A Formal Description Specification for Multi-Resolution Modeling Based on DEVS Formalism and its Applications

Liu Baohong
Institute of Automation
College of Mechatronics Engineering and Automation
National University of Defense Technology
Changsha, Hunan, China
liu_baohong@hotmail.com

Multi-Resolution Modeling (MRM) is a relatively new research area. With the development of distributed interactive simulation, especially as the emergence of HLA (High Level Architecture), multi-resolution modeling becomes one of the key technologies for advanced modeling and simulation. But there is little research in the area of the theory of multi-resolution modeling, especially the formal description of MRM. In this paper, a new concept for the description of multi-resolution modeling, named Multi-resolution model Family (MF) is presented. A multi-resolution model family is defined as the set of different resolution models of the same entity. The description of MF includes two parts: models of different resolution and their relations. Based on this new concept and DEVS (Discrete Event Specification) formalism, a new multi-resolution model system specification, named MRMS (Multi-Resolution Model system Specification) is proposed. Some important properties of MRMS, especially the closure of MRMS under coupling operation are given and proved. MRMS provides a foundation and a powerful description tool for the research of MRM. An example to illustrate how to describe a multi-resolution model using our specification is given. Using this description, the theory and implementation of MRM can be further studied.

Keywords: multi-resolution modeling, DEVS, model family, multi-resolution model specification, closure under coupling

1. Introduction

Multi-Resolution Modeling (MRM) is a relatively new research area. With the development of distributed interactive simulation, especially as the emergence of high level architecture (HLA), multi-resolution modeling becomes one of the key technologies for advanced modeling and simulation. MRM has deep influence on the development of modeling and simulation. However the research on MRM is now on its very initial stage.

Resolution is the degree of detail and precision used in the representation of real world aspects in a model or simulation [1]. There is still no widely accepted definition of multi-resolution modeling. Here we use the definition given by P. K. Davis [2]:

(1) Building a single model with alternative user modes involving different levels of resolution for the same phenomena;

(2) Building an integrated family of two or more mutually consistent models of the same phenomena at different levels of resolution; or

(3) Both.

Though many researches have been done, there is little formal specification to describe the multi-resolution model and multi-resolution model system. Without this, it is difficult to establish a common language among different researchers and model developers, and it is impossible to develop a multi-resolution modeling framework and tools for modeling automation. In this paper, we proposed a new multi-resolution model specification based on the concept of a multi-resolution family which is proposed in this paper first and the DEVS which was developed by B. P. Zeigler. We hope our work can be helpful to the development of multi-resolution modeling.

This paper is organized into seven sections. In section 2, the MRM state of the art is introduced briefly. In section 3， we summarize the general modeling formalism DEVS developed by B. P. Zeigler and a specific model specification for the dynamic structure discrete event system developed by F. J. Barros. In section 4, we give the definition and the specification of multi-resolution model family and prove the related theorems. In section 5, we propose our specification for a multi-resolution model system and summarize some of its key properties, especially its closure under coupling. Section 6 gives an example of describing the multi-resolution model system using our proposed specification. In the last section, we sum up the whole paper and introduce our future work.

2. Background

In this section, we briefly summarize the status of MRM. We summarize the MRM status from the aspect of MRM's concept and formal specification, multi-resolution modeling methods and MRM's application.

2.1 The Concept and Formal Description of MRM

As most of the other newly developed domains, many researchers have given the definition of MRM. D. Caughlim [3] and Kangsum Lee [4] define MRM from the aspect of model abstraction. R. M. Cubert and P. A. Fishwick [5, 6] define MRM using inheritance and aggregation in object-oriented software development. P. K. Davis and his colleagues also give their definition of MRM [2]. B. P. Zeigler describes MRM using SES/MB [7]. D. Caughlim and A. F. Sisti describe MRM using model abstraction and view the relation between a high resolution model and a low resolution model as function mapping [8]. It should be pointed out that there is currently no widely accepted definition of MRM.

Few formal specifications of MRM have been proposed and most of them are too simplified to be used in real MRM problems. The lack of formal specification of MRM has become a main obstacle for the development of MRM.

2.2 Methods of MRM

Some multi-resolution modeling methods have been developed. Aggregation/disaggregation is a widely used MRM method, especially in military simulation [9]. Aggregation/disaggregation can be further divided into full aggregation, full disaggregation, dynamic aggregation and pseudo aggregation/disaggregation [10].

Selective Viewing [10] is another traditional MRM approach, in which the most detailed model is simulated at all times. The advantage of this method is that it is simple to realize and easy to maintain the consistency of different resolution models. Its disadvantage is its computational complexity, lack of flexibility, low level of modularization and difficulty to reuse.

IHVR (Integrated Hierarchical Variable Resolution Modeling） is a MRM method developed by P. K. Davis [11]. It is a procedure-oriented method using a hierarchical variable tree.

Another MRM method is the UNIFY method proposed by Anand Natrajan [12, 13]. Its key concepts are multiple representation entity, attribute relation graphic and consistency enforcer.

Though these methods attempt to solve some specified problems in MRM, there is no generic method to solve all MRM problems as to the intrinsic complexity of MRM. Maybe there is no “silver bullet” in the area of MRM.

2.3 The Application of MRM

MRM has been used in all kinds of simulation problems. In traditional simulations, the typical works include: P.K.Davis uses MRM in exploratory analysis [14, 15]; Michael Kantner uses MRM in numerical simulation [16]; J.G.Taylor uses MRM to connect Lanchester equation-based simulation with tactical simulation based on entities [17]; Kang Sun Lee and Paul A. Fishwick research the application of MRM in real-time simulation [18]; Satoshi Sekine et al research the use of MRM in traffic simulation [19].

MRM is widely used in synthetical environment simulation: Brett Butler [20] and Richard Schafer [21, 22] research the problem of MRM in environment simulation; Paul Wonnacott researches the consistency maintenance of multi-resolution terrain data base [23]; Dale D. Miller researches the description of multi-resolution terrain information [24]; Robert A. Reynolds researches the MRM problems in atmosphere and ocean modeling [25].

Distributed simulation is a main application area of MRM. The typical applications include: (1) Tiger Team implement a framework named military Modeling Framework(MMF) in JSIMS which support MRM[26]; (2) Robert McGraw et al in RAM Labs design and implement a semiautomatic MRM assistant tool named MRMaide[27, 28]; (3) Martin Adelantado and Pierre Siron in French Aeronautics and Space Research Centre discuss the multi-resolution service which can be added to RTI or written by using existing HLA services[29,30]; (4) Andy Bowers in MITRE connects JATS(Joint Conflict and Tactical Simulation) and JTLS(Joint Theater Level Simulation) in HLA with MRM[31]; (5) Gary Plotz and John Prince connect JMASS(Joint Modeling and Simulation System) and JWARS(Joint Warfare System) using MRM[32,33].

Multi-resolution modeling is especially useful in command and control modeling and simulation. Many valuable works have been done by some researchers. Andreas Tolk identifies the multi-resolution challenges for command and control M&S services [34]. He proposes that the era of service-oriented architectures (SOAs) raised the discussion on multi-resolution modeling to a new quality. And he also regards multi-resolution modeling as one of the challenges in the coupling of C3I and M&S system [35]. Steven L. Gorsythe et al. evaluate the net-centric command and control via a multi-resolution modeling evaluation framework [36]. In the 2003 NATO Modeling and Simulation Group Conference, entitled "C3I and Modeling and Simulation (M&S) Interoperability," many papers took notice of the problem of MRM and interoperability in C3I modeling and simulation. For example: Charles David Allmon and André Schoonen use Cannon Cloud 2002 as a case study highlighting the main domains of C3I and M&S interoperability, which includes typical simulation-to-simulation challenges, such as aggregation and other multiple resolution issues[37]; Marko A. Hofmann regards the resolution as one of the essential preconditions for coupling model based information systems[38]. Joseph A. Giampapa et al extend the OneSAF testbed baseline modeling and simulation system into a C4ISR testbed, where the problem of multi-level information fusion is discussed [39].

3. Foundations

There are many symbols, for simplifying the description, a table of symbols is given below:

Symbol	Meaning	Symbol	Meaning
γ	The resolution set of an entity	φ	the resolution mode of a specified model
r	Resolution of a specific model	Ψ	the set of resolution mode of a model
X	The input of a model, X_d mean the input of component d, X^i the input of model with resolution i	Y	The output of a model, Y_d mean the input of component d, Y^i the input of model with resolution i

Other symbols used only once will be explained where they appear.

For most multi-resolution models, hierarchy is its intrinsic property. So a MRM specification should be hierarchy. A model's resolution is a relative concept. A model's resolution is high relative to one model and is low relative to another model. So closure under coupling is an important character for MRM specification. Fortunately, DEVS is just a formal specification with the good characteristics of hierarchy, modularization and closure under coupling. So we develop a formal MRM specification based on DEVS.

Many simulation system implementations based on DEVS have been developed, for example ADEVS, DEVSJAVA, Collaborative DEVS Modeler (CDM) and so on. An implementation of the DEVS formalism over the HLA/RTI has also been developed. Based on these implementations, we can develop MRM engine easily and connect it with HLA/RTI.

In this section, we will introduce DEVS and Dynamic Structure DEVS briefly. Our MRM specification is based on these two specifications.

3.1 DEVS Specification

DEVS is a system theory based model description specification. Here we only introduce the basic concept of DEVS for the convenience of our specification on multi-resolution model. A detailed description on DEVS can be found in [40].

A basic discrete event system specification is a structure

$M = < X, Y, S, \delta_{ext}, \delta_{int}, \lambda, ta >$

Where:

X : is the set of inputs

Y : is the set of outputs

S : is the set of sequential states.

$\delta_{ext} : Q \times X \rightarrow S$, is the external state transition function

$\delta_{int} : S \rightarrow S$, is the internal state transition function

$\lambda : S \rightarrow Y$, is the output function

$ta : S \rightarrow R^{+}_{0,} \cup \infty$, is the time advance function

$Q = \{(s,e) \mid s \in S, 0 \le e \le ta(s)\}$ is the total state set, e is the time elapsed since last transition.

The classic DEVS coupled model can be described as:

$N = < X, Y, D, \{M_d\}, \{I_d\}, \{Z_{i,d}\}, Select >$

Where:

X: the set of inputs

Y: the set of outputs

D: a set of component references, usually component names

For $\forall d \in D, M_d$ is a Basic DEVS model;

For $\forall d \in D \cup \{N\}, I_d$ is the influencer set of d, i.e. $I_d \subseteq D \cup \{N\}, d \notin I_d$;

and for $\forall i \in I_d$, $Z_{i,d}$ is a function, the *i*-to-*d* output translation with:

$$Z_{i,d} : X \rightarrow X_d,\ if \quad i = N;$$

$$Z_{i,d} : Y_i \rightarrow Y, \quad if \quad d = N;$$

$$Z_{i,d} : Y_i \rightarrow X_d,\ if \quad d \neq N \quad and \quad i \neq N;$$

Select is a function

Select:$2^D \rightarrow D$

Select is the tie-breaking function to arbitrate the occurrence of simultaneous event.

3.2 Dynamic DEVS Specification

Allowing changes in model structure during execution is a challenging area of development in modeling and simulation. Obviously, a model's structure in MRM often changes dynamically during executing. Dynamic Structure DEVS (DSDEVS) specification introduced by F.J.Barros [41, 42], strengthens DEVS with the ability to describe the dynamic structure change of a model. A concept of system network is used to represent systems that are able to undergo structural change. Change in structure is defined in general terms, and includes the addition and deletion of systems and the modification of the relations among components. The structure of a system network is stored in the network executive. Any change in structure related information is mapped into modifications in the network structure.

In DSDEVS, the basic models are the same as classic DEVS basic models, but the structure of coupled models can change over time.

A DSDEVS coupled model is defined as

$$DSDEN_N = < X_N, Y_N, \chi, M_\chi >$$

Where: *N*: is the DSDEVS network name

X_N: is the input events set of the DSDEVS network

Y_N: is the output events set of the DSDEVS network

χ: is the DSDEVS network executive name

M_χ: is the model of χ.

The M_χ can be defined with the following 10-tuple:

$$M_\chi = < X_\chi, Y_\chi, S_\chi, \xi, \Sigma^*, \delta_{int_\chi}, \delta_{ext_\chi}, \lambda_\chi, ta_\chi >$$

Where：

X_χ is the input set of χ

Y_χ is the output set ofχ

S_χ : is the set of the network executive states

δ_{int_χ} is the internal state translation function of χ

δ_{ext_χ} is the external state translation function of χ

λ_χ is the output function ofχ

ta_χ is the time advance function of χ

Σ^* : is the set of network structures;

$\xi : S_\chi \rightarrow \Sigma^*$, is called structure function;

Assume $s_{a,\chi} \in S_\chi$ and $\Sigma_a \in \Sigma^*$, we get:

$$\Sigma_a = \xi(s_{a,\chi}) =< D_a, \{M_{i,a}\}, \{I_{i,a}\}, \{Z_{i,a}\} >$$

where

D□is the set of component names associated with $s_{a,\chi}$

for all *i* □*D*□

$M_{i,a}$ is the DEVS model of component *i*

for all *i* □*D*□□□□,*N*□

$I_{i,a}$ is set of components influencers of *i*

for all *i* □*D*□□□□□

$Z_{i,a}$ is the input function of component *i*

$Z_{N,a}$ is the network output function

The meaning of these elements is similar as the coupled DEVS model. A more detailed description of DSDEVS semantics can be found in [41, 42].

4. Multi-resolution Model Families

This section gives the definition of Multi-resolution model Family (MF) and proves some important properties of MF.

4.1 The Concept of Multi-resolution Model Families

In multi-resolution modeling, different resolution models of the same entity are not isolated. They are related to each other. During the running of multi-resolution models, different resolution models should be collaborated to maintain a consistent description of different resolution models. So we call the set of different resolution models of the same entity a Multi-resolution model Family (MF).

The description of MF includes three parts: models of different resolutions, the resolution of each model and their relations. The relations between models with dfferent resolutions of the same entity are the focus of MF. The formal specification of MF is shown below:

$$MF = <\gamma, \{M_r\}, \{R_{i,j}\}>$$

Where:

γ : is the set of model resolutions, which can be regarded as the index of models with different resolutions of the same entity.

For $r \in \gamma, M_r$ represents the model with resolution *r*, $\{M_r\}$ means the set of all models of the same entity. M_r can be specified by DEVS:

$$M_r = < X^r, S^r, Y^r, \delta^r_{int}, \delta^r_{ext}, \lambda^r, ta^r >$$

$R_{i,j}$ is used to describe the relationship between different resolution models.

$R_{i,j} : Y^i_R \rightarrow X^j_R,\ where\ i, j \in \gamma.$ $X^j_R \subset X^j, Y^i_R \subset Y^i$ is multi-resolution-related inputs and outputs，X_j is the set of inputs of the model with resolution *j*, Y_i is the set of outputs of the model with resolution *i*.

This specification of MF is given according to the definition of MRM given by P. K. Davis [2].For modularization simulation design, the modules in MF should not access the inner information of each other, and models of different resolution can only coordinate through input and output interface.

4.2 Key Properties of MF

Now, let's introduce some important properties of MF.

Theorem 4.1 When $|\gamma| = 1$, MF degenerates into normal DEVS specification.

Intuitively, when $|\gamma| = 1$, there is only one model with only one resolution, so it becomes a normal model.

Proof: when $|\gamma| = 1$, there is only one model *M*, so $R_{i,j} = \varnothing$. Obviously, MF can be described by normal DEVS specification. ■

Theorem 4.2 Each MF can be rewritten to a DEVS coupled model.

Proof: Through theorem 4.1, we know when $|\gamma|=1$, the conclusion is obviously correct.

Now, let $|\gamma|\neq 1$, according to the definition of MF, we can describe models in MF by Classic DEVS model:

$$MF = <\gamma, \{N_r\}, \{R_{i,j}\}>,$$

$$N_r = < X_r, S_r, Y_r, \delta_{int,r}, \delta_{ext,r}, \lambda_r, ta_r >.$$

Let the equivalent DEVS coupled model be

$$N = < X, Y, D, \{M_d\}, \{I_d\}\{Z_{i,d}\}, Select >.$$

We need to prove that *MF* can be transformed into *N*.

The input and output of each model N_r can be divided into two parts, i.e. MRM-related part and MRM-unrelated part. For input, we have $X_r = X_r^M \cup X_r^R$, where the former means the MRM-unrelated input of N_r, the later means the MRM-related input of N_r. Similarly for output, we have $Y_r = Y_r^M \cup Y_r^R$. Obviously, we have

$$X = \bigcup_{r\in\gamma} X_r^M,\ Y = \bigcup_{r\in\gamma} Y_r^M,\ D = \bigcup_{r\in\gamma} N_r$$

$$M_d = N_r = < X_r, S_r, Y_r, \delta_{int,r}, \delta_{ext,r}, \lambda_r, ta_r >, \text{ where } d = r \text{ and } r \in \gamma.$$

I_d is the models in MF which have relationship with model of resolution *d*. In order to rewrite *MF* using coupled DEVS specification, the key is to construct the relations between different resolution models. Models of different resolution in *MF* are inter-effective, from the viewpoint of MRM, we can get $Z_{i,d}=R_{i,d}$.

Select is the tie-breaking function to arbitrate the occurrence of simultaneous events at different resolution. So we can define select as following:

$$Select : 2^{N_r} \rightarrow N_r$$

From above all, we can say each MF is equivalent to DEVS coupled model. ■

Theorem 4.3 Each MF specification is equivalent to a DEVS atomic specification.

Proof: From theorem 4.2, each MF model can be described as a DEVS coupled model. And we have already known that the classic DEVS specification is closed under coupling. So we proved that each MF specification can be described as a DEVS atomic specification. ■

Corollary 4.1 the subset of Multi-resolution family is also a multi-resolution family.

The above theorems show that: (1) when what we are concerned with is not the resolution of the models, we can regard MF as a normal DEVS model; (2) the MF also has a structure of hierarchy. In principle, a multi-resolution model family can be expressed by an atomic DEVS model or a coupled DEVS model, but this description is very complex and can't show the relations between different resolution models clearly.

MF is a static definition and MRMS, which will be introduced below, is a dynamic description of MRM. MRMS will pick up proper modular from MF during execution. With the definition of MF, we can clearly describe the relationship between models of the same entity with different resolution. And we can further analyze the consistence between models of different resolution.

5. Multi-Resolution Model System Specification

In this section, we will give a new multi-resolution model system specification, named MRMS (Multi-Resolution Model system Specification). This specification is based on MF which is introduced in section 4 and DSDEVS. We will also prove its closure under coupling.

5.1 Introduction to Multi-resolution Model System Specification

The atomic model of MRMS is the same as classic DEVS basic specification. The coupled specification is shown as following:

$$MRMS =< X_S, Y_S, \kappa, \{\boldsymbol{M}_k\}, \chi, M_\chi >$$

Where:

X_S: is the set of system inputs;

Y_S : is the set of system outputs;

κ: is the set of entities;

$\boldsymbol{M}_k$: $\boldsymbol{M}_k \subset MF_k$, the subset of multi-resolution model family of entity $k, k \in \kappa$, MF_k means the multi-resolution model family of entity k;

$\boldsymbol{M}_k =< \gamma_k, \{M_r^k\}, \{R_{i,j}^k\} >$.

χ: is model resolution controller;

M_χ: is the model of χ.

$$M_\chi =< X_\chi, s_{0,\chi}, S_\chi, Y_\chi, \pi, \psi, \{M_\varphi\}, \delta_\chi, \lambda_\chi, \tau_\chi >,$$

Where:

X_χ: is the input of χ;

$s_{0,\chi}$: is the initial state of χ;

S_χ : is the set of χ ' states;

Y_χ : is the output of χ ;

$\psi = \underset{i \in \kappa}{\times} \{2^{\gamma_i} - \varnothing\}$: is the collection of resolution mode of the model.

$\pi : X_\chi \times S_\chi \to \psi$:is a map form the input and state of χ to resolution mode, we have $\pi(x_\chi, s_\chi) = \varphi \in \psi$;

$M_\varphi =< D_\varphi, \{I_{\varphi,d}\}, \{C_{\varphi,d}\}, \{Z_{\varphi,d}\}, \{R_{\varphi,d}\} >$, represents running model of the system when the resolution mode of the model is φ , where:

D_φ : the set of modules of the system;

$I_{\varphi,d}$ the set of influencers of module *d*;

$C_{\varphi,d}$: the set of modules which should maintain consistency with module *d*;

$Z_{\varphi,d}$: the internal relations in module *d*;

$R_{\varphi,d}$: the relations between different resolution models including module *d*;

δ_χ : the state transfer functions of χ ;

λ_χ : the output functions of χ ;

τ_χ : the time advance function of χ ;

The resolution mode of a system at time *t* is noted as $\varphi(t)$.

There are two categories of MRM problems: model abstraction problem and aggregation/disaggregation problem. The first one can be described by atomic DEVS specification, i.e. $M_r^k =< X_r^k, Y_r^k, S_r, \delta_r, \lambda_r, ta_r >$; the second one can be described by coupled DEVS specification, i.e. $M_r^k =< X_r^k, Y_r^k, D_r^k, \{M_{k,d}^r\}, \{I_{k,d}^r\}, \{Z_{k,d}^r\} >$. Unless explained, we usually do not distinguish these two kinds of specifications.

This specification shows the idea of separating the model from model control. In our specification, we use a special module named resolution controller χ to support multi-resolution modeling. The resolution related information and resolution control information are viewed as the state of χ. All resolution switches are transferred to state transition of states in χ .

5.2 The Key Properties of MRMS

To use a specification for representing large simulation models, one must guarantee that models can be constructed in a hierarchical and modular manner. In order to describe complex systems such as multiple federations HLA simulation systems using MRMS, MRMS specification should be closed under coupling. If a system specification is closed under coupling, we can describe a system with a hierarchical manner. For a multi-resolution model system, its coupled model specification should be equivalent to the basic DEVS formalism, and then a MRMS model can be viewed as an atom basic model to construct more complex MRMS models. Since MRMS basic formalism is DEVS, closure under coupling can be accomplished by demonstrating that the resultant of a MRMS coupled model is equivalent to a basic DEVS specification.

Intuitively, when each entity has only one model and their resolution is the same in MRMS, MRMS can be degenerated into a normal coupled DEVS specification.

Theorem 5.1 When each entity has only one model and each model's resolution is the same in MRMS, MRMS degenerates into a normal DEVS specification.

Proof: we need to prove that when the model of each entity only has one resolution, MRMS can be simply described by basic DEVS. We suppose the corresponding DEVS is $N =< X, Y, J, \{M_j\}, \{I_j\}\{Z_j\} >$.

Obviously, when each entity only has one resolution, i.e. $\forall i \in \kappa, |\gamma_i| = 1$, we have

$MRMS =< X_S, Y_S, \kappa, \{\boldsymbol{M}_k\} >$.

We can rewrite $\boldsymbol{M}_k =< \gamma_k, \{M_r^k\}, \{R_{i,j}^k\} >$, $M_r^k =< X_r^k, Y_r^k, D_r^k, \{M_{k,d}^r\}, \{I_{k,d}^r\}, \{Z_{k,d}^r\} >$ to

$\boldsymbol{M}_k =< X^k, Y^k, D^k, \{M_{k,d}\}, \{I_{k,d}\}, \{Z_{k,d}\} >$,

Because of the closure of DEVS models under coupling, the above specification can be written as:

$$M_k =< X, s_0, S, Y, \delta_{int}, \delta_{ext}, \lambda, ta > .$$

Let the resolution of each model is r_0, then $X_\chi, s_{0,\chi}, S_\chi, Y_\chi$ are constant. φ is also a constant. So $M_\varphi = \{D, \{I_d\}, \{Z_d\}\}$. Because $|r| = 1$, $D = \kappa$, replacing $\boldsymbol{M}_k$ with these constant, we have $MRMS =< X_S, Y_S, \kappa, \{M_k\}, \{I_k\}, \{Z_k\} >$.

So we have $X = X_S, Y = Y_S, J = D = \kappa, M_j = \boldsymbol{M}_k = M_k, I_j = I_k, Z_j = Z_k$. ■

From this Theorem, we can see that MRMS is the extension of normal DEVS. The normal DEVS can be regarded as a special case when all entities are simulated in only one resolution.

Before further exploring the properties of MRMS, we need to first introduce a new specification named Structured Discrete Event Specification (SDE) [43]. SDE provides a formalism for obtaining a fine-grained control over model components. In the SDE formalism, a model is described by

$$S =< X, s_0, Y, \Theta, I, \{\delta_i \mid i \in I\}, \{\lambda_i \mid i \in I\}, \{\tau_i \mid i \in I\} >$$

where $\Theta : S \to I$, is the index function.

A key property of SDE is that a SDE model $S =< X, s_0, Y, \Theta, I, \{\delta_i \mid i \in I\}, \{\lambda_i \mid i \in I\},$ $\{\tau_i \mid i \in I\} >$ is equivalent to the DEVS model $M =< X, s_0, Y, S, \delta, \lambda, \tau >$. Reference [43] gives more information about SDE.

Now, let's return to the study of MRMS again.

Theorem 5.2 Every MRMS coupled model is equivalent to a DEVS basic model.

As a special DEVS specification, MRMS should have the common character of DEVS, so closure under coupling is required. And if MRMS is closed under coupling, we can view a multi-resolution coupled model as an atomic model and use it to construct more complex models.

Proof: Supposing the MRMS coupled model is $MRMS =< X_S, Y_S, \kappa, \{\boldsymbol{M}_k\}, \chi, M_\chi >$ and the DEVS basic model is $M =< X, s_0, S, Y, \delta_{int}, \delta_{ext}, \lambda, \tau >$. Because a SDE model is equivalent to a DEVS basic model, we only need to prove that every MRMS coupled model is equivalent to a SDE model $S =< X, s_0, S, Y, \Theta, I, \{\delta_i \mid i \in I\}, \{\lambda_i \mid i \in I\}, \{\tau_i \mid i \in I\} >$.

We define C_φ as the set of modules corresponding to resolution mode φ, $C_\varphi = D_\varphi \cup \chi$. Obviously, we have:

$$X = X_S, \quad Y = Y_S, \quad S = \bigcup_{\varphi \in \Psi} (\times_{i \in C_\varphi} Q_i), \quad s_0 = \times_{i \in C_0} q_{0,i}$$

$$\tau(s) = min\{\sigma_i \mid i \in C_\varphi\}, s \in S, \sigma_i = \tau_i(s_i) - e_i$$

For convenience, we define $\eta(s) = \pi(x_\chi, \delta_{ext}(s_\chi, e, x_\chi))$. Suppose the state of χ is $S_\chi = \{s_{0,\chi}, s_{1,\chi}, s_{2,\chi}, ..., s_{j,\chi}, ...\}$, and let the set of index $I = \{0,1,2,..., j,...\}$. We define the index function $\Theta : S \to I$ as follows:

$$\Theta(s) = \Theta((s_{a,\chi}, e_\chi), ...) = \alpha$$

For index α , *The partial output function at index a is defined by* $\lambda_\alpha(s) = Z_{N,\alpha}(\underset{i\in I_{N,\alpha}}{\times} \Lambda_{i,\alpha}(s_i, e_i + \tau_\alpha(s)))$ and the output function at index a is defined by $\Lambda_\alpha(s,e) = Z_{N,\alpha}(\underset{i\in I_{N,\alpha}}{\times} \Lambda_{i,\alpha}(s_i, e_i + e))$.

The set of states Q is given by $Q = \{(s,e) \mid s \in S, 0 \le e \le \tau(s)\}$ as defined before,

$\delta_a : Q \times X^{\varnothing} \to S$ is define as $\delta_a(\underset{i\in C_a}{\times} q_i, e, \chi) = \underset{j\in C_\beta}{\times} q_j$

In order to calculate δ_α , we need calculate the current state $s_{\beta,\chi}$ of χ from the previous state $s_{\alpha,\chi}$ of χ .

$$
\begin{aligned}
q_{\beta,\chi} \quad &= (s_{\alpha,\chi}, e_\chi + e) && if\ x_\chi = \varnothing \wedge \sigma_\chi > e \\
&= (\delta_\chi(s_{\alpha,\chi}, e_\chi + e, x_\chi), 0) && if\ x_\chi \ne \varnothing \vee \sigma_\chi = e
\end{aligned}
$$

where $x_\chi = Z_{\alpha,\chi}(\underset{i\in I_{\chi,\alpha}}{\times} v_i)$

$$
\begin{aligned}
v_i \ &= \Lambda_\chi(s_i, e_i + e) && if\ i \ne N \\
&= x && if\ i = N
\end{aligned}
$$

The resolution mode associating with $s_{\beta,\chi}$ is $\varphi_\beta = \eta(s_{\beta,\chi})$, so the according model is

$M_{\varphi_\beta} =< D_\beta, \{M_{i,\beta}\}, \{I_{i,\beta}\}, \{Z_{i,\beta}\} >$

The newly added module set due to the changing of resolution mode is $A = C_\beta - C_\alpha$, and the unchanged module set is $K = C_\alpha \cap C_\beta$. So for arbitrary $q_i \in Q_i, i \in C_\beta$

$$
\begin{aligned}
q_i \quad & = (s_i, e_i + e) && if\ i \in K \wedge (x_i = \varnothing \wedge \delta_i > e) && (1) \\
& = (\delta_{i,\alpha}(s_i, e_i + e, x_i), 0) && if\ i \in K \wedge (x_i \neq \varnothing \vee \delta_i = e) && (2) \\
& = q_{0,i} && if\ i \in A && (3)
\end{aligned}
$$

where $\quad x_i = Z_{i,a}(\underset{i \in I_{i,\alpha}}{\times} v_i)$,

$$
\begin{aligned}
v_i & = \Lambda_{i,a}(s_i, e_i + e) && if\ i \neq N \\
& = x && if\ i = N
\end{aligned}
$$

equation（1） is used for calculating the states of the unchanged modules in set K when the input is zero and $\sigma_i > e$. From (1) ,we know that models in K only update its time *e*. Equation （2）is used for calculating the states of the unchanged models in K when the input is not zero or $\sigma_i = e$. Here all output occurred simultaneously and the state is calculated using the current structure $< D_\alpha, \{M_{i,\alpha}\}, \{I_{i,\alpha}\}, \{Z_{i,\alpha}\} >$, the new structure is used when the next state change occur. Equation（3）is used for calculating the state of newly-added modules.

From the above, we proved that every MRMS coupled model is equivalent to a DEVS basic model. ■

An MRMS model's structure needs to be changed when running, so we can view the MRMS specification as a specific case of DSDEVS.

Theorem 5.3 An MRMS coupled model is equivalent to a DSDEVS coupled model.

Proof: we need to prove that an MRMS can be rewritten as the following DSDEVS specification:

$$DSDEN_N =< X_N, Y_N, \omega, M_\omega >,$$

$$M_\omega =< X_\omega, s_{0,\omega}, S_\omega, Y_\omega, \rho, \Sigma^*, \delta_\omega, \lambda_\omega, \tau_\omega >,$$

Where:

$\rho : S_\omega \rightarrow \Sigma^*$,

For $\forall s_{a,\omega} \in S_\omega$, $\rho(s_{a,\omega}) = \Sigma_a \in \Sigma^*$,

$\Sigma_a = \rho(s_{a,\omega}) = (D_a, \{M_{i,a}\}, \{I_{i,a}\}, \{Z_{i,a}\})$.

Obviously, $X_N = X_S, Y_N = Y_S$. Now, we need prove $\omega = \chi, M_\omega = M_\chi$. Because M_ω is the model of ω and M_χ is the model of χ, so we only need to prove $M_\omega = M_\chi$ ·

We define $X_\omega = X_\chi, s_{0,\omega} = s_{0,\chi}, S_\omega = S_\chi, Y_\omega = Y_\chi, \tau_\omega = \tau_\chi, \delta_\omega = \delta_\chi, \lambda_\omega = \lambda_\chi$,

Supposing the system changes its states when MRMS's state is s_χ and the input is x_χ, so we have

$$\pi(s_\chi, x_\chi) = \varphi, \quad M_\varphi =< D_\varphi, \{I_{\varphi,d}\}, \{C_{\varphi,d}\}, \{Z_{\varphi,d}\}, \{R_{\varphi,d}\} >$$

Let the module set associating with D_φ is $g(D_\varphi) = \{M_d\}, \ M_d \subset \{\boldsymbol{M}_k\}$.

Accordingly, let $s_a = \delta_\chi(s_\chi, e, x_\chi)$, then $\rho(s_a) = \Sigma_a = (D_a, \{M_{i,a}\}, \{I_{i,a}\}, \{Z_{i,a}\})$ ·

Lastly, let

$$D_a = D_\varphi$$

$$\{M_{i,a}\} = g(D_\varphi) = \{M_d\}, \{I_{i,a}\} = \{I_{\varphi,d}\} \cup \{C_{\varphi,d}\}, \{Z_{i,a}\} = \{Z_{\varphi,d}\} \cup \{R_{\varphi,d}\}$$

Thereby we have rewritten MRMS to DSDEVS. ■

Actually, a DSDEVS coupled model is equivalent to a DEVS basic model, and an MRMS coupled model is equivalent to a DSDEVS coupled model, so an MRMS coupled model is equivalent to a DEVS basic model. This is what theorem 5.2 means. So theorem 5.2 can be derived from theorem 5.3.

In principle, a multi-resolution model can be transformed into a DSDEVS model and executed without any support for multi-resolution modeling property but with the support for dynamic structure. Of course, every multi-resolution model is a dynamic structure DEVS model and it should be, because the structure of the multi-resolution model will change during execution. But DSDEVS does not give any resolution related information. Furthermore, a multi-resolution model can be transformed into a classic DEVS model and executed without any support for multi-resolution modeling and for dynamic structure. However, in real applications it would be prohibited by model complexity. It is just like the inherent relationship in object-oriented programming. MRMF is an extension of Dynamic structure DEVS, DSDEVS and DEVS can't exhibit the characters of multi-resolution models clearly. In such applications, it would be very difficult or even impossible to represent the resolution-related information without the help of a formalism with complete resolution semantics.

6. An Example

In this section, we will give an example to illustrate how to describe a multi-resolution model system using MRMS. Let's consider the following scenario: an aircraft formation on the blue side attacks an antiaircraft gun company equipped with an air surveillance radar station on the red side. The aircraft formation is modeled with two different resolutions: formation and single aircraft. When the distance between radar and aircraft is less than some certain value, the aircraft should be modeled at the resolution of a single aircraft, otherwise, the aircraft should be modeled at the resolution of formation. When the distance between the aircraft and the antiaircraft gun company is less than some given distance, the antiaircraft gun can attack the aircraft and the aircraft can retaliate. Because the antiaircraft company is modeled at low resolution, the aircraft should also be modeled at low resolution when interacting with the antiaircraft gun company.

According to MRMS formalism， we get:

$$MRMS = < X_N, Y_N, \kappa, \{M_k\}, \chi, M_\chi >$$

Where: $X_N = Y_N = \varnothing, \kappa = \{R, G, A\}$, the symbol A represents aircraft.

M_R and M_G represent the single resolution DEVS model of radar and antiaircraft gun company respectively, whose resolution is r_R and r_G respectively.

$M_A = \{\gamma_A, \{M_r^A\}, R_{i,j}^A\}$, where $\gamma_A = \{r_P, r_F\}$, M_P^A and M_F^A are classic DEVS model.

χ is the resolution control module, M_χ is the model of χ.

$$M_\chi = < X_\chi, s_{0,\chi}, S_\chi, Y_\chi, \pi, \Psi, \{M_\phi\}, \delta_\chi, \lambda_\chi, \tau_\chi >$$

For this simple example, we can enumerate all of its resolution modes:

$$\{\{r_G, r_R, r_F\}, \{r_G, r_R, r_P\}, \{r_G, r_R, \{r_F, r_P\}\}\}$$

At the initialize state $s_{0,\chi}$, the aircraft is modeled with the resolution of formation, as showed in Fig.1.

According to MRMS， we have：

$$\varphi = \pi(x_\chi, s_{0,\chi}) = \{r_G, r_F, r_F\},$$

$$M_\varphi = < D_\varphi, \{I_{\varphi,d}\}, \{C_{\varphi,d}\}, \{Z_{\varphi,d}\}, \{R_{\varphi,d}\} >$$

$D_\varphi =< F, R, G >,$

$I_{\varphi,F} = \{G, \chi\}, I_{\varphi,R} = \{F\}, I_{\varphi,G} = \{F\}$;

$I_{\varphi,\chi} = \{F, G, R\}$,

$C_{\varphi,i} = \varnothing, i \in \{F, R, G\}$, $R_{\varphi,i} = \varnothing, i \in \{F, R, G\}$;

$Z_{\varphi,F} : Y_\chi \times Y_G \to X_F$, $Z_{\varphi,R} : Y_F \to X_R$; $Z_{\varphi,\chi} : Y_R \times Y_G \to X_\chi$.

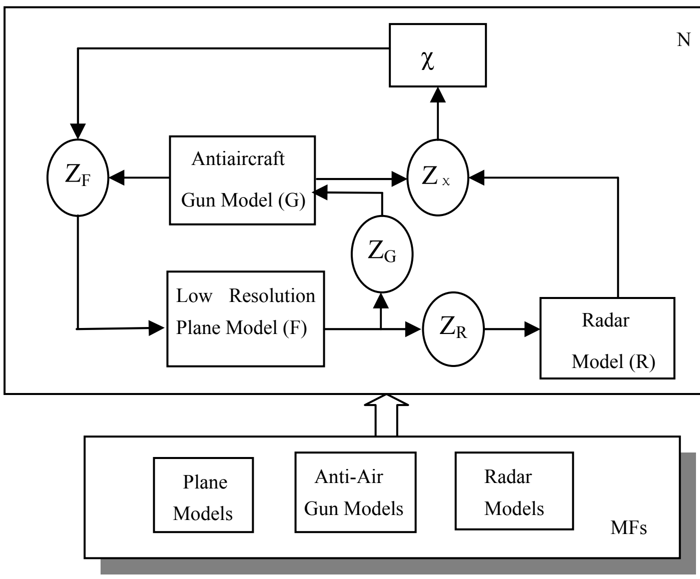

Fig. 1. MRMS-based multi-resolution model description (before resolution change)

At some time， the distance between the aircraft and the radar is less than some value, the radar needs the high resolution model of the aircraft and the antiaircraft gun needs the low resolution model of aircraft as shown in Fig.2. So:

$x_\chi = Z_{\varphi,\chi}$ ， $s_\chi^{'} = \delta_{ext}(s_{0,\chi}, e, x_\chi)$ ， $\varphi' = \pi(x_\chi, s_\chi^{'}) = \{r_R, r_G, \{r_F, r_P\}\}$ ，

Accordingly，

$M_\varphi =< D_\varphi, \{I_{\varphi,d}\}, \{C_{\varphi,d}\}, \{Z_{\varphi,d}\}, \{R_{\varphi,d}\} >,$

$D_\varphi =< F, P, R, G >,$

$I_{\varphi,F} = \{G, \chi\},\ I_{\varphi,R} = \{P\},\ I_{\varphi,G} = \{F\}, and\ \ I_{\varphi,\chi} = \{F, P, G, R\}.$

$C_{\varphi,F} = \{P\},\ C_{\varphi,P} = \{F\},\ R_{F,P} : Y_F \to X_P,\ and\ \ R_{P,F} : Y_P \to X_F.$

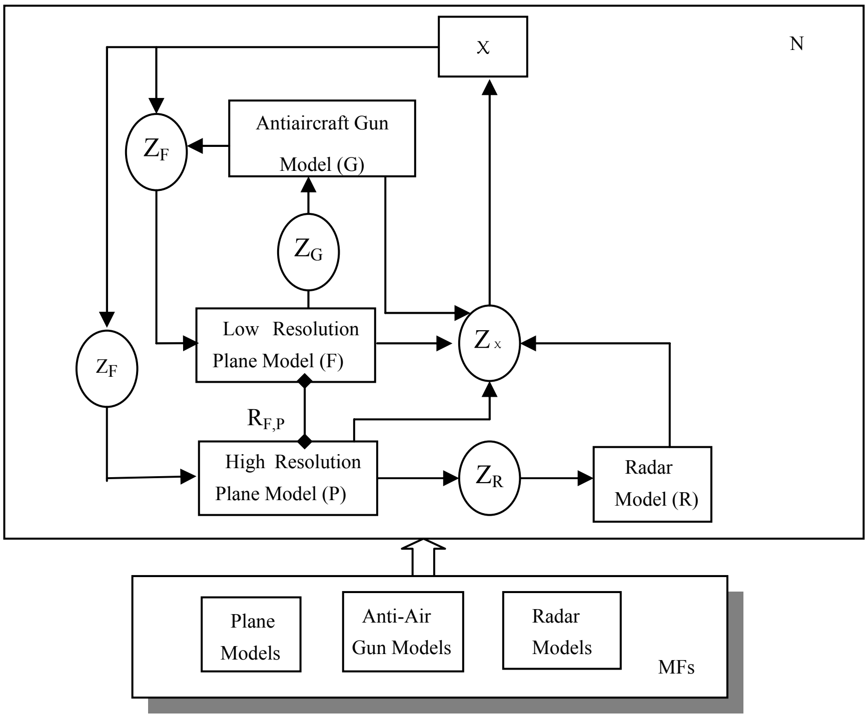

Fig. 2. MRMS-based multi-resolution model description (after resolution change)

7. Conclusion and Future Work

In this paper, we proposed a new concept called multi-resolution model family and established a new multi-resolution model description formalism called multi-resolution model system specification. As DSDEVS, Symbolic DEVS, Fuzzy DEVS and Real-Time DEVS, MRMS is an extension of DEVS formalism. Our MRMS specification has the following characteristics: it clearly describes the fact that there are different resolution models of an entity in a system; it describes the relationship between different resolution models; it has the ability to describe the dynamic change of model resolutions; it can be used to describe different modeling methods; it has the property of closure under coupling. This specification may also contribute to the component-based simulation, VVA, interoperability and other related areas.

This is only a coarse formal description of multi-resolution modeling, so there is much space to improve. It only gives a high level description of MRM and this specification is only applicable to problems with hierarchy. For many specific MRM problems such as cross-resolution interaction and multi-resolution models without hierarchy, this specification should be improved to adapt to these specific problems.

Based on MRMS, an MRM framework in HLA has been designed and implemented [44], the consistency maintenance problem has been researched and a consistency measurement method has been developed [45], some specific problems in parallel implementation of multi-resolution models in distributed interactive simulation are studied [46]. Some further study topics may include: Exploring new methods for multi-resolution modeling; Designing simulation model-base supporting multi-resolution model storing and querying using MRMS; Developing standard reference FOM for MRM according to IEEE1516; Expressing MRM interface with BOM; Studying the MRM problems in conceptual modeling; Researching the problem of consistency in multi-resolution model family; Solving the multi-resolution modeling problems encountered in C4ISR modeling and simulation; And developing multi-resolution modeling assistant tools.

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Author Biography

Liu Baohong is an associate professor at National University of Defense Technology. He received his Ph.D. degree in system modeling and simulation from the National University of Defense Technology. Now his research interests include the theory of multi-resolution modeling, modeling and simulation of complex systems, and design and analysis of simulation experiments.