SCENE TRANSITION NETS SIMULATOR FOR MULTI-ASPECT MODELING OF DISCRETE-CONTINUOUS HYBRID SYSTEMS

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Abstract: Scene Transition Nets (STN) are graphical modeling tools and simulators for discrete-continuous hybrid systems. Designers have previously built complex STN models of large-scale systems on the basis of a single aspect. However, many large-scale systems consist of several sub-systems designed for different purposes and based on different aspects. In addition, these subsystems are complexly intertwined with each one another. For verifying the behavior of such complex systems in simulations, it is necessary to construct multiple STN models of the subsystems, integrate them by taking into account the relationships among the subsystems, and simulate them in parallel. Kawata has proposed ”multi-aspect modelingh using STNs in order to realize abovementioned modeling concepts. However, the interaction of the sub-STN models with other models is difficult according to the basic STN concepts. This shortcoming interferes with the practical implementation of multi-aspect modeling. The authors overcome this shortcoming by enabling the sharing of the state variables of the actors (actors correspond to tokens in Petri nets). Called ”actor-link”, the simple concept enables to construct complex layered and parallel structures of STNs and perform multi-aspect modeling. The experimental results for the modeling and simulation of certain complex industrial systems demonstrate the effectiveness of the proposed method and simulation tool.

1 INTRODUCTION

Simulation is an effective technique for verifying the behavior of complex systems such as manufacturing systems and chemical plant systems. However, many complex industrial systems are actually combinations of both continuous systems and discrete-event systems and are called ghybrid systems.h Hence, it is difficult to model and simulate such systems by using only the modeling methods applicable to continuous systems (e.g., differential equations) or those used discrete-event systems (e.g., Petri nets(Murata, 1989)). Kawata et al. have proposed scene transition nets (STNs)(Kawata et al., 1994a)(Kawata et al., 1994b) as graphical modeling and simulation tools for discrete-continuous hybrid systems. Although STNs are based on the concept of Petri nets, in STNs, designers construct models of continuous systems using differential equations and then embed them into discrete-event system models. By using STNs, designers can easily construct models of hybrid systems and conduct simulations. STN programming requires STN designers to possess considerable object-oriented programming skills and excellent knowledge. In our study, we aim to develop an gSTN graphical user interface (GUI) simulator(Tateyama et al.,)(Tateyama et al., 2010)h that will enable designers to easily and graphically edit and simulate STN models.

System designers have previously built complex STN models of large-scale systems on the basis of a single aspect. However, many large-scale systems consist of several subsystems designed for different purposes and based on different aspects. In addition, these subsystems are complexly intertwined with one another. For verifying the behavior of such complex systems in simulations, it is necessary to construct multiple models of the subsystems, integrate them by taking into account the relationships among the subsystems, and simulate them in parallel. Kawata et al. have proposed ”multi-aspect modelingh using STNs(Kawada et al., 1996) in order to realize the abovementioned modeling concepts. In this modeling method, it is necessary to create models of interactions among submodels. However, an actor can be

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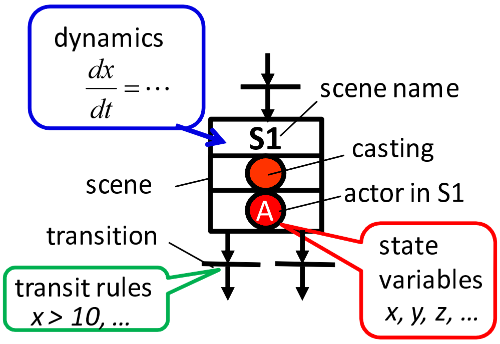


Figure 1: STN components.

present only in one scene at a time and cannot communicate with other actors according to the basic STN concept. These shortcomings make the interaction of the sub-STN models with other models difficult. As a result, this problem interferes with the practical implementation of multi-aspect modeling.

In this study, the authors overcome this shortcoming by enabling the sharing of the state variables of the actors. This concept is called ”actor-link”. In addition, the authors implement the concept in the STN GUI simulator as useful functions so that the designers can easily apply the modeling methods to a wide variety of systems. The proposed method and tool enable system designers to construct STN models of complex systems as a combination of simple submodels based on different aspects and make large-scale modeling and verifications by multiple professionals easy. Our tool also assists professionals in verifying the behavior of complex systems from many different aspects and meet the users’ requirements using graphical STN simulations.

The experimental results for the modeling and simulation of certain complex industrial systems demonstrate the effectiveness of the proposed method and tool.

2 SCENE TRANSITION NETS (STN)

An STN is a graphic modeling method for discrete-continuous hybrid systems: it uses the concept of gactorsh and gscenes.hIt is based on the Petri net, which is a modeling method for discrete event systems. It can express hybrid systems by using the concept of a Petri net and by inputting differential equations in scenes. In an STN, an actor corresponds to a subsystem of a hybrid system. Designers can simulate interactions between the subsystems that act in parallel by describing the models by using object-oriented programming languages (e.g. Smalltalk, JAVA). An STN comprises actors, scenes, transitions, and arcs, as shown in Figure 1. Details of these components are described below.

2.1 Actor Classes and Actors

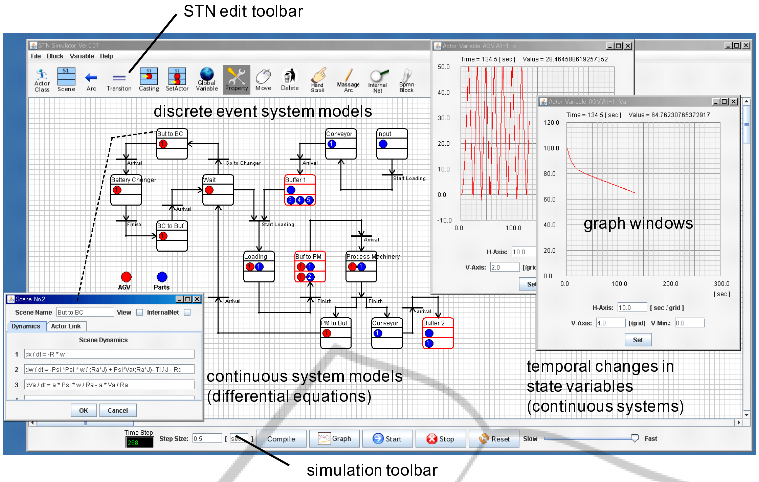
Actors in an STN correspond to the tokens in a Petri net. However, unlike tokens, actors have state variables whose values change dynamically. An actor is one of the objects in an STN and belongs to an ”actor class”. Actors belonging to the same actor class have common data structures (same types of constants and variables) and are called instances of the actor class. Actors are defined as subsystems of an entire system, which is defined as an observed system. It is a set of actors that interact with each other. Through these interactions, the states of actors and state variables change according to their dynamics described by using differential equations in scenes, as explained in the following section.

2.2 Scenes, Castings, and Performers

Scenes in an STN correspond to places in a Petri net. In an STN, scenes are combinations of activities defined in discrete event systems and dynamics for changing variables of actors in the activities. Figure 1 shows STN components, including a scene and an actor, by using the description format of an STN. The circle A1 shown at the bottom of the scene indicates the location of the actor named A1. The circle A at the middle of the scene indicates casting of the scene. A casting of a scene indicates an actor class whose instances (actors belonging to the actor class) can transit to the scene. An actor located in a scene is called a performer of the scene. Designers write dynamics by using differential equations in each scene in order to dynamically change variables of the performers of the scene.

2.3 Transitions and Arcs

Transitions in an STN correspond to those in a Petri net and indicate scene transition boundaries that correspond to events in discrete event systems. Transitions and scenes are connected by arcs. Transitions connected to scenes with input arcs leading into the scenes are called input transitions of the scenes. In contrast, transitions connected to scenes with output arcs exiting from the scenes are called output transitions of the scenes. In a similar manner, transitions have some input scenes and output scenes. Designers write firing conditions of the transitions for which



Scene No.2

Scene Name: But to BC View ☐ InternalNet ☐

Dynamics | Actor Link

Scene Dynamics

1 dx / dt = -R * w
2 dw / dt = -Psi *Psi * w / (Ra*J) + Psi*Va/(Ra*J)- Tl / J - Rc
3 dVa / dt = a * Psi * w / Ra - a * Va / Ra

OK Cancel

Time Step 268 Step Size: 0.5

Figure 2: STN GUI simulator.

the actors in input scenes transit to output scenes, and they write transit rules for the state variables.

2.4 Related Methods

This section describes related modeling and simulation methods for discrete event systems and hybrid systems. Petri nets(Murata, 1989) are popular methods to model and simulate discrete event systems. However, it is difficult to model and to simulate changes in continuous values. Fishwic have proposed a modeling approach for hybrid systems by combining different types of multiple modeling methods(Fishwick, 1991). However, it is difficult for this approach to model and simulate behaviors of multiple sub-systems, which operate concurrently, influencing each other. Arena(W. D. Kelton and Sturrock, 2003) is also a very useful software tool for discrete event systems. This tool can be used as a simulation tool for discrete-continuous hybrid systems, However, it is not easy for designers to build hybrid models because this tool is not designed on the premise of hybrid system simulation.

3 STN GRAPHICAL USER INTERFACE (GUI) SIMULATOR

The present authors have developed an STN GUI (Graphical User Interface) simulator so that designers can easily edit and simulate STN models. Figure 2 shows an overview of the GUI simulator. This simulator consists of an STN edit toolbar, workspace, simulation toolbar, and graph windows. In simulation phases, it displays multiple graphs which show dynamical changes in designated actors' state variables. The designers analyze the behaviors of continuous variable systems by observing these graphs. In addition, it also displays animation that shows the transitions of the actors and they also analyze the behaviors of the actors as discrete event systems. The details of these components are described in (Tateyama et al.,).

4 MULTI-ASPECT MODELING USING STN

Many large-scale industrial systems such as manufacturing systems include multiple subsystems that are constructed for different purposes and different aspects. In addition, they include layered and parallel structures that operate concurrently, influencing each other. For verifying the behavior of such complex systems in simulations, it is necessary to construct multiple models of the sub-systems, integrate them by taking into account the relationships among the subsystems and simulate them in parallel. For example, the model of an automated transportation system in a factory can be divided into the following three different submodels: (1) a dynamics model of an automated guided vehicle (AGV), (2) a decision-making model of the AGV (for planning the navigation of the AGV in a factory-like environment), and (3) a model of transportation sequences of the product and its parts. To verify the behavior of this system using STNs, it is important to construct three sub-STN models through a thinking process called "envisioning(de. Kleer, 1977)" and conduct simulations in parallel. Kawata et al. call this concept gmulti-aspect modelingh using STNs(Kawada et al., 1996). In this

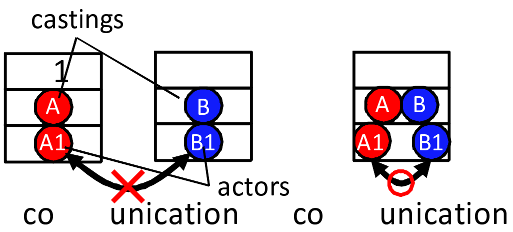


Figure 3: Possibility of communication between actors.

modeling method, as multiple independent STN models are constructed, the same actor is necessarily included in multiple submodels(Kawada et al., 1996). In the abovementioned example, the same AGV is included in the three submodels (1), (2), and (3). The behavior of an actor in a submodel influences behavior of the actors in other submodels. Therefore, it is necessary to create models of interactions among submodels for effective multi-aspect modeling. However, an actor can be present only in one scene at a time and cannot communicate with other actors (as shown in Fig.3) in the basic STN concept. These shortcomings make the interaction of sub-STN models with other models difficult.

In this section, the authors resolve this shortcoming by enabling the sharing of the state variables of actors. This concept is called ”actor-link”. The following subsections describe this concept in detail and show that this simple concept enables us to construct layered and parallel structures of STNs and to perform multi-aspect modeling.

4.1 Actor-link

Figure 4 shows the concept of actor-links for sharing the state variables of actors. In this concept, actors that are instances of the same actor class share their state variables. Figure 4 shows that actors $A_1, A_2, \ldots, A_n$, which are instances of actor A, share their state variables $x, y, z, \ldots$. Each shared state variable is incremented according to multiple differential equations (continuous system models) written in multiple scenes at every simulation time step. Therefore, the variation in x is expressed by the following formula.

$$\Delta x(t) = \sum_{i=1}^{N} \Delta x_i(t) \qquad (1)$$

Here, $\Delta x(t)$ is the variation in the state variable x at time t. $\Delta x_i(t)$ is the variation in x in the submodel i.

This concept realizes parallel simulation of multiple sub-STN models by considering the interactions among them. The authors have implemented this concept in the STN GUI simulator. Figure 12 shows a setting window of the actor-links. This figure indicates that actors ”AGV1,” ”AGV2,” ”AGV3,” and ”AGV4” share their state variables. With this interface, users can easily use the function of actor-links.

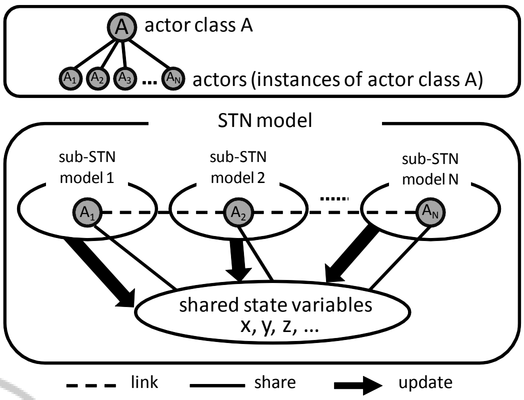


Figure 4: Concept of actor-links.

4.2 STN Modeling of Layered Structures and Parallel Structures using Actor-link Concepts

The actor-link concept enables us to construct layered and parallel structures of STNs and realize multi-aspect modeling. Details of the manner in which layered and parallel structures are constructed are given below.

4.2.1 Layered Structure Modeling

Figure 5 shows a two-layered structure of an STN model. Submodel 1 is an upper model, and submodel 2 is a lower model. This figure shows that submodel 2 is a detailed model of scene S1-2 in sub model 1. In this model, actor A1 in submodel 1 and actor A2 in submodel 2 are made equal by using actor-link concepts. For example, in the modeling of manufacturing systems, an upper model is a rough process sequence and a lower model includes detailed processes in the sequence. This multi-aspect modeling is based on two aspects (a rough process sequence and a detailed process).

4.2.2 Parallel Structure Modeling

Figure 6 shows a parallel structure in which three submodels run in parallel and interact with each other. In this model, actors A1, A2, and A3 in submodels 1, 2, and 3, respectively are considered to be equal. All the state variables of the three actors are updated according to the differential equations written in all the three submodels. For example, a parallel process system

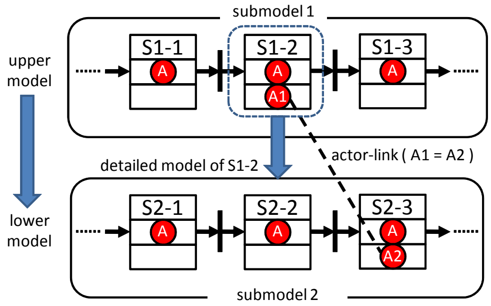


Figure 5: Layered structure modeling using actor-link concepts.

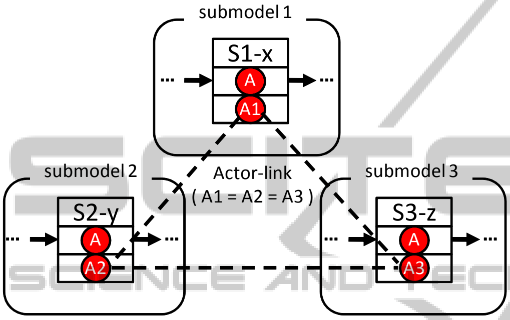


Figure 6: Parallel structure modeling using actor-link concepts.

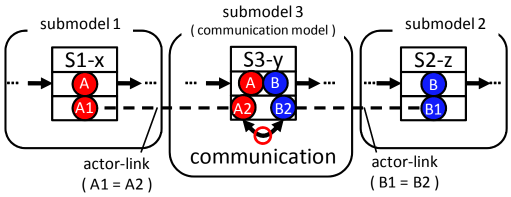


Figure 7: Modeling of communication between two different actors.

which processes in parallel parts by using three types of process machines.

4.2.3 Modeling of Communication among Different Actors

Different actors in different submodels can communicate by using actor-link concepts. In Fig.7, actors A1 and B1 communicate through the communication model (submodel 3) because actors A1 and A2, and B1 and B2 are considered equal. For example, it is possible to simulate autonomous distributed controls of AGVs that wirelessly communicate with each other.

It may possible to construct STN models of highly complex systems by combining the abovementioned structures.

5 AN EXAMPLE: AN AUTOMATED TRANSPORTATION SYSTEM USING A BATTERY-POWERED AGV

5.1 An Automated Transportation System using a Battery-powered AGV

This section describes an example of the modeling and simulation of an automated transportation system with a battery-powered AGV (automated guided vehicle). Figure 8 shows the outline of the example. The purpose of this system is to produce the products that consist of parts A, processed by a process machinery, and parts B. The AGV carries parts A from buffer 1 to the process machinery using a battery-powered AGV. The AGV moves between buffer 1 and the process machinery (distance: 50[m]) and between buffer 1 and the battery changer(distance: 10[m]). The AGV can carry only one set of parts A at a time. After the AGV throws parts A in the process machinery, it returns to buffer 1. When the AGV reaches buffer 1, it checks its battery voltage. If the voltage is higher than V_{th}, it continues to carry other parts; otherwise, it goes to the battery changer in order to replace its battery. The authors define the dynamics of the AGV and the voltage of the batteries as follows:

$$\begin{bmatrix}\dot{x}\\ \dot{\omega}\\ \dot{V}_a\end{bmatrix} = \begin{bmatrix}0 & \pm R & 0\\ 0 & -\psi^2/R_aJ & \psi/R_aJ\\ 0 & a\psi/R_a & -a/R_a\end{bmatrix}\begin{bmatrix}x\\ \omega\\ V_a\end{bmatrix} + \begin{bmatrix}0\\ -Tl/J-R_c\\ 0\end{bmatrix} \qquad (2)$$

Here, $x(-10 \leq x \leq 50)$[m] is the current position of the AGV, ω [rad/sec] is the angular velocity of the AGVfs motor, V_a[V] is the current voltage of the battery, R is the final reduction ratio, $R_a[\Omega]$ is the armature circuit resistance, J[kgm] is the total moment of inertia of the rotational system, ψ[Nm/A] is the torque constant of the armature, Tl[Nm] is the counter torque supplied to the motor shaft, R_c[Ns/m] is the viscous frictional drag, and a[V/As] is the characteristic constant of the battery. The initial value of V_a is 100[V] and V_{th} is 40[V]. The purpose of this simulation is to observe the AGVfs behavior, changes in the battery voltage and efficiency of transportation of the parts.

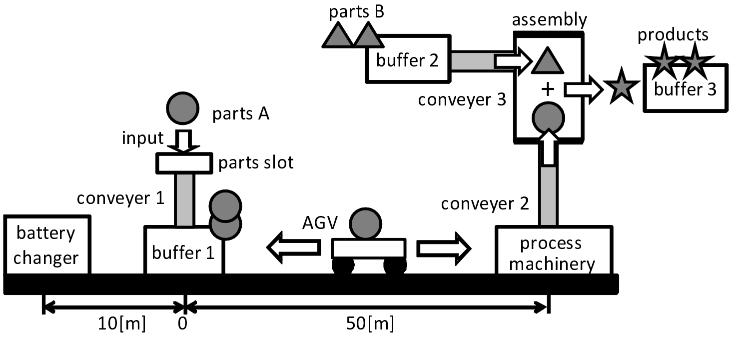


Figure 8: An automated transportation system using a battery-powered AGV.

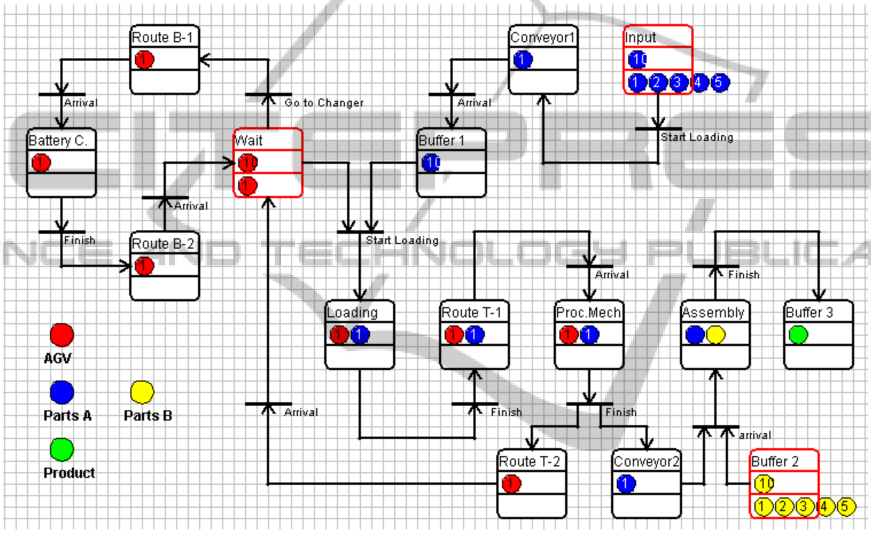


Figure 9: An STN model constructed from a single aspect.

5.2 STN Modeling from a Single Aspect

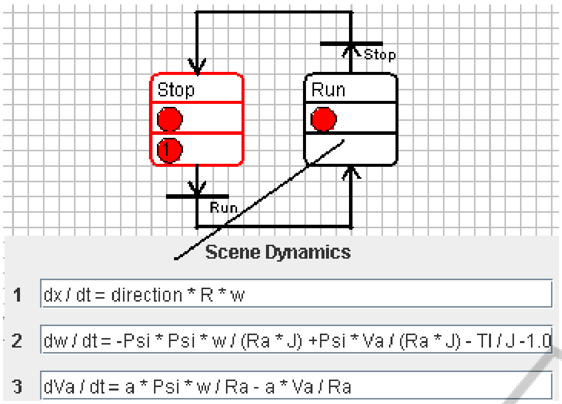
Figure 9 shows an STN model constructed from a single aspect using our old version simulator. This model illustrates the whole transportation system by using a single network. However, this modeling method has some shortcomings. It includes several models constructed from different aspects such as models of the AGV dynamics, temporal changes in the battery voltage, procedure of change of battery, and transportation routes. When we construct a complex system model using a single STN, the procedure of modeling also becomes complex. For example, we have to write the AGV dynamics and battery voltage model for all the scenes where the AGV functions. Specifically, we have to write equations (2) for four scenes (routes T-1, T-2, B-1, and B-2). It also requires time and effort to rewrite them when we change the specifications of the system. This example is relatively simple. However, when system designers want to simulate a large-scale and complex system model, it is difficult for them to express it by using a single network and to observe its behavior.

5.3 Multi-aspect STN Modeling and Simulation

In this section, we have tried to construct the following four simple sub-STN models and integrate them for a concurrent and hierarchic simulation: (1) an AGV dynamics model, (2) an AGV state model, (3) a transportation process model and (4) a battery change process model. The following subsections describe the details of these submodels.

5.3.1 An AGV Dynamics Model

An AGV dynamics model is a very simple model, which consists of only two scenes and an actor. The actor is the AGV, which has ten state variables $(x, \omega, V_a, R, R_a, J, \psi, Tl, R_c, a)$. The AGV actor transits to either ”stop” or ”run”. The two transitions in



1 dx / dt = direction * R * w

2 dw / dt = -Psi * Psi * w / (Ra * J) +Psi * Va / (Ra * J) - Tl / J -1.0

3 dVa / dt = a * Psi * w / Ra - a * Va / Ra

Figure 10: AGV dynamics model.

this model fire depending on the actors' behaviors in other models. We write the AGV's dynamics only for its motors and battery voltage in the scene "run" as shown in Fig.10, in order to temporally change the values of its state variables during its motion. We need not write the AGV's dynamics in other models.

5.3.2 An AGV State Model

An AGV state model, shown in Fig.11 consists of three scenes ("wait", "transport" and "battery change") and an AGV actor. The scene "wait" is a scene in which the AGV is waiting for the parts A to arrive at buffer 1. However, this model need not include the actors of parts A and the buffer model. We only write the AGV's simple decision rules in the scene "wait" based on the current battery voltage of the AGV.

5.3.3 A Transportation Process Model

This is a detailed model of the process of transportation, manufacturing, and assembly of parts A and B. This model corresponds to the right side of the single aspect model shown in Fig.9. The AGV transits depending on its position x which temporally changes according to the dynamics written in the AGV dynamics model. For example, the transition between scene "route T-1" and "process machinery" fires when the value of x becomes 50[m].

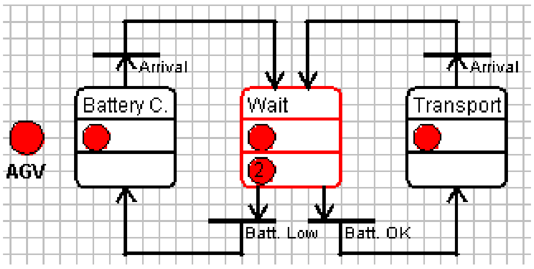
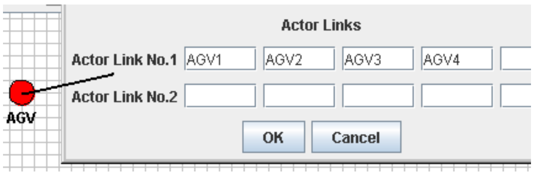


Figure 11: AGV state model.



Actor Link No.1 AGV1 AGV2 AGV3 AGV4

Actor Link No.2

Figure 12: Actor-link setting window.

5.3.4 A Battery Change Process Model

This is a detailed model of the routes between buffer 1 and the battery station. This model corresponds to the left side of the single aspect model. We write certain firing conditions for transitions with respect to the distance between buffer 1 and the battery station. This model also need not consider other dynamics and rules, like the transportation process model.

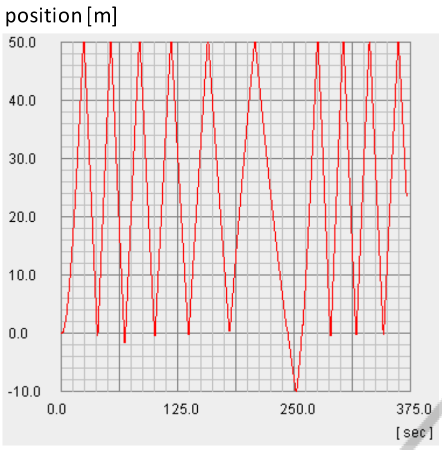
5.3.5 Actor-links and Multi-aspect Simulation

Finally, we define the links of the actors in order to perform parallel simulation of the four STN models. The STN GUI simulator makes it easy to define them. Figure 12 is the user interface of the simulator for setting the links. It shows that the four AGV actors in the four STN models are regarded as same and they share their state variables. The concept of actor-links realizes the parallel simulation of the sub-STN models considering their interactions, without making direct connections between them using arcs and transitions.

5.4 Simulation and Results

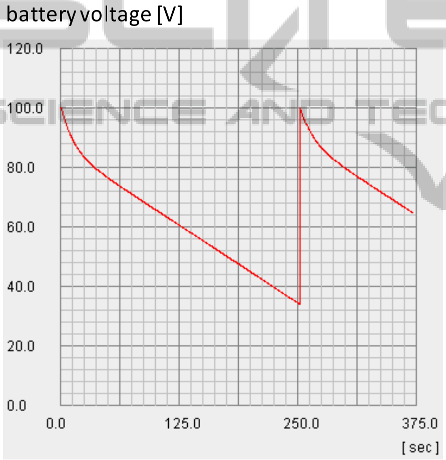
We set ten sets each of parts A in the scene "input" and parts B in the scene "buffer 2" and conduct parallel simulation. First, we observe the simulation result from the viewpoint of discrete-event systems. All AGV actors are appropriately linked to each other and move normally in the submodels. For example, when the AGV stay in the scene "route T-1" (it is moving from buffer 1 to the process machinery) in the transportation process model, it is also present in the scenes "run" in the AGV dynamics model and "transport" in the AGV state and battery change process models. By contrast, when it stays in the scene "change", it is also present in the scenes "stop" in the dynamics model and "battery change" in the AGV state and transportation process models.

Next, we observe the temporal changes in the state variables as continuous systems expressed by the differential equations. Figures 13 and 14 show the tem-



(a) the position of the AGV[m]

Figure 13: Temporal change of the position of the AGV [m].



(b) the battery voltage of the AGV [V]

Figure 14: Temporal change of the battery voltage of the AGV [V].

poral changes in the AGV's position x and the battery voltage V_a. These graphs show that the speed of the AGV decreases according to the decrease in the voltage of the battery. They also indicate that the AGV goes to the battery station after the sixth transportation of parts A and it changes the battery at time $t \approx 250$[s]. After changing the battery, the speed of the AGV increases. In this way, we have confirmed that the proposed parallel simulation works accurately, and this method enables us to observe the behaviors of the system from the viewpoint of discrete-continuous hybrid systems.

6 DISCUSSION

In multi-aspect modeling, we first construct a few simple sub-STN models and integrate them. This modeling procedure is very effective for modeling complex systems. We have confirmed that the division of a complex STN model using the concept of multi-aspect modeling makes the working of STN modeling easier through experiments. In addition, the number of dynamics models we must write in the STN model has also decreased. As a result, the modeling method also simplifies the modification of STN models. Multi-aspect modeling also contributes to easy observation of the behaviors of complex systems. Each simple sub-STN model provides simple and useful information to observers. The observers easily obtain the necessary information by focusing on appropriate submodels. For example, if an observer wants to determine the AGV's operating rate, he obtains the required information by observing only the behavior of the AGV dynamics model. On the other hand, the AGV state model provides information about the frequency of battery change. If an observer wants to prove the efficiency of the transportation system, he should analyze the behavior of the transportation process model. The concept of multi-aspect modeling and the STN GUI simulator the authors have developed will be more useful when we verify more complex and larger-scale systems.

7 CONCLUSIONS

In this paper, the authors have proposed an STN modeling concept called "actor-link" that enables the sharing the state variables of the actors. This simple concept enables to construct complex layered and parallel structures of STNs and perform multi-aspect modeling. The experiment with the case study of an automated transportation system using a battery-powered AGV has shown that the proposed method and tool assist users to easily construct multi-aspect models of STNs and verify the behaviors of complex systems from many different aspects.

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REFERENCES

de. Kleer, J. (1977). Multiple representations of knowledge in a machanics problemsolver. *Proceedings of 5th IJCAI*, pages 299–304.

Fishwick, P. A. (1991). Hetrogeneous decomposition and inter-level coupling for combined modeling. *Proceedings of the 1991 Winter Simulation Conference*, pages 1120–1128.

Kawada, S., Kawata, S., Kawai, S., Matsunaga, S., and Watanabe, A. (1996). Some extensions of a scene transition net by introducing actor transformation and multi-aspect stn. *Transactions of the Japan Society of Mechanical Engineers*, C62(599):2905–2912(in Japanese).

Kawata, S., Kawada, S., and Watanabe, A. (1994a). The discrete/continuous hybrid simulation using the scene transition net. *Proceedings of the First Asian Control Conference(ASCC94)*, 1:567–570.

Kawata, S., Kawada, S., and Watanabe, A. (1994b). A manufacturing system modeling using a scene transition net. *New Direction in Simulation for Manufacturing and Communication*, pages 86–92.

Murata, T. (1989). Petri nets: Properties, analysis and application. *Proceedings of the IEEE*, 77(4):541–580.

Tateyama, T., Chin, T., Kawata, S., and Shimomura, Y. Development and improvement of scene transition nets(stn) gui simulator for discrete-continuous hybrid systems. *International Journal of CAD/CAM*, 8(1).

Tateyama, T., Shimomura, Y., Mikoshiba, S., and Kawata, S. (2010). Service flow simulator using scene transition nets (stn) including satisfaction-attribute value functions. *Proceedings of the 15th Design for Manufacturing and the Lifecycle Conference - DFMLC2010 -*.

W. D. Kelton, R. P. S. and Sturrock, D. T. (2003). *Simulation with Arena*. McGraw-Hill Science/Engineering.