Modeling and Simulation of Combined Discrete Event-Continuous Systems Using DEVS Formalism and Object-Oriented Paradigm

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Abstract

This paper presents an approach to a simulation-based design methodology and is motivated by the need to provide models representation schemes and simulation software tools for combined discrete event-continuous systems. Our approach is based on an extension of the *DEVS (Discrete Event System Specification)* introduced by Zeigler, to include a combined discrete event-continuous systems. We show how the interactions between the discrete-event part and the continuous part and their consequence on the system behavior can be expressed. By employing the Object-Oriented paradigm, the extended model is implemented as an abstract class, in which the methods describe the model's behavior and data represent its variables.

Keywords

Modeling and simulation, combined simulation, discrete event simulation, continuous system simulation

1 Introduction

In addition to discrete event models and continuous models, combined discrete-event-continuous modeling and simulation is finding ever more application in the analysis and design of complex manufacturing systems. A lot of complex systems, such as steel-making, metallurgy, chemical industry ..., involve both processes which are easily described by differential equations and processes which are better described by models whose changes in state occur at discrete instants rather than continuously in time.

Classical approaches to simulation typically use:

- differential equations based models and frequency models for continuous systems (continuous states, continuous time),
- state-transition, automaton and Markovian models for discrete-time and discrete-events dynamic systems.

Unfortunately, these different models are incompatible because they deal with variables which don't belong to the same mathematical space, and the time variable is not used in an identical manner.

In fact, the same physical system may be modeled in an entirely continuous or an entirely discrete fashion depending on the modeler point of view and the duration for which the system will be observed. However, many works, (Wang, 89), (Cellier, 79), (Fahrland, 70), show that there exist classes of problems which can not be modeled satisfactorily by either a purely discrete or a purely continuous formulation. And the choice between the two points of view is not always easy, since any system optimization study must be global and the continuous part and the discrete part of a process are often closely linked (Caristi, 91).

Although many formalisms have been developed to study, on the one hand discrete event dynamic systems and on the other hand, continuous system, there is no formulation that meets them all. Indeed, each of these various formalisms can be viewed as offering a potential application benefit based on the particular form of abstraction implicit in its "*world of view*". However, since reality does not usually constrain itself to one such "*world view*", the need to formulate representation schemes which allow to bridge the gap between the two description form becomes essential.

Two main approaches to the modeling of combined systems have recently emerged :

- defining a single formalism which encompasses the discrete event and continuous behavior and which uses a homogeneous model structure (Praehofer, 90, 92) (Zeigler, 89), (Buisson, 93)
- using a specific formalisms for each class of system components and defining an appropriate interface between them (Stiver, 93) (Antsaklis, 93) (Alla, 94).

The DEVS formalism, initially developed for formalizing simulation models of discrete event systems to be simulated, supports an open approach for the exploration of new simulation-based representations for many classes of systems. It provides a mechanism for the specification of simulation models in a modular and hierarchical manner and represents an alternative to the traditional worldviews of discrete-event-simulation languages.

To shed some light on the *DEVS* formalism (Zeigler, 76), a conceptual framework underlying the formalism is first described. We illustrate how basic models are specified and how these models are connected together in hierarchical fashion to form complex models. Then we show how continuous states are introduced to extend the *DEVS* expressibility to combined discrete-continuous systems. Thus, the extended scheme represents both types of system and the interactions between them in the same modeling framework.

After developing a mapping of the extended scheme onto a generic description so that classes of objects form a *taxonomical hierarchy* in which they are arranged according to their degree of generality, we describe an implementation of the simulation strategy using the *abstract simulators* principles (Concepcion, 88) applied to discrete event-continuous simulation.

2 THE DEVS FORMALISM

DEVS (Discrete EVent System Specification) (Zeigler, 76, 84, 87) is a set-theoretic based formalism that provides a system theoretically grounded means of expressing hierarchical and modular discrete event simulation. It is the shorthand formulation needed to specify systems whose input, state and output trajectories are piecewise constant.

2.1 Basic model

In this formalism a basic model (called atomic model) is defined by the structure:

$$M = \langle X, S, Y, \delta_{int}, \delta_{ext}, \lambda, ta \rangle,$$

where

X = set of external input event

S = set of sequential states

Y = set of output

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

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

where $Q = \{ (s, e) \mid s \in S, 0 \leq e \leq ta(s) \}$ is the total state set

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

$ta : S \rightarrow R_0^+$ the time advance function.

There are two kinds of events; external events (input events) and internal events which are time scheduled events. For each state s the time advance function ta , which is a mapping from state space S to positive real numbers, defines the time interval to the next internal event. When this time given by $ta(s)$ has elapsed, an internal event occurs. The system produces an output $\lambda(s)$ and the internal transition function specifies the next state $s' = \delta_{int}(s)$ to which the system will transit. If an external event (an input) occurs at elapsed time e which is less than $ta(s)$ time units, then a new state s' is computed by means of the external transition function $\delta_{ext}(s, e, x)$.

2.2 Multicomponent Model

Several atomic models can be coupled to form a multicomponent model defined by the structure:

$$DN = \langle D, \{M_\alpha\}, \{I_\alpha\}; \{Z_{\alpha\beta}\}, select \rangle$$

where

D = set of component names,

For each α in D

M_α = the component model

$I_\alpha \subseteq D$ set of influences of α

and for each β in I_α

$Z_{\alpha\beta}$ is the α -to- β output translation function

$select : 2^D \rightarrow D$ is the tiebreaking selector function. It selects a component from the imminent components having the minimum next event time. This component is then allowed to execute its next event transition.

A coupled model DN can be expressed as an equivalent atomic model and can itself be employed in a larger coupled model. This shows that the *DEVS* formalism is closed under

coupling and hence the construction of modular hierarchical models is possible and formally well defined.

3 EXTENDED DEVS EXPRESSIBILITY TO CONTINUOUS STATES SYSTEMS

In this section, we introduce an extension of *DEVS* formalism to combined systems whose input and output are eventlike. The systems contain both discrete states and continuous states and the dynamic behaviour of the continuous components can be described by differential equations.

3.1 Example : The Bottle-filling process

Consider a cylindrical tank with two threshold sensors at two levels called *L* (Low) and *H* (High) and a bottle conveyor as it shown in the figure 1 below ;

Figure 1. Bottle -filling example.

The filling process receives three types of event:

- e_{11} / e_{12} : Open_influx_valve/ Close_influx_valve ;
- e_{21} / e_{22} : Stop_on_error/ Re-Start; (from the higher level Control System.)
- e_3 : Bottle_Arrived ; (from the conveyor when an empty bottle arrive under the tank's outlet.)

And it transmits

- an event $o_1 = \text{move_conveyor}$ when a bottle is full (to the conveyor)
- and two events $o_2 = \text{Underfilled}$ and $o_3 = \text{Overfilled}$ (to the higher level control system.)

Figure 2. A coupled discrete event-continuous system.

When the filling process receives an event e_{11} the influx valve (*iv*) is fully open and the tank is filled with constant flow F_{in} . *iv* is closed when e_{12} is received. When it receives an event e_{22} ; this means that there is an error (bottle overflow, a failure of sensors, a leak in the tank,...) then the filling process is stopped. Event e_3 indicates a bottle-arrival, then the bottle-filling-valve (*bfv*) is fully open; the flow out is given by $F_{out}(t) = R \cdot l(t)$ (R is the fill rate, some positive real number and $l(t)$ is the level of the liquid in the tank). When the volume of the bottle is reached the *bfv* is closed and an event *move_conveyer* is sent to the conveyer.

3.2 Extended DEVS Model

The example shows that, in addition to the sequential states, the total state contains some continuous variables (Figure 3) (the level of the liquid in the tank and the volume out in the filling process).

Figure 3 - Combined Discrete event-continuous system.

Moreover, two types of internal event are distinguished :

- The state-events, which are not time scheduled events but are caused by the continuous changes of the continuous states.
- The time events, which are time scheduled as in the DEVS definition given above.

A Combined Dynamic System is a tuple $\langle X, Q, Y, E, \delta, \mathcal{F}, \lambda, \sigma, ta \rangle$

where :

- X is a finite set of input events and Y is a finite set of output events
- E is a finite set of internal state-events;
- Q is the state set range defined by : $Q = S \times R^n \times R^+$, S is discrete state set and R^n is a continuous state-space;

$$Q = \{q = (s, v, e) \mid s \in S, v \in R^n, e \in R^+ \}$$

- The conditions of occurrence of internal state-events are given by the function σ which associates at each $e_s \in E$ a predicate $P(q)$ where q is the total state variable and $P(q)$ is a logical expression

Whenever the condition $P(q)$ becomes true, an internal state-event occurs.

- An internal time event ε occurs if the condition $e \geq ta(s)$ becomes true
- δ is the discrete state transition defined by the two functions δ_{int} and δ_{ext} as follows :

$$\begin{aligned} \delta_{ext} &: Q \times X \rightarrow Q; \\ \delta_{int} &: S \times E \cup \{\varepsilon\} \rightarrow Q; \end{aligned}$$

- $\mathcal{F}$ is the differential equation defining the rate of change of the continuous state variables;
- $\lambda : S \rightarrow Y$ is the output function

3.3 The Filling-Process Model

For the filling process described above, the sets X , Y are defined by :

$$X = \{e_{11}, e_{12}, e_{21}, e_{22}, e_3\};$$

$$Y = \{o_1, o_2, o_3\};$$

Let $s = \begin{bmatrix} L \\ H \\ bfv \\ iv \\ phase \end{bmatrix}$ denote the sequential state and $v = \begin{bmatrix} l \\ v_out \end{bmatrix}$ denote the continuous state

where : $L, H, phase \in \{ON, OFF\}$; $phase = OFF$ if the system is stopped ; ON otherwise;
 $bfv, iv \in \{0, 1\}$, the two variables take the value 0 when the corresponding valve is closed and 1 if it is fully open

the total state set is

$$Q = \{q = (s^T, v^T, e)\} = S \times R^2 \times R_w^+; \quad S = \{ON, OFF\} \times \{ON, OFF\} \times \{0, 1\} \times \{0, 1\} \times \{ON, OFF\};$$

The set E of the state-events contains five events : $E = \{e_{s_1}, e_{s_2}, e_{s_3}, e_{s_4}, e_{s_5}\}$

and σ is given by :

$$\begin{aligned} e_{s_1} &\mapsto l \geq HIGH \\ e_{s_2} &\mapsto l < HIGH \\ e_{s_3} &\mapsto l > LOW \\ e_{s_4} &\mapsto l \leq LOW \\ e_{s_5} &\mapsto v_out \geq B_volume \end{aligned}$$

$$ta(s) = \infty, \forall s \in S \text{ No time event}$$

The external transition function δ_{ext} is :

$$\begin{aligned} ((L, H, bfv, 0, ON), v, e, e_{11}) &\mapsto ((L, H, bfv, 1, ON), v, 0) \\ ((L, H, bfv, 1, ON), v, e, e_{12}) &\mapsto ((L, H, bfv, 0, ON), v, 0) \\ ((L, H, bfv, iv, ON), v, e, e_{21}) &\mapsto ((L, H, 0, 0, OFF), v, 0) \\ ((L, H, bfv, iv, OFF), v, e, e_{22}) &\mapsto ((L, H, 0, 0, ON), v, 0) \\ ((L, H, 0, iv, ON), v, e, e_3) &\mapsto ((L, H, 1, iv, ON), v, 0) \end{aligned}$$

the internal transition function is defined by :

$$\begin{aligned} ((L, OFF, bfv, iv, ON), e_{s_1}) &\mapsto ((L, ON, bfv, iv, ON), v, 0) \\ ((L, ON, bfv, iv, ON), e_{s_2}) &\mapsto ((L, OFF, bfv, iv, ON), v, 0) \\ ((OFF, H, bfv, iv, ON), e_{s_3}) &\mapsto ((ON, H, bfv, iv, ON), v, 0) \\ ((ON, H, bfv, iv, OFF), e_{s_4}) &\mapsto ((OFF, H, bfv, iv, ON), v, 0) \\ ((L, H, 1, iv, ON), e_{s_5}) &\mapsto ((L, H, 0, iv, ON), (l, 0, 0)) \end{aligned}$$

The differential equations are given by :

$$\mathcal{F} = \begin{cases} \frac{dl}{dt} = \frac{1}{TS} \cdot [F_{in} \cdot i_v - R \cdot l(t) \cdot b_f_v] : \text{where } TS \text{ is the cross - sectional area} \\ \frac{dv_out}{dt} = R \cdot l(t) \cdot b_f_v : \text{of the tank} \end{cases}$$

the output function :

$\lambda (OFF, OFF, bfv, iv, ON) = (o_2, H_L_C);$ *Tank_underfilled* (to Higher level control)
 $\lambda (ON, ON, bfv, iv, ON) = (o_3, H_L_C);$ *Tank_overfilled* (to Higher level control)
 $\lambda (L, H, 0, iv, ON) = (o_1, Conveyor);$ *move_conveyer* (to CONVEYER)
 $\lambda (s) = \phi$; for the other cases (ϕ = no event)

4 SIMULATION WORLD VIEW

The *Object-Oriented Concept* is not only a useful programming style and an efficient way to organize software systems, but it is also regarded as a powerful paradigm that can serve as a useful way to express computational models for large, complexly interacting systems. Encapsulation, inheritance, abstraction and evolution of individual objects support concurrency, incremental modifiability and reusability of models. Thus, it provides a common basis that can be used to implement modular simulation programs.

The simulation strategy for DEVS models is based on the abstract simulator principles developed by Zeigler et al (Zeigler, 84) (Concepcion, 85, 88) (Kim, 88, 89). The abstract simulator includes the algorithmic interpretation of the dynamic behaviour implicitly specified by the model.

The abstract simulator has the same structure as the hierarchical structure of the DEVS models. Thus the model can be directly transformed into an executable simulation program using the object oriented concept. A full explication and the class specialization hierarchy are given in (Zeigler, 90).

Figure 4. The abstract classes hierarchy.

The root class *ENTITY* provides general definitions for data and methods of general utility. The class *MODELS* which in turn is specialized into more specific classes *ATOMIC* and *COUPLED* provide the basic constructs needed to specify a model's variables (Instance variables) and its behavior (methods). The class *PROCESSORS* and its subclasses implement methods to carry out the simulation and compute the states and outputs trajectories.

Using the same methodology, we have developed an implementation using the C++ language according to the class hierarchy shown in figure 4 (Teggar, 96). Since these classes are defined as abstract classes, they are implemented in generic form as template classes. The methods expressing a specific behavior of user model are defined as virtual functions with template data types.

4.1 The class combined model

The inheritance mechanism supports incremental specification and composition of behaviour so that user methods are defined as subclasses, which inherit the code representing data and behaviour common to the other models. The class for *Combined models* is a specialization of the class *ATOMIC* in which we can add new instance variables for the continuous states and new methods :

- *sigma* : which returns a state event identifier when the associated condition becomes true and 0 otherwise
- *derivative* : computes the derivative values of the continuous states .

Using pseudo-code, we describe the class of the filling process model as a subclass of *combined_models*.

```

class Filling_Process : Combined_model
  ClassVars
    LOW , HIGH      : real
    B_volume        : real
  InstVars
    L , H , phase    : [ON , OFF]
    bfv , iv         : 0..1
    l , Dl , v_out , Dv_out : real
    e                : real

  Methods

Int_Trans ( event es)
  case es of
    es1 : if (H=OFF) and
           (phase = ON) then
            H := ON;
            e := 0
          else error
    es2 : if (H=ON) and
           (phase = ON) then
            H := OFF;
            e := 0
          else error
    es3 : if (L=OFF) and
           (phase = ON) then
            L := ON;
            e := 0
          else error
    es4 : if (L=OFF) and
           (phase = ON) then
            L := ON;
            e := 0
          else error
    es1 : if (bfv=1) and
           (phase = ON) then
            bfv := 0;
            e := 0
            v_out := 0
          else error
  end

Ext_trans ( event x)
  case x of
    e11 : if (phase = ON) and
            (iv = 0) then
            iv := 1
            e := 0
    e12 : if (phase = ON) and
            (iv = 1) then
            iv := 0
            e := 0
    e21 : if (phase = ON) then
            iv := 0
            bfv := 0
            phase := OFF
            e := 0
    e11 : if (phase = OFF) then
            phase := ON
            e := 0
    e3 : if (phase = ON) and
           (bfv = 0) then
            bfv := 1
            e := 0
  end

Derivative ( )
  Dl := ((Fin*iv )-(R* l * bfv ))/TS
  Dv_out := bfv * R * l
end

```



```

Sigma ( )
  if (l >= HIGH ) then
    return (es1)
  if (l < HIGH ) then
    return (es2)
  if (l > LOW ) then
    return (es3)
  if (l <= LOW ) then
    return (es4)
  if ( v_out >= B_volume) then
    return (es5)
return (0)

end

Output_func ( )
  if (L = OFF) and (H = OFF)
    and (phase = ON) then
    send ( O2 , H_L_C)
  if (L = ON) and (H = ON)
    and (phase = ON) then
    send (O3 ; H_L_C)
  if ( bfv = 0)
    and (phase = ON) then
    send (O1 , CONVEYER)
end

```

The specialization gives the specific definitions by overriding the virtual methods *Int_Trans*, *Ext_Trans* and *Output_Func*, of the class *atomic* and *Derivative* and *Sigma* of the class *Combined_model*

4.2 Abstract simulator principles

The abstract simulators are defined as the interpretation of dynamic behaviours specified by models. Essentially, they are objects whose methods are an algorithmic description of how to carry out the instructions implicit in models to generate their behavior. Simulators are assigned to handle basic models in a one-to-one manner. The whole simulation program is then represented by a network of such (*model*, *simulator*) pairs.

There are two types of abstract simulator: Simulators and Coordinators; assigned to handle atomic-DEVS models, and coupled models in a one-to-one manner respectively. Simulation proceeds by messages that carry data and synchronization information passed among the abstract simulators.

4.2.1 The Abstract Simulator of Discrete Event System

The operation of an abstract simulator involves four types of messages : $*$, x , y and done-messages. It consists of two methods that handle four main variables :

Figure 5. Discrete Event Simulator

- s : is the sequential state variable,
- e : the elapsed time since the last state transition,

-tL : the time of the last event and

-tN : is the time of the next internal state transition.

The algorithm of the abstract simulator is divided onto two parts : One method is activated on a reception of an (x,t) message, and the other one corresponds to an (*,t) message.

```

When receive an input (x,t)
  if tL <= t <= tN then
    e := t-tL
    s :=  $\delta_{ext}$  (s e x)
    tL := t
    tN := tL + ta (s)
    send (d,tN) to co-ordinator
  else error
end

When receive an input (*,t)
  if t = tN then
    y :=  $\lambda$  (s)
    send (y,t) to co-ordinator
    s :=  $\delta_{int}$  (s)
    tL := t
    tN := tL + ta (s)
    send (d,tN) to co-ordinator
  else error
end

```

In (Zeigler, 1984), the abstract simulator was shown to satisfy the criterion of correct simulation of a DEVS model. The *-message indicates that an internal event shall be executed and is transmitted to the imminent component. If there are more than one imminent component, the tie breaking function Select is used to select one of them. When a *-message is received by a simulator, it sends its output as a y-message and carries out the internal transition in the associated DEVS model. The output (y-message) is sent back to the parent coordinator which consults the external output coupling and the internal couplings to obtain the addresses to which the message should be sent as an x-message. When a Coordinator receives an x-message, it consults the external input coupling to generate the appropriate x-message for the subordinate influenced by the external event. When a Simulator receives an x-message, it executes the external transition of the associated DEVS. A done-message indicates the completion of the state transition and contains the time of the next internal transition.

4.2.2 The Abstract Simulator for Combined Model

The simulators described in the preceding paragraph, are defined to handle discrete event systems. So to simulate a combined discrete event-continuous state system, we must define a special simulator which has methods to compute the continuous state values during the observation time.

The extension retains the basic structure of the abstract simulators. Since the state-events are not time scheduled events, a simulator for a combined model can not determine the time of the next internal transition. To solve this problem, we use a sampling method which predicts the occurrence of an internal event with an estimated time tNe . If a state event occurs at time $t < tNe$, a time warp mechanism is used to correctly simulate a multicomponent model. The mechanism to rollback an object is the heart of the time warp. The time warp exerts no effort

to ensure that messages are delivered to an object in increasing timestamp order. Instead, the simulation proceeds on the assumption that there will be no stragglers (messages with time stamps less than the local time). But if a straggler should arrive at time t , the object must roll back to the time t and cancel all the side effects that occurred as a result of processing messages with timestamps greater than t (Jefferson, 85,87, 89).

```

When receive an input (x,t)
  if tL <= t <= tN then
    compute the continuous state and update e from tL
    until t or tE the time of state-event
    if e = t -tL then
      s :=  $\delta_{ext}$  (s e x)
      tL := t
      tN := tL + ta (s)
      send (d,tN) to co-ordinator
    else
      send (anti-message, tN)to co-ordinator
      send (d,tE)to co-ordinator
    else Rollback (Time Warp mechanism)
  end

When receive an input (* ,t)
  if t = tL then
    y :=  $\lambda$  (s)
    send (y,t) to co-ordinator
    s :=  $\delta_{int}$  (s)
    tL := t
    tN := tL + ta (s)
    send (d,tN) to co-ordinator
  else if t = tN
    compute the continuous state and update e from tL
    until t or tE the time of state-event
    if there is a state-event (tE)
      y :=  $\lambda$  (s)
      send (y,t) to co-ordinator
      s :=  $\delta_{int}$  (s)
      tL := tE
      tN := tL + ta (s)
    else Rollback
  end

```

Figure 6. A model -Simulator pair.

Note that:

- The messages exchanged among the abstract simulators are timestamped.
- When a simulator of combined model receives an (x, t) or $(*, tNe)$ message, before executing the external or internal transition it updates its local clock by employing the solver based on a numerical integration method to compute the continuous states value step by step and the event detector method to check the value of the sigma function. If a state event occurs at time $tN < tNe$, the simulator transmits an $(*, tN)$ to the parent coordinator (figure 7).
- When a Coordinator receives a message with a timestamp tN less than its local clock, it releases the rollback mechanism by means of the *antimessages*, and start again with the new value tN of the internal state-event.

Figure 7. The Coordinator of Coupled Model.

4 CONCLUSION

A variety of paradigms are being actively explored to deal with systems where a large number of discrete events and continuous dynamic behaviours are simultaneously important. An extension of the DEVS formalism shows how it is possible to express models of combined discrete event-continuous systems, so that the whole formalism guarantees the strength of the theoretical based methods for simulation. By the bottle-filling process example, we have illustrated that the proposed modeling framework makes a clear description of complex combined systems possible. The object oriented paradigm provides convenient tools to carry out this abstract formalism concept and improves the isomorphic relation between the model and its representation in the simulation program.

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