analyzed.
3. CONSTRUCTION OF SIX DEGREE OF FREEDOM SIMULATION META MODEL OF PERFORMANCE PROTOTYPE

In this paper, all kinds of mathematical formulas when the performance of the prototype aircraft system element model of multidisciplinary design optimization and design simulation requires various types of meta model contains, so the need for various types of aircraft mathematical function formula element model for analysis.

A typical hypersonic vehicle model consists of six degrees of freedom element 12 constitute the state vector, namely: $HVMU = [u,v,w,\phi,\theta,\psi,p,q,r,x,y,z,h]$ (20)

And controlled by the $[\delta_r, \delta_v, \delta_h, \delta_{\phi}, \delta_{\theta}, \delta_{\psi}]$ four input variables, $u,v,w,\phi,\theta,\psi,p,q,r,x,y,z,h$ are respectively, airspeed, angle of attack, sideslip angle, roll angle, pitch angle, yaw angle, roll angle rate, pitch rate, yaw rate, longitudinal displacement, lateral displacement and height; $\delta_r, \delta_v, \delta_h, \delta_{\phi}, \delta_{\theta}, \delta_{\psi}$ are respectively elevator deflection, aileron, rudder and engine throttle.

The mathematical functions of these variables are analyzed in detail. The motion of the aircraft is selected as the inertial coordinate system. Therefore, the motion equation of the aircraft based on the body coordinate system should be taken into account. In the body coordinate system, the equation of equation (6) can be expressed as:

$$\frac{d\bar{V}}{dt} = l_v \frac{dV}{dt} + \bar{W} \times \bar{V}$$ (21)

$$\frac{dL}{dt} = l_\mu \frac{dL}{dt} + \Omega \times L$$ (22)

Where,

$l_v$ represents the unit vector along the $\bar{V}$; $\bar{W}$ represents a moving coordinate system of inertial angular velocity vector of the total; $\bar{W} \times \bar{V}$ is the rate of change due to the rotation vector moving coordinate system caused. And $I_v$ is calculated as:

$$I_v \times \frac{dv}{dt} = i\bar{u} + j\bar{v} + k\bar{w}$$ (23)

The formula implicated acceleration $\bar{W} \times \bar{V}$ is:

$$\bar{W} \times \bar{V} = \begin{vmatrix} i & j & k \\ p & q & r \\ u & v & w \end{vmatrix} = i(wq - vr) + j(wp - uq)$$ (24)

Moment of momentum $L$ is calculated as follows:

$$L = \int dL = \int \rho \times (i\bar{W} \times \bar{V})dm = iL_h + jL_v + kL_r$$ (25)

Where, the diameter $\bar{r} = ix + iy + kz$, angular velocity $\bar{W} = ip + jq + kr$, the angular motion model can be got from the formula 24 and the formula 25:
In the aircraft flight kinematics model, through the relationship between the body axis and axis lines, find out the body axis angular velocity, displacement and ground shafting angular velocity and displacement relationship. Wherein the angular position of the kinematic equation describes the relationship between p, q, r and \( \theta, \varphi, \psi \), angular motion kinematic model is shown in Figure 3.

4. EXPERIMENT AND SIMULATION

Aircraft control system based augmentation system, including dampers, control augmentation system and automatic navigation system. Due to the requirements of aircraft mission is very high, the flight speed and altitude range expanding, according to the model mentioned above, the application of Matlab is simulated and the results are shown in Figure 4, In order to improve the performance of the angular motion of the aircraft, the flight control system, such as damper and augmentation system, is installed in the vehicle.

Modern aircraft flying at high angle of attack, and the longitudinal static stability and the derivative of \( C_m = \frac{\partial C_m}{\partial a} \) varies with elevation increase, and even become positive, the use of aircraft longitudinal static instability.

The longitudinal moment coefficient \( C_m \) is a function of elevation angle and Maher \( C_m = C_m(a, Ma) \). The variation gradient of the longitudinal moment system is:

\[
dC_m = \frac{\partial C_m}{\partial Ma} dMa + \frac{\partial C_m}{\partial a} da
\]  

(27)

The formula right side first reflects the effect of Maher number on the longitudinal gradient of torque coefficient \( C_m \), the second item reflects the influence of elevation angle. The partial derivative \( \frac{\partial C_m}{\partial a} \)
indicates the change of pitching moment caused by the elevation change and the relationship between the longitudinal static stability and the speed of the vehicle.

![Graph showing thrust coefficient under different conditions of Mach curve](image1)

**Figure 4.** Thrust coefficient under different conditions of Mach curve

According to the simulation model of the aircraft performance prototype lateral control system, which has increased the stability of the system, the elevation changes tend to be stable, as is shown in figure 5.

![Graph showing elevation changes tend to be stable state](image2)

**Figure 5.** Elevation changes tend to be stable state

5. CONCLUSIONS

This paper discusses the construction of co-simulation model of the role and significance of the library, using the Analytic Hierarchy Process to various subsystems of complex aerospace products and digital performance prototype performance parameters contained in the decomposition model. Taking the Winged-cone prototype design of hypersonic concept aircraft as an example, the definition criterion of performance prototype simulation model is presented.

Based on the analysis on the structure of the model the performance prototype system, the construction of six degree of freedom simulation model performance prototype of hypersonic vehicle, simulation model of multiple disciplines and aerodynamics, structure, propulsion, control, performance/ballistic, aerodynamic heating and cooling/ etc. Constructions of these models are available for the simulation model libraries such as Matlab/Simulink-domain simulation tools.

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