Numerical Backward Simulation Model with Case Branching Capability

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Abstract: The authors are studying backward simulators which trace from results to causes for comprehensive verification of system safety. It is not easy to make a backward simulation model because the forward model may not be expressed in a reversible formula, or it is not reversible in cases of multiple inputs or inclusion of internal state variables. In this paper, we propose a backward simulator which can incorporate numerical simulation models and has a case branching capability to deal with multiple inputs. As a practical simulation target, we implemented a simulator for testing stability of dynamic pricing for power usage control as a smart grid application. We show some illustrating results of the backward simulation.

1 INTRODUCTION

Securing proper operation of software systems is a great concern for our IT centric society. Software engineers are doing their elaborate work to achieve safety of their system by tests, which cannot be fully done for almost all the applications. Essential difficulty in the work comes from the fact that engineers start their design by a forward thinking for implementing functions to accomplish the objective of the system, and they will take in unexpected situations in their system, unintentionally.

A secure system might be designed by a backward thinking to use only secure components with a safe structure by considering all the unfavorable conditions which may be encountered. However, it may be a practical way that we design a system in a forward thinking and check the safety of it by backward testing. We describe a method for such check with rounding up failure conditions by a backward simulator in this paper.

2 BACKWARD SIMULATION AND TARGET SIMULATION

We describe our backward simulator for a case of control situation. As a smart power grid application, dynamic pricing is planned and evaluated for suppressing electricity consumption (Schweppe et al, 1981, Freeman, 2005, Mohsenian-Rad 2010, Fan, 2011, Koulsopoulos and Tassiulas, 2011). The idea is simple enough that consumers will reduce their usage if the power company raise the price of electricity. However, some may worry about the dynamic behaviour of user and price determination. If many consumers use some kind of automatic cost cutter or economizing unit, power usage will be decreased instantly after the price raised or announced to be lowered and will be increased instantly after the price lowered or announced to be raised, and then, oscillation should be observed, which might be uncontrollable at the worst.

We should investigate full consequences of the system behaviors. Usually, it is not possible to test all the conditions that the system would encounter by using a forward simulator because the cases to be tested would be huge in number.

There are backward approaches to search a reasonable solution under certain restrictions such as a dynamic allocation of resources (Huang et al., 2009) and fault analysis (FTA). However, there is no practical backward simulator for detecting unfavorable conditions without leak.

So, we created a backward simulator to round up all the unfavorable conditions by defining range signals (Hiranaka et al., 2012). A range signal expresses the range of values on control links and it is used to calculate the possible input signal in the backward simulation. If we start with unfavorable output range, we can calculate input range signal which covers the condition on which the unfavorable output occurs. Our aim is to detect such range, to narrow down the condition and, then, to verify whether the system would output unfavorable value.

Our backward simulator was implemented by using Scala Language to use its Actor functions. Range signals are expressed in XML style data format (we call it as UCF Universal Communication Format) which is comprised of the destination part and the content part. The simulator has forward simulation functions and distinguishes forward and backward signal by the destination part of range signals. If the destination is an input (typically identified by <i>) of the block, then the content part will be processed by the forward algorithm. If the destination is an output (typically identified by <o>), then the content part will be processed by the backward algorithm.

It is not an easy task to make a backward simulator, generally. The difficulties are encountered to make a backward algorithm for each simulation component when the forward algorithm is not expressed in a simple formula, when it has multiple inputs and when it has inner state variables which cannot be determined from the output. Our solutions to such situations are by using numerical inclusive algorithm, by case branching (Hiranaka et al., 2013) with dividing the possible conditions into finite cases of input range pairs, and by externalizing the inner state variables out of simulation blocks, respectively. This paper shows the former two methods.

Fig.1 is the whole view of a simple forward simulation structure for testing dynamic pricing. Four blocks represent a pricing block, a room temperature sensor block, a user response block and a heater block. The block named as sim is the simulation controller which can intervene or advance the simulation sequences by its coordination function. All the simulation blocks send their range signal messages to sim and sim relays them to the predetermined block(s) down the flow.

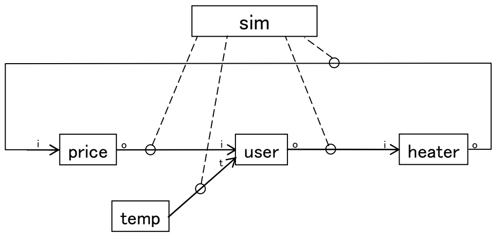


Figure 1: Forward simulator example.

Fig.2 shows the backward simulation structure corresponding to Fig.1, just reversed the direction of signal flows indicated by dashed lines. The component manin is a signal injection component for initiating backward simulation. Along the backward flow, the value range expressed by the range signal will gradually become wider because the backward algorithm needs to be designed to a safer side, not to leak unfavourable conditions.

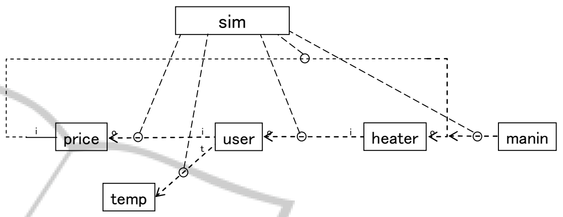


Figure 2: Backward simulator corresponding to Fig.1.

3 NUMERICAL FORWARD AND BACKWARD MODEL

This section describes how the numerical model blocks are formed. As for a case of electric oil heater (De'Longhi TDD0915W), we measured switch position to power usage relation, which is summarized in Table 1. Then, the forward algorithm of heater is to output power usage corresponding to the input switch position (0 to 3). The backward algorithm is to output the range of switch position corresponding to the power usage range, e.g. range 1 to 2 switch position in response to 0.5 kW to 1 kW backward signal. If the incoming power usage range does not cover any of the values, this component sends an out of range message to the simulation controller.

An example of backward range signal from heater component to user component is

<user><s>delong<s>i</s></s><t>100.0</t><o>1, 2</o><user>

where <s> tag means message source with nested source i, which means the input port of delong heater, and <o> tag means the entry point of the range data "1,2." The tag <t> means timestamp indicating output time relative to the forward simulation start time. It is advanced in forward simulation and rewound in backward simulation for the specified value predetermined by each simulation component.

Table 1: Characteristics of De'Longhi heater.

Switch position	power usage(kw)
0	0.0
1	0.58
2	0.83
3	1.39

Forward pricing model was set as in Table 2, where p is the price (Yen/kWh), u is the total usage (kW) and C is the supply capacity (kW). It may be determined by a mathematical formula (such as in Fan, 2011). Backward model for the price component (Table 3) is just an exchange of input and output of Table 2, from which the range of power usage divided by the capacity is determined by price value or by range of price values.

Forward user model was set as in Table 4, representing a user who determines the switch position of the heater responding to the electricity price and the selected room temperature. Backward model for the user component (Table 5) is derived from Table 4, from which range of room temperature is determined by the switch position depending on the electricity price. In this case, we need to select which price value to be simulated further. Such selection and proceeding is dealt by case branching described latter.

Table 2: Forward price model.

u/C		P (Yen/kWh)
low	high	
0	0.5	11
0.5	0.8	22
0.8	∞	44

Table 3: Backward price model.

p (Yen/kWh)	u/C	
	min	max
11	0	0.5
22	0.5	0.8
44	0.8	∞

Table 4: A forward user response model.

room temperature	p (Yen/kwh)		
	11	22	44
0	3	3	3
5	3	3	3
10	3	3	2
15	3	2	1
20	2	1	0
25	0	0	0

Table 5: Backward user response model corresponding to Table 4.

Switch position	room temperature range		
	price=11	price=22	price=44
0	22.5 – ∞	22.5 – ∞	17.5 – ∞
1	22.5 – 22.5	17.5 – 22.5	12.5 – 17.5
2	17.5 – 22.5	12.5 – 17.5	7.5 – 12.5
3	- ∞– 17.5	- ∞ – 12.5	- ∞ – 7.5

The forward temp component is just send the current room temperature to the user block. We set it as constant for the simulation period. Backward temp model has a special function. It can accept any valid room temperature range, but it assumes that the temperature is constant for the simulation period and do not allow the incoming temperature range to be outside of the former range, then, gradually narrowed by successive backward temperature range signal. If it detects invalid temperature range, it informs sim that the current case corresponding to the invalid range signal is not feasible.

4 RANGE VS. RESOLUTION

As stated in the section 2 referring to Fig.2, value range of range signals are getting wider through the backward simulation and would spread too much. However, we can get detailed results by dividing the range.

Fig. 3 shows how the division of range signal affects the simulation resolution, which means the degree of coincidence between the resultant range and the true area of unfavorable conditions. In the figure, (a) shows the true area of unfavorable conditions, (b) shows the rectangle which is defined by the range of x and the range of y, (c) shows a narrowed area defined by a combination of rectangles for each divided range of x and range of y. And if we proceed the range division further as in (d), we will come closer to the true area of question. Such improvement of resolution can be done by dividing the temperature range in the user model.

5 CASE BRANCHING CONTROL

In this section, we describe the details of case branch processing. All the components in the Fig. 2 except manin deals branch related messages of branch, clearCase, nextCase, branchCompleted, which are control messages between simulation components.

A component which needs to branch pushes the cases to be tested further onto its case stack and sends a branch signal with a unique branch id to sim.

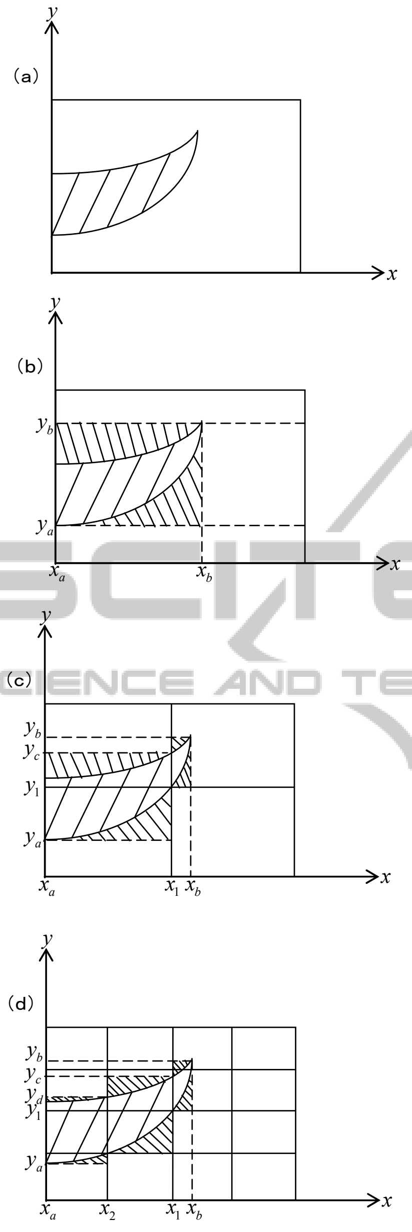


Figure 3: Range signal division and result resolution.

In the response to it, sim sends a branch signal and a clearCase signal in sequence, each with the branch id, to all the components.

Receiving the branch signal, every component prepares to branch by storing the internal states and keeps branch id in its local branch id stack. Receiving the clearCase signal, it resets the internal state to be the saved status, and sends a ready signal to sim. Receiving ready signals from all the components, sim sends a nextCase signal to all the components. Receiving the nextCase signal, only the component which generated the branch id coinciding with the branch id in the nextCase message pops up a case from its case stack and sends the related range signal for the selected case backward to the connected upstream component through sim. Then sim proceeds simulation for the case selected by the branch generated component.

If any of the components detects invalid incoming range signal, it will send nextCase message to sim. Receiving nextCase message, sim sends a clearCase message to all the components and return to the state of waiting ready signals from all the components before to proceed to the next nextCase. If all the cases for one branch have been tested, the component which generated the branch sends a branchCompleted message to sim with branch id, and sim sends the branchCompleted message to all the components. Receiving branchCompleted message, all the components including sim pop the branch id stack and prepares to proceed the former simulation before that branch.

An example of branch message from user to sim is

<sim><s>user</s><branch>user#1</branch></sim>

where “user#1” is the branch id generated by the user component. Other messages like clearCase, nextCase, breanchComplete and ready use the same format by changing the <branch> tag to a tag of each message’s name.

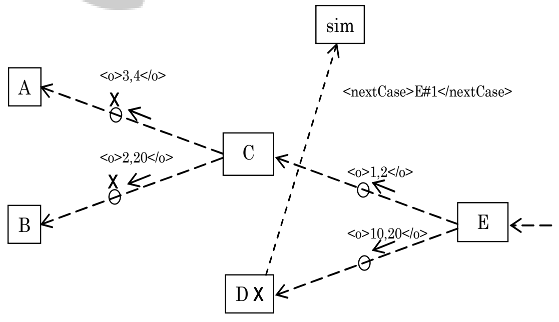
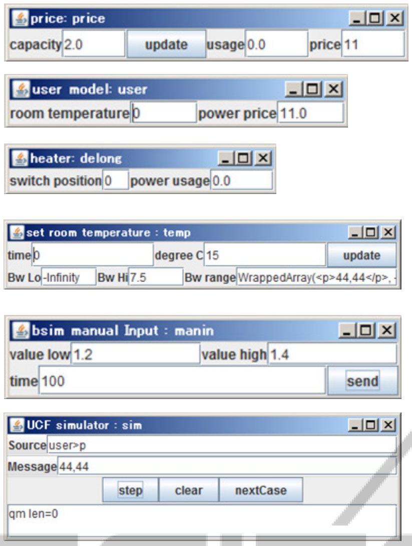


Figure 4: Invalid signal to stop processing the case.

6 IMPLEMENTATION AND RESULTS OF OPERATION

Fig. 5 shows GUI windows of simulation components. Fig.6 shows an example of command window display. The simulation controller sim has a step button for stepwise checking. And also, it has a nextCase button for manually skip the current case to the next case because we have no algorithm to stop a branched case which may run forever.



price: price
capacity 2.0 update usage 0.0 price 11

user model: user
room temperature 0 power price 11.0

heater: delong
switch position 0 power usage 0.0

set room temperature : temp
time 0 degree C 15 update
Bw Lo -Infinity Bw Hi 7.5 Bw range WrappedArray(<p>44,44</p>,

bsim manual Input : manin
value low 1.2 value high 1.4
time 100 send

UCF simulator : sim
Source user>p
Message 44,44
step clear nextCase
qm len=0

Figure 5: GUI for each simulation component.

```
$ scala P.P
Iprice        started. capacity=2.0
Iuser         started. room temperature=0 power price=11.0 Yen/kwh
Idelong       started. switch positon=0
Itemp         started. time=0 value=15
Imanin        started. time=100 low=1.1 high=2.2
Isim          started.
Btemp    0    15
Duser    0.0  3
Ddelong 1.0   1.39
Dprice   2.0  22
Duser    7.0  2
Ddelong 8.0   0.83
Dprice   9.0  11
Duser    14.0 3
Ddelong 15.0  1.39
Dprice   16.0 22
```

Figure 6: Console example of forward simulation.

Fig.7 shows a console display of a backward simulation. The starting power usage value is injected manually by using manin component. The left end shows the type of console message and the source of the message. At the center, time of message generation is displayed and it goes backward. The remaining message shows the range values and supplemental information.

By injecting a range signal of power usage, e.g. 0 to 0.5kW, backward into the simulator, we can determine whether the injected range is feasible or not. If some component detects that incoming range is not allowed, any value in the injected range cannot be reached by the system. If the simulation continues without such detection, it shows that there is a condition which causes the system to output the value inside the injected range. In such cases, we can obtain temperature range for the injected range because temp component of our implementation keeps temperature range narrowed by successive backward range signals.

Fig. 8 shows temperature range in relation to injected power usage range of 0-0.5, 0.5-1.0, 1.0-1.5 or 1.5-2.0, each with 0.5kW interval. The hatched area means the area of possibility. Fig.9 shows the same relation in the case of 0.2kW interval. The hatched area in Fig.9 is within that of Fig.8. It indicates that we can arbitrary control the resolution of the result.

```
Iprice          started. capacity=2.0
Iuser           started. room temperature=0 power price=11.0 Yen/kwh
Idelong         started. switch positon=0
Itemp           started. time=0 value=15
Imanin          started. time=100 low=1.1 high=2.2
Isim            started.
Bmanin          100     1.4,1.6
Wdelong         99.0    input 1.4, 1.6 is out of range 0.0, 1.39
Isim                    simulation completed.
Bmanin          100     1.2,1.4
Bdelong         99.0    input 3,3 for 1.2,1.4
Buser           94.0    input price=44,44 temp=-Infinity,7.5
Bdelong         92.0    input 2,3 for 0.8,Infinity
Buser           87.0    input price=44,44 temp=-Infinity,12.5
Bdelong         85.0    input 2,3 for 0.8,Infinity
```

Figure 7: Console example of backward simulation.

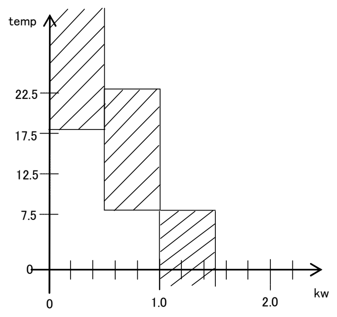


Figure 8: Simulation result for 0.5kW step ranges.

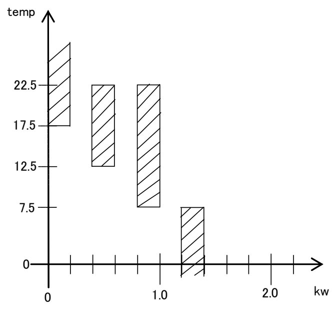


Figure 9: Simulation result for 0.2kW step ranges.

Although the above results are for a simple simulation model, it was shown that the backward simulator can catch the unfavorable conditions and can narrow down the area of such conditions.

To make Figs 8 and 9, we need to judge the simulation trace displayed in Fig.7 whether it continues forever or not for the feasible cases. Probably, we have to set some time limit for each case's calculation, beyond which the simulator automatically judges the case feasible.

7 CONCLUSION AND FUTURE WORK

We designed the forward and backward simulator with capability of using numerical simulation models, backward range processing and case branching. The implemented simulator shows validity of the backward simulation for a simple case of dynamic pricing control model planned for smart grid.

We need to have many experiences by applying the simulator to practical applications. Multiple user simulation (Fig.10) is the top on our list, which requires multiple branching components and a backward sum component. We have to estimate processing time of our backward simulator in the case of large number of branches. Also, we plan to design automatic judging algorithm for cases of continuing or vibrating simulation. And also, externalization of internal state variables will be demanded in a complex system simulation.

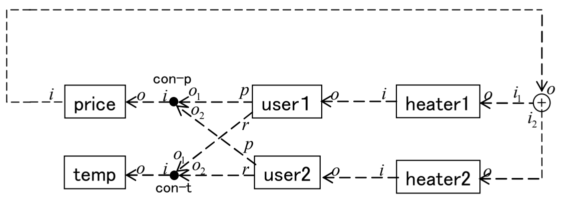


Figure 10: A backward simulation structure for two users.

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