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Variable Structure in DEVS Component-Based Modeling and Simulation

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Variable structure refers to the ability of a system to dynamically change its structure according to different situations. It provides component-based modeling and simulation environments with powerful modeling capability and the flexibility to design and analyze complex systems. In this article, the authors discuss variable structure—specifically, the structure change and interface change capability—in DEVS-based modeling and simulation environments. The operations of structure change and interface change are discussed, and their respective operation boundaries are defined. Three examples are given to illustrate the role of variable structure and how it can be used to model and design adaptive complex systems. Principles for the implementation of variable structure are also presented and illustrated in the DEVSJAVA modeling and simulation environment.

Keywords: Variable structure, component-based modeling and simulation, DEVS, adaptive complex systems

1. Introduction

With the rapid advance of component-based technology in software engineering, component-based software has been widely used to develop highly modular simulation environments. The integration of component-based technology with modeling and simulation environments gives the latter powerful capability and greatly supports reusability of components and interoperability of simulation environments. The reuse of components, together with visual programming technology, makes it possible to drag and drop existing components during the modeling process, thus easing system modeling and significantly reducing development time. With component-based technologies such as the federate concept introduced by the High Level Architecture (HLA) [1-3], different simulation environments can interact through standard interfaces and work together. Thus, interoperability is achieved, and more powerful simulations can be conducted. Component-based technology also makes the modeling of a complex system easier to manage because a complex system can be divided into several manageable pieces, each referring to a component. It also promotes distributed simulation as component-based technology has a natural fit to distributed environments.

Motivated by these advantages, various component-based modeling and simulation environments have been developed. Furthermore, HLA was developed to enhance the interoperability of models and simulation environments. In HLA, component models are referred to as federates. Each federate provides an interface through which messages can be passed and received. Because these interfaces comply with the same HLA interface specification, federates developed by different developers can communicate with each other via the runtime infrastructure. Other works such as JSIM [4], SIMKIT [5], Silk [6], and VSE [7] focus on the implementation of component-based modeling and simulation environments. For example, the JSIM simulation environment uses Java and Java beans technology to support component-based modeling and simulation. A visual design interface is provided for users to develop and assemble components.

The Discrete Event System Specification (DEVS) [8] supports component-based modeling and simulation by emphasizing the theory of hierarchical modular modeling. In a DEVS-based environment such as DEVSJAVA [9], a component is a model with clear-defined interfaces called input and output ports. A model could be an atomic model or coupled model, which is composed from other DEVS models. By adding couplings between output/input ports...
of different components, messages can be passed from one component to another. Under the property of closure under coupling, a coupled model itself can be treated as a subcomponent of other models. This kind of hierarchical modular construction makes each DEVS model a self-contained component that can be easily reused. Because of this, the DEVS component-based modeling and simulation environment does not rely on the underlining implementation language. In fact, various DEVS environments such as DEVSC++, DEVSJAVa, DEVSCorba, and so forth [9-11] have been developed. The DEVS/HLA [12] was also developed to allow DEVS to work with HLA.

A component system is built by composition of individual components. Thus, in a component-based modeling and simulation environment, the modeling process is to build components and to assemble them to capture a system’s structure and behavior. For some complex systems, the structures and behaviors could be very complex as the systems may continuously reconfigure themselves to adapt to different situations. For example, a distributed computing system may dynamically add or remove computing nodes according to the load of the system. Other examples include the ecological systems that typically evolve over time to adjust to the new environment. To model these complex systems, a variable structure modeling capability is needed. As variable structure greatly enhances the modeling capability, it also raises special design issues for component-based modeling and simulation environments.

In this article, we discuss the variable structure modeling capability in DEVS component-based modeling and simulation. While previous work [13-17] has established a theoretical background for the variable structure of DEVS, this article discusses it in the context of component-based technology and covers more aspects of it. The article first elaborates on the conceptual development of variable structure in component-based modeling and simulation. Then it discusses three examples to illustrate the role of it. After that, the implementation of variable structure in a DEVS modeling and simulation environment is presented. Finally, conclusions are drawn, and some open issues are discussed.

2. Conceptual Development for Variable Structure in DEVS

A component is “a nontrivial, nearly independent, and replaceable part of a system that fulfills a clear function in the context of a well-defined architecture. It conforms to and provides the physical realization of a set of interfaces” [18]. A component system is built by composition of individual components and by establishing relationships among them. As each component holds a high degree of autonomy and has well-defined interfaces, variable structure of components can be achieved during runtime. For component-based modeling and simulation, variable structure provides several advantages: (1) it provides a natural and effective way to model those complex systems that exhibit structure and behavior changes to adapt to different situations.

Examples of these systems include distributed computing systems, reconfiguration computer architectures [19, 20], fault-tolerance computers [21], and ecological systems [15]. Structure changing and component upgrading is an essential part of these systems. Without the variable structure capability, it is very hard, if not impossible, to model and simulate them. (2) From the design point of view, variable structure provides the additional flexibility to design and analyze a system under development. For example, as will be illustrated later, variable structure gives us the flexibility to design and simulate a distributed robotic system in which robots form relationships dynamically. (3) Variable structure makes it possible to load only a subset of a system’s components for simulation. This is very useful to simulate very large systems with a tremendous number of components, as only the active components need to be loaded dynamically to conduct the simulation. Otherwise, the entire system has to be loaded before the simulation begins.

In general, there are six forms of reconfiguration of component-based systems [22]: addition of a component, removal of a component, addition of a connection between components, removal of a connection between components, update of a component, and migration of a component. The first four operations result in a structure change of the component-based system. In DEVS, they are usually referred to as variable structure modeling. The update of a component means a component is updated by a new version that might have a totally different behavior or interface from the old one. This can be accomplished either by replacing the old version with a new one or by directly upgrading a component to a new version. Replacing a component involves the process of adding the new component and removing the old one, as can be realized by the addition and removal operations. In this article, we are also interested in the upgrade of a component. Specifically, we discuss how a DEVS model (component) may change its interface by adding or removing its input and output ports in different stages. The migration of a component actually implies two involved entities: a component and the location (physical or soft) of the component. Since this is usually researched in mobile agent systems, it is not discussed in this article.

Figure 1 gives an example that shows a simple process of structure change. In this example, the initial system has two components, A and B. Then, component C and the connection from C to B are added. After that, component A is removed, resulting in a final system with two components, C and B. Note that removal of a component will automatically remove all the connections related to that component. In a modular DEVS environment, DEVS models are the components, and DEVS couplings are the connections. Thus, variable structure in DEVS means that DEVS models and couplings can be added or removed dynamically. Corresponding to the four operations of structure change, four methods are provided in a DEVS environment. They are addModel(),/removeModel() to add/remove...
Another important question for variable structure systems arises concerning the authorization and timing of the structure changes. Generally speaking, there is no specific restriction on which component cannot initiate a structure change. However, because a DEVS coupled model does not have its own behavior, an atomic model is needed to initiate a structure change. The initiation typically happens in the atomic model’s internal or external transition functions. This is reasonable because a structure change is usually triggered by situation changes, which are captured as events in DEVS and are handled by the external or internal transition functions. In this sense, the atomic model acts as a supervisor to monitor the conditions of interest. For the system shown in Figure 1, component B could be the one to monitor the system’s situations and initiate the structure change. For example, it may monitor the input from A. If this input is less than a predefined value, it adds component C and the coupling from C to B. Then it monitors the input from C, and if this input is greater than a predefined value, it removes A.

2.1 Operation Boundary

Another important question for variable structure systems is how to determine the particular components that can be affected by a structure change operation. To answer this question, we introduce the operation boundary concept and define it as the safe scope to conduct a meaningful operation. For example, in a distributed environment, a component can remove components on its local computer, but it is not allowed to remove components on remote computers. The latter violates the operation boundary of the remove operation in a distributed environment. To support the operations boundary in DEVS, models can maintain information on their locations in relation to the hierarchical structure of the overall coupled model. Components of the same coupled model, therefore belonging to the same parent, are called brothers. This approach is based on the structure knowledge maintenance concepts in Zeigler [23].

Thus, the structure change operations also need to work within this hierarchical structure and to maintain this structure. On the basis of this, we define the operation boundaries of the four structure change operations as follows:

- **addModel( . . . )**: a model can only add components to its parent coupled model.
- **removeModel( . . . )**: a model can only remove itself and its brothers.
- **addCoupling( . . . )**: a model can only add couplings involving itself, its parent, and its brothers.
- **removeCoupling( . . . )**: a model can only remove couplings involving itself, its parent, and its brothers.

These clearly defined operation boundaries make it easier for a user to check if an operation is legal or illegal. For example, it can easily be seen that a model can remove itself, but it cannot remove its parent. Our approach differs from that formalized by Barros [24], who uses a central network executive to initiate structure changes. We find that much greater flexibility, at minimal cost, is achieved by allowing any component in a coupled model (or network) to initiate changes within the operations boundary.

We note that operations boundaries are defined in terms of the model hierarchical structure independently of any distribution considerations. In distributed simulation, components reside on different computers, and it is up to the distributed environment to ensure that the correct structure changes are carried out as prescribed by the structure modification commands. The distributed coupling change capability is supported by the DEVSJAVA environment. That is, couplings can be added or removed between models on different computers. It is up to the DEVS simulators to determine whether the coupling change is local or involves other computers. However, remotely adding/removing models in DEVSJAVA is currently not supported.

2.2 Changing Port Interfaces

Besides structure change, another reconfiguration feature is provided in DEVS to allow an atomic model to add/remove input or output ports dynamically. For this purpose, the **addInport()** and **addOutport()** are provided for an atomic model to add new input and output ports, respectively; the **removeInport()** and **removeOutport()** are

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1. Although it can be accomplished by sending a message to a remote simulator, which then conducts the adding/removing operation locally, we have not completed the design details.

Figure 1. A variable structure process
provided for an atomic model to remove existing input and output ports, respectively. As input and output ports are the interfaces of DEVS models, changing ports of a model usually requires that the model's behavior also change accordingly. Thus, special attention has to be paid when adding/removing ports dynamically. The modeler has to ensure that if a model receives a new input (or output) port, the model has, or obtains, a corresponding way to handle the possible input received (or generated) on this port. We define the operation boundary of adding/removing ports as a model can only add/remove ports of itself and its brothers. Thus, atomic models inside a coupled model have the capability to modify the interfaces of their brothers, although the functionality to handle messages at those interfaces should be there or should be provided in the modified models. Particular ways of accommodating new ports are known. For example, one can make ports adhere to a labeling scheme such as name + index, which can be analyzed and interpreted. Detailed explanation will be given in section 3.3. As a new feature of DEVS variable structure, more research is needed to answer questions such as how to provide a general mechanism to update a model's external transition and output functions accordingly after the model's input and output ports are added/removed dynamically.

3. Examples of Variable Structure

To illustrate the role of variable structure in component-based modeling and simulation, we describe three examples in this section. The first example shows how a complex distributed robotic system can be designed and simulated using the variable structure capability. The second example illustrates the ability to employ variable structure to dynamically emulate the system entity structure (SES). The last one describes an advanced workflow model that dynamically reconfigures itself by adding/removing models and changing the interface of models.

3.1 Dynamic Team Formation of a Distributed Robotic System

Distributed robotic systems have been a very active research topic recently. In Zhang et al. [25] and Butler, Fitch, and Rus [26], a group of robots that can change their shape has been reported. As those robots change hardware components of their own, in this section, we describe a distributed multirobotic system that changes its software components. This system exhibits dynamic team formation in which independent robots form teams dynamically and then conduct a Leader-Follower march. We first describe a system that has been realized by two real mobile robots [27]. Then we discuss a more scalable system with an indefinite number of robots. The robot we use in the example is a car-type mobile robot with wireless communication capability [28].

For the system with two robots, the team formation process starts with both robots moving around and trying to find each other. Initially, there is no connection between these two robots, although they are connected to a software process, called a Manager, on a wireless laptop. When two robots find each other, the Manager establishes direct connections between them and asks them to organize into a Leader-Follower team. Then they begin to march: one follows the other with the same movement. During the march, if two robots lose each other, they will inform the Manager and then go back to the initial state to search for each other.

From the above description, we can recognize three basic components in this system: the Manager, which resides on a laptop (computer), and robot1 and robot2, which reside on mobile robots. Figure 2a shows the model of this system, where the Manager is an atomic model, and each robot is a coupled model (Fig. 2b). A complete description of the robot model can be found in Hu and Zeigler [27]. The coupling of the system is as follows (R1 stands for robot1, R2 stands for robot2, man stands for Manager, and distanceData, report, check, etc. refer to the port names):

```
removeCoupling(R1, “distanceData,” man, “Robot1_distanceData”);
addCoupling(R1, “distanceData,” man, “Robot1_report”);
addCoupling(R2, “distanceData,” man, “Robot2_distanceData”);
addCoupling(R2, “report,” man, “Robot2_report”);
addCoupling(R2, “check,” R1, “check”);
```

As we can see, there is no coupling between robot1 and robot2. Each robot has output ports distanceData and report. These ports are coupled to the Manager's corresponding input ports. Meanwhile, the Manager has output ports coupled to each robot's input port check, so that Manager can ask them to check if they are within the line of sight. The robots return the check result using the report port. Once the report messages returned from the robots are both positive, it means two robots are close and they see each other. In this case, the Manager will change the couplings of the system dynamically to establish a direct connection between the two robots. Specifically, in this example, the manager executes the following DEVSJAVA code:

```
removeCoupling(R1, “distanceData,” man, “Robot1_distanceData”);
addCoupling(R1, “readyOut,” R2, “readyIn”);
addCoupling(R2, “readyOut,” R1, “readyIn”);
```

Note that the addCoupling method is overloaded so it accepts strings to specify components in addition to object references. This feature makes it convenient for the modeler to keep track of models that have been added using
string names. Explicit references can also be obtained from the parent coupled model by supplying the string names. This requires that all models be given unique names. After executing the DEVSJAVA code, a bidirectional connection is established by coupling two robots’ Ready port to each other, so they can communicate directly. The distanceData and check couplings between robots and Manager are removed because they are no longer needed during the process of the robot march. The report coupling remains so robots can still inform the Manager in case they lose each other. During the march, if two robots lose each other, they send the “Lost Partner” message to the Manager using the report port. This will trigger the Manager to add and remove couplings among the components. As a result, the system goes back to the initial situation, where two robots move independently and try to find each other.

As the above system only includes two robots, more scalable systems with an indefinite number of robots can be developed based on the same variable structure idea. Figure 3 shows an example with 10 independent robots searching for each other, forming groups dynamically, and finally organizing into one large Leader-Follower team. During this process, couplings between models are added and removed, resulting in a variable structure system.

3.2 Dynamically Emulate the System Entity Structure (SES)

The system entity structure (SES) provides a way for specifying system composition [29] with information about decomposition, coupling, and taxonomy. It also provides a formal framework for representing the family of possible structures. From the design point of view, SES represents the design space with various possible design configurations. Thus, the process of design/analysis is to prune SES—in other words, to search the best design configuration. For complex systems, the number of the combination of different configurations is very large. Thus, it is desirable to be able to emulate SES and automatically search the best design configuration. In this section, we show an example that demonstrates how this can be achieved by employing the variable structure capabilities.

This example system is ef SES, as shown in Figure 4a. It has two components: an experimental frame model ef and a processor model that has three specializations representing three design choices of the system. The specializations of the processor model include a single processor, proc; a divide-and-conquer processor, DandC3; and a pipeline processor, pipeLine. To automatically simulate all these alternatives of the processor model, ef SES employs an
A simple workflow prototype is referred to as GPT. This is a specialized entity developed to emulate the SES of a system. In this example, the user defines procSpec, a subclass of specEntity, and provides it with the first and subsequent specializations: proc, DandC3, and pipeLine. Then, as shown in Figure 4b, the user adds procSpec to the coupled model and tells it which component to control (the dashed lines in Figure 4b show that procSpec is linked to the processor model’s specializations). Based on this information, during simulation, the procSpec automatically replaces the processor model with different specializations until all of them are tested. Since the addition of local control components preserves the hierarchical, modular structure, the hierarchical properties of the SES are automatically obtained. Moreover, this variable structure capability provides a general way to emulate the SES and automatically test all the alternatives of a system’s design space, as described in Couretas, Zeigler, and Patel [30].

While the SES involves only replacement of components by alternatives, the approach can be further extended to allow a restructuring executive to observe the simulation and make decisions regarding the alternatives to employ based on prevailing conditions. Such restructuring is discussed in the following example.

### 3.3 A Reconfigurable Workflow System

A simple workflow prototype is referred to as GPT. This is a coupled model that is composed of a Generator, a Processor, and a Transducer. It is the simplest self-contained model that simulates three basic components of any workflow system. The Generator generates jobs, the Processor processes them, and the Transducer keeps track of the system state as a whole computing performance indexes such as system throughput (jobs processed per second) and average job turnaround time. In this section, we describe a reconfigurable GPT system where the Processor(s) can be dynamically added or removed and the Generator and Transducer can change their interfaces accordingly.

As shown in Figure 5a, this system starts with the basic GPT components: Generator, Proc1, and Transducer. Generator generates jobs and sends them out through the out1 port coupled to the Proc1’s in port. Proc1 executes the job and sends the solved job to the Transducer at the solved1 port. Note that the Generator has input ports add and addBank, and the Transducer has output ports addModel and addProcBank coupled to the two Generator ports, respectively. This suggests that the system has the capability to add a processor and a processor bank.

In this example, the Transducer makes decisions of when to add or remove processor(s). The Generator executes the addition or removal operations. Thus, if the Transducer notices that Proc1 cannot handle all the generated jobs, it sends out a message to the Generator, which then adds another processor, Proc3. As shown in Figure 5b, Proc3 is in a similar position as Proc1 in the system. Note that the interfaces of Generator and Transducer also change accordingly. Besides the Generator’s earlier output port out1, a new output port, out3, has been added explicitly for Proc3. Similarly, the Transducer has added input port Solved3 to collect jobs processed by Proc3. Also, the Generator and Transducer are now outfitted with ports for removing the processor (remove and removeModel ports). This is a new functionality that has been added in this stage. The interface change of Generator and Transducer is a reflection of the system’s structure change. Initially, there was no functionality to remove models, as there was no need of it. As new processors are added, so is the corresponding functionality to remove them. A typical set of commands that were executed by the Generator after receiving the addition message from the Transducer is as follows:

![Figure 4. Dynamically emulate the system entity structure (SES)](image)
mg = new modelProc("Proc" + index); // in this example, the value of index is 3
addModel(mg);
addOutport(“Transducer,” “removeModel”);
addOutport(“Generator,” “remove”);
addInport(“Transducer,” “out” + index);
addInport(“Generator,” “solved” + index);
addCoupling("Transducer," “removeModel, “Generator," “remove”);
addCoupling(“Proc” + index, “in”);
addCoupling(“Proc” + index, “out,” “Transducer," “solved” + index);

Notice that a labeling scheme is used as the Generator model adds output port out + index for the new processor. Similarly, the Transducer handles the jobs solved by the processor using input ports with name solved + index. This allows expressing the Transducer’s processing by parsing port names to obtain their role and index parts, independently of the number of processors. The Transducer retains its basic behavior independent of the structure change by providing the code in advance to handle the messages coming on new ports. More flexible approaches may be obtained by providing schemas that can be accessed at runtime to support desired interfaces, a subject for further research.

In this example, after Proc3 is added, it can also be removed when the Transducer thinks Proc1 alone is enough to process all the generated jobs. To achieve this, the Transducer sends out a removal message using the removeModel port to the Generator. The Generator then removes Proc3, and the system goes back to the initial stage. Similarly, a processor bank (a coupled model) that contains multiple processors can also be added and removed.

From the above description, we can see that the system is able to expand itself, modify the interfaces of its components according to the structure change, and then shrink back to the original system. It displays a complete cycle of growth, from a basic functional level to an expanded system capable of high throughput and coming back to the initial state when its job (maximizing throughput) is done.

4. Implementation of Variable Structure in DEVS

The implementation of variable structure is based on the earlier development of the DEVSJAVA modeling and simulation environment. So our discussion starts from a review of this environment, with emphasis on the hierarchical structure of DEVS models and simulators. Although a particular implementation environment is employed as a basis, the design is generic and can be employed in any hierarchical, modular DEVS environment.

4.1 Hierarchical Structure of DEVS Models and Their Simulators

In a DEVS modeling and simulation environment, there is a clear separation between models and their simulators. DEVS models are defined by the users to model the system under development. DEVS simulators are provided by the DEVS simulation environment to simulate or execute DEVS models. Corresponding to the hierarchical structure of a DEVS model, its simulators also form a hierarchical structure. Figure 6 gives an example that shows the relationship of a hierarchical coupled model and its corresponding simulators (the dashed lines show the hierarchical relationship between simulators). This model has three components: Atomic3, Atomic4, and Coupled1, which has two subcomponents: Atomic1 and Atomic2. The simulators manage the information of the hierarchical coupled model in a hierarchical way. On the very top level, there is a coordinator assigned to the coupled model. This coordinator is the parent of all its subsimulators, which have a one-to-one relationship to the components of the coupled model. Following the hierarchical structure of the coupled model, there is a coupledSimulator assigned to each atomic model and a coupledCoordinator assigned to each coupled...
model. A coupledCoordinator acts as both a coordinator and a coupledSimulator. This is because it needs to communicate not only with its children (like a coordinator) but also with its parent and brothers (like a coupledSimulator).

This hierarchical structure of models and simulators requires several data structures to keep information so that the system can be efficiently implemented. Figure 7 shows the related data structures managed by simulators and models. This figure also shows that the atomic class implements variableStructureInterface, which defines the methods for adding/removing DEVS models, couplings, and ports. For simplicity, Figure 7 only shows the information related to the implementation of variable structure.

First, let us see the data structures managed by DEVS coupled models, as shown by the digraph class in Figure 7 (atomic models do not need them). This is straightforward because coupled models need to keep track of their subcomponents and the couplings among them. Thus, each coupled model has two variables as defined as follows:

- ComponentsInterface components;
- coupel cp;

The data structure for simulators can be categorized into three categories to store three different types of information as shown as follows:

- Children simulator info: ensembleSet simulators;
- Model’s coupling info: coupel coupInfo, extCoupInfo;
- Model-simulator mapping info: Function modelToSim, internalModelToSim;

The first variable, simulators, is used by a coupledCoordinator (coupledSimulator does not use it) to store its children simulators. For example, in Figure 6, the simulators variable for coordinator has three instances: coupledCoordinator1, coupledSimulator3, and coupledSimulator4. The simulators variable for coupledCoordinator1 has two instances: coupledSimulator1 and coupledSimulator2. The second group of variables, coupInfo and extCoupInfo, is used by simulators to store the models’ coupling information. Specifically, coupInfo stores the couplings that start from a model and end with the model’s brothers or parent. extCoupInfo is used by coupledCoordinator (coupledSimulator does not use it) to store the couplings that start from a model and end with the model’s children models. Using coupledCoordinator1 in Figure 6 as an example, the coupInfo has one coupling instance that starts from Coupled1 and ends with Atomic3. The extCoupInfo has two coupling instances; both of them start from Coupled1 and end with Atomic1. The third group of variables, modelToSim and internalModelToSim, is used by simulators to store the model-simulator mapping information. Again, using coupledCoordinator1 in Figure 6 as an example, the modelToSim has three instances: (Coupled1, coupledCoordinator1), (Atomic3, coupledSimulator3), and (Atomic4, coupledSimulator4). The internalModelToSim has two instances: (Atomic1, coupledSimulator1) and (Atomic2, coupledSimulator2).

Note that in this implementation, each model and simulator manages its own copy of information. This approach relieves the central coordinator’s involvement in its child simulators’ local activities. For example, by keeping a local copy of the coupling information, a simulator can send its model’s output messages directly to the destination simulators. More information about the advantages of this approach can be found in Cho, Hu, and Zeigler [31] and Cho [32].
4.2 Add/Remove Coupling Dynamically

Because DEVS models and simulators use coupling data structures to keep all the coupling information, the basic idea to implement this feature is to update those data structures. Below, we use `addCoupling()` to show how it works.

```java
public void addCoupling(String src, String p1, String dest, String p2){
    digraph P = (digraph)getParent();
    P.addPair(new Pair(src,p1),new Pair(dest,p2)); // update its parent model's coupling info
    coordinator PCoord = P.getCoordinator();
    PCoord.addCoupling(src,p1,dest,p2); // update the corresponding simulator's coupling info
}
```

The method first gets its parent, which is a coupled model. Then it calls its parent’s `addPair()` method to update the parent’s coupling information, the `cp` variable, as described in section 4.1. To update the coupling information of the affected simulators, the atomic model then calls the coordinator’s `addCoupling()` method. This method uses the source model’s name to find the corresponding simulator and then updates that simulator’s coupling information, which is kept in the `coupInfo` or `extCoupInfo` variables. Note that for implementation convenience, the `getParent()` method is used. This method returns the parent model’s reference that was established during the simulation’s construction stage. As this method is not accessible to the modelers, it does not violate the hierarchical modular property of DEVS models.

4.3 Add/Remove Model Dynamically

Adding a model dynamically means not only that a new model is added but also that a new simulator needs to be created and added into the system. Furthermore, the new simulator needs to be initialized and synchronized with the ongoing simulation system. The `addModel()` method is shown as follows:

```java
public void addModel(IODevs iod){
    digraph P = (digraph)getParent();
    P.add(iod);
    coordinator PCoord = P.getCoordinator();
    PCoord.setNewSimulator((IOBasicDevs)iod);
}
```

This method first adds the model as a new component to its parent by calling the `add()` method (update parent’s components variable). Then it calls the coordinator’s `setNewSimulator()` method. This method creates a new simulator for the added model and initializes that simulator. It is shown as follows:

```java
public void setNewSimulator(IOBasicDevs iod){
    if(iod instanceof atomic){ //do a check on what model it is
        coupledSimulators = new coupledSimulator(iod);
        . . . . . . . . . . //update the corresponding data structures;
        s.initialize(getCurrentTime());
    } else if(iod instanceof digraph){
        coupledCoordinator = new coupledCoordinator((Coupled) iod);
        . . . . . . . // same as when the model is atomic
    }
}
```

As can be seen, the method creates a new simulator based on the model type (atomic model or coupled model).
The method is basically the reverse of what addModel() does. These clients connect to a CoordinatorServer and then it calls the model. One extra step here is the removeModelCoupling() method to remove the simulator of that model. As in Figure 6, in this example, the three components of the coupled model—Coupled1, Atomic3, and Atomic4—are distributed on three different computers. As can be seen, for each distributed component on a computer, there is a client simulator assigned to it (CoupledSimulatorClient for a coupled model). These clients connect to a CoordinatorServer, which may reside on another computer (the dashed circles mean different parts of the system reside on different computers). During initialization, the CoordinatorServer waits for connections from clients. For each client, the CoordinatorServer creates a SimulatorProxy to communicate with it. After all the connections are received, the CoordinatorServer establishes the modelToSim and coupInfo and downloads them to SimulatorProxies. As modelToSim and coupInfo are kept in SimulatorProxies (not in the client simulators), all messages sent between clients will be first passed to SimulatorProxies. For example, in Figure 8, if Atomic4 sends a message to Coupled1, the message will first be sent to SimulatorProxy3. Based on the coupInfo and modelToSim, SimulatorProxy3 passes the message to SimulatorProxy1, which then sends the message to CoordinatorClient1 (Coupled1).

As the coupling information of distributed models is kept in SimulatorProxies, the basic idea of implementing distributed coupling change is to update those SimulatorProxies’ coupling information. To implement this, whenever an atomic model wants to add or remove a distributed coupling, the CoupledSimulatorClient for that atomic model generates a distributed coupling change request and sends it to the SimulatorProxy as shown as follows:

```java
public void addDistributedCoupling(String src, String dest, String p1, String p2)
{
    String dcc = Constants.addCouplingSymbol+"."
        +src+":"+p1+":"+dest+":"+p2;
    client.sendMessageToServer(dcc);
}
```

On the SimulatorProxy’s side, the waitForMessageFromClient() method is modified so that it can handle the distributed coupling change request. This method is shown as follows:

```java
protected void waitForMessageFromClient() {
    String string = readMessageFromClient();
    //check to see if the message is a dynamic coupling change message
    if(string.startsWith(Constants.addCouplingSymbol)
        || string.startsWith(Constants.removeCouplingSymbol))
    {
        DynamicCouplingStrReceived(string);
    }
    else{ // this is a regular DEVS message
        . . . . . . . // process the message
    }
}
```

The method checks to see if the received string starts with addCouplingSymbol or removeCouplingSymbol. If that is true, the received string is a distributed coupling change request, so the DynamicCouplingStrReceived() is called. Otherwise, the received string is a regular DEVS message, so the method processes it as usual. The DynamicCouplingStrReceived() method processes the string to get the source, the source’s port, destination, and the destination’s port of the coupling. Then it calls the CoordinatorServer’s addCoupling() or removeCoupling() methods to update the coupling information of SimulatorProxies.

4.5 Add/Remove Ports

The operation of adding and removing ports dynamically is done by
4. Interface Alteration

The functionality of modifying interfaces exists just at one horizontal level and is not present a level above (parent level) and a level below (brother’s children). This restricts the ability of a model to alter the dynamics of the system to within its operations boundary. As mentioned above, the four forms of adding/removing inports/outports take the modelName as a parameter referring to the destination model to which the change is desired. The functioning of these methods can be seen in the reconfigurable GPT model. Internally, they are implemented as

```java
public void addInport(String modelName, String portName) {
    digraph P = (digraph)getParent();
    IODevs iod = (IODevs)P.withName(modelName);
    if (P != null) {
        if (iod instanceof atomic)
            iod.addInport(portName);
        else
            ((digraph)iod).addInport(iod.getName(), portName);
    }
}
```

The above function adds an input port to the model specified by the modelName. Inside the function, the model is accessed through the common parent (as they are brothers), and if it is an instance of an atomic model, then the port is added here directly; otherwise, the corresponding function in the digraph model is called, which adds the port to this brother digraph.

The mechanics of addOutport() is the same as that of addInport(). For the removal of ports, internally they are implemented in the same manner as the code described above, except that the line iod.addInport(portName) is replaced by the line iod.removeInport(port), where the variables have their usual meaning. The same situation happens in the case of removeOutport(), which is implemented on the same lines, with the change in the line mentioned above (iod.removeOutport(port)).

5. Conclusion

Variable structure capability provides a natural and effective way to model and simulate complex systems that exhibit structure, behavior, and interface changes to adapt to different situations. They also provide the additional flexibility to design and analyze a complex hierarchical system under development, as supported by the dynamic SES capability. In addition to the previously well-known structure operations, we introduced port (interface) alteration possibilities that greatly increase structure change flexibility. To maintain the hierarchical modular property of models, special attention has to be paid to the control of structure and interface changes. We introduced operation boundary constraints on structure change operations for this purpose. In general, as variable structure changes a component-based system during runtime, safety and security are a very important issue. More research on distributed reconfiguration and port-based structure transformation is needed.
conduct safe and efficient dynamic change of component-based systems.

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7. References


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