*Proceedings of the Conference on Modelling and Simulation 1994*
*eds. Guasch and Huber*

# STRUCTURE IDENTIFICATION IN VARIABLE STRUCTURE SYSTEMS BY MEANS OF QUALITATIVE SIMULATION

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**Abstract**

This paper shows the application of Fuzzy Inductive Reasoning (FIR), a qualitative simulation methodology, to structure identification in Variable Structure Systems (VSS). This method is capable to decide by observations of system inputs and outputs alone, which mode the VSS is in at any point in time, and when structural transitions take place. Detection and discrimination are carried out by forecasting the future behavior of all possible structures in parallel. This methodology opens up the possibility of combining a qualitative supervision and control system on-line with a quantitative VSS. Two examples, a simple two-water-tank system and an electric circuit, are included to demonstrate the validity of the chosen approach.

## INTRODUCTION

Variable structure systems and controllers associated with them have originally been mostly studied by Soviet researchers (Emelyanov, 1970; Utkin, 1977, 1984), but lately, an interest in these systems has also been expressed by researchers in the West (Slotine, 1984; Sira, 1990; Hung *et al.*, 1993). Variable Structure Systems (VSSs) are commonly defined as non-linear, time-varying, and uncertain systems. In this paper, a somewhat more narrow or specific definition of a VSS will be used: A VSS is a system in which the computational causality of one or several laws governing the behavior of that system changes during the simulation as a consequence of a change in the value of a boolean variable in the model. For example, an electrical circuit containing a switch element is a VSS, since, if the switch is in its *closed* position (the position indicator is a boolean variable in the model), the voltage across the switch is 0.0, while the current through the switch must be computed from some other physical law, whereas, if the switch is in its *open* position, the current through the switch is 0.0, while the voltage across the switch must be computed from some other physical law (Elmqvist *et al.*, 1993). Such systems present serious difficulties to both simulation and control.

From the point of view of simulation, difficulties are caused precisely by the changing computational causalities. In the past, different simulation programs were usually written, one for each of the structures of the VSS, and a mechanism was encoded to switch at run-time from one model to another. An alternative solution was recently proposed by (Elmqvist *et al.*, 1993) that allows to encode a single simulation program that encompasses and is valid for all different structures within the VSS.

From the point of view of control, difficulties are caused by the abrupt change in the system structure. Even if the controller is switched at the same time as the plant, the control system nevertheless experiences a shock that may lead to undesirable transient behavior. Such shocks need to be damped out either by means of quite complex and costly non-linear compensation algorithms, or by means of a geometrical approach that considers each transition from one structure to another as a finite surface along which the system is to slide (Sliding Mode Control).

It is important to know when such a transition takes place, and to which other mode (or structure) the system changes at this time. This question is not always easily decidable, since the switching condition may itself be internal to the model. A methodology is therefore needed that will make it possible to decide by observations of system inputs and outputs alone, which mode the system is in at any point in time, and when structural transitions take place. It is this question that will be pondered in the paper.

## QUALITATIVE SIMULATION APPLIED TO VARIABLE STRUCTURE SYSTEMS

Qualitative simulation has recently become a promising methodology for solving problems in various disciplines where the more classical quantitative techniques have led to complications or even failures. The qualitative simulation technique advocated in this paper is called *Fuzzy Inductive Reasoning*. A number of publications on inductive reasoning have previously been published. The methodology is fully explained in (Cellier, 1991), and has been successfully applied to a number of different applications including: combining quantitative and qualitative models of dynamic systems in a mixed simulation (Cellier *et al.*, 1992), supervision and control of large-scale systems (de Albornoz and Cellier, 1993a, 1993b), and the systematic

*Supported by Consejo Nacional de Ciencia y Tecnología (CONACyT) México
†Supported by BAUXILUM and CONICIT. Venezuela

design of fuzzy controllers (Cellier and Mugica, 1992). For this reason and in interest of saving space, the results that were presented in the aforementioned publications will not be repeated here. The interested reader is friendly invited to consult the earlier publications to familiarize him or herself with the details of the methodology. In this section only a very short description will be provided.

Fuzzy Inductive Reasoning (FIR) is a technique for constructing qualitative models that are represented by a special class of fuzzy Finite State Machines (FSMs). The FIR methodology does not require any knowledge of the structure of the system under investigation or any other knowledge except for time histories of input/output behavior. The FIR methodology predicts the system behavior in qualitative terms. This behavior is then compared against the real values obtained from either a quantitative model of the system or from the physical system itself. As the prediction is based on the recent past behavior of the system, it is somewhat adaptive to slow changes in system parameters or a slow drift in the steady–state, but a structural change is immediately detected since the behavior of the system can no longer be predicted with the fuzzy FSM that had been determined for the previously active system structure.

In order to continue with the prediction of system behavior after a structural change has taken place, the fuzzy FSM must be swapped for another FSM that has been determined under the newly active system structure. The inductive reasoner is not capable of predicting the behavior of a system that it has never observed before. For this reason, a successful prediction of the system behavior after the change is only possible if one of two assumptions holds:

a) The system has previously been observed by the inductive reasoner in all its structural modes, and different fuzzy FSMs, one for each mode, have been stored away in a *qualitative model library* for later reuse. The model library is now searched for a model that leads to qualitative behavior that is consistent with the real system behavior observed after the change.
b) The inductive reasoner switches from a *prediction mode* to a *training mode*, in which it observes new incoming data for a sufficiently long period of time to generate a new fuzzy FSM. Only after this phase has been successfully completed will the inductive reasoner switch back to its prediction mode and resume its original duties.

Both scenarios have severe drawbacks in a real–time control environment. Both options require time after a structural change has taken place for determining the new qualitative model to be used. During this time period, the supervisory control is disabled for all practical purposes. However, it is exactly this time period when the transient takes place, and when knowledge of what is going on would be most valuable to dampen out the transition shock and to steer the system smoothly into its new mode of operation.

In two previously published papers (de Albornoz and Cellier, 1993a, 1993b), a qualitative simulation method based on the FIR methodology capable of dealing with anomalous behavior in large–scale systems had been proposed. The method was based on scenario (a) above and worked fine for the tasks at hand. However, in both cases, there was only one normal mode in which the system was operating. The structural changes encountered were related to accidents taking place. The purpose of the supervisory control was limited to providing a human plant operator with aditional information that might prove useful when dealing with a developing emergency.

## Forecasting all Possible Structures

The VSS situation is quite different. Here, the transition from one structural mode to another is not an emergency, but a normal event that will happen regularly during system operation. The purpose of the supervisory controller is to provide the mode transition controller (usually either a hardwired controller or a program) with sufficient information to allow it to perform its task. This information must be provided on–line and very fast. The mode transition must be both detected and discriminated almost immediately.

The proposed method for dealing with VSSs is also based on FIR. Like in option (a) above, all possible structural modes must have been previously modeled and characterized. However, instead of placing them in a model library, all qualitative models are used *in parallel* to constantly predict different qualitative behaviors of the system, i.e., all models corresponding to all structural modes are used in parallel to predict the future behavior of the system. Obviously, only one of the models can represent the true behavior of the system at any one time. It is identified by continuously comparing all predictions against the real measurement data.

Evidently, it will sometimes happen that a prediction is kind of poor even if the correct model is in use, maybe poorer than another prediction. It may also happen that a prediction is right on the mark even though the incorrect model is being used. In both cases, a mode selector basing its decision on instantaneous errors alone would be destined to making mistakes. In order to overcome this dilemma, the instantaneous error vectors are first being "purified" by sending them through an error filter. The error filter accumulates errors over $n$ steps, i.e., it generates a moving average of the errors accumulated over the most recent $n$ steps. The mode selector then bases its decision on the smallest among the filtered errors. In this way, local aberrations or accidental hits can be filtered out and won't influence the decision making process.

Figure 1 shows a schematic diagram of the whole process including the qualitative simulation, the comparison, and the identification procedures. The measured data are fed in parallel to the different masks representing the different structural modes. Each of them produces a stream of qualitative forecasts. These are then compared with the measurement data, and streams of instantaneous errors are produced. These errors are then filtered in the manner described above leading to a cumulative error stream, which

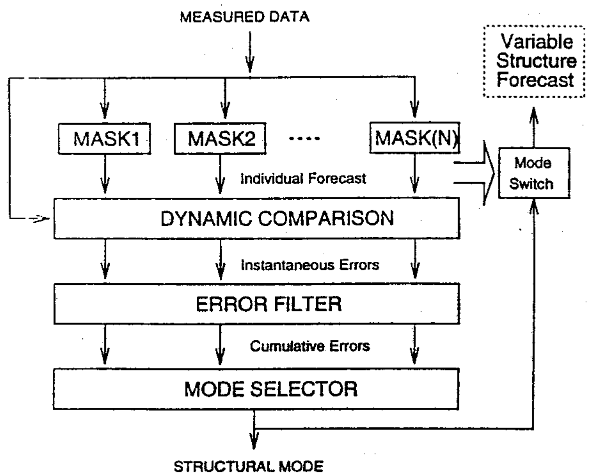


Figure 1: Mode switch detection and mode characterization.

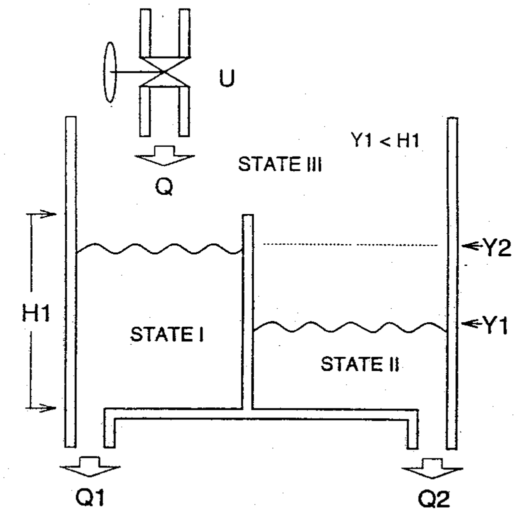


Figure 2: Interconnected water tanks.

in turn is used by the mode selector for guessing the currently correct structural mode.

In this way, the FIR can switch from one qualitative model to another immediately after a structural change has taken place. The determination of a qualitative model capable of representing the behavior of the system at all times is guaranteed, irrespective of the structural mode the real system is in. Of course, it can happen that two structural modes have so similar effects on the input/output behavior of the system that the reasoner cannot discriminate between them. In all likelihood, this will then lead to oscillatory behavior, i.e., the reasoner will switch back and forth at a fairly high switching rate between the two *plausible* modes.

## THE EXPERIMENTS

### The Interconnected Tank Model

In order to demonstrate the approach, two examples will be presented. The first describes two interconnected water tanks (Strömberg *et al.*, 1993), and is shown in figure 2.

The system can operate in three different structural modes:

(i) the first tank is being filled while the second tank can only be emptied,

(ii) the first tank is full up to the separating wall between the two tanks while the second tank can be either filled or emptied, and

(iii) both tanks are full to or beyond the level of the separating wall and are now being filled or emptied together.

A simulation was conducted across 1000 seconds of simulated time. During the simulation, four structural changes took place that drove the system through the three possible modes. The real and predicted modes are shown in figure 3 as functions of time. Notice that there usually is a short delay after the true mode changed, before the mode switch is activated. This delay is mainly caused by the error filter. If the number of past points used in the filter is reduced, the delay time will be shortened, but this goes at the expense of occasional errors in determining the correct operating mode of the system.

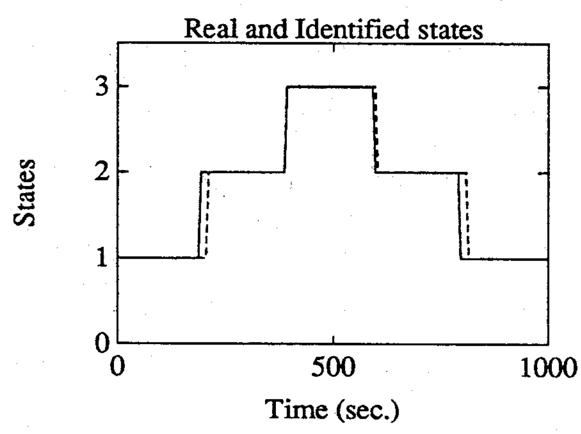


Figure 3: Real and identified modes.

This is a fairly straightforward example since the different modes can easily be discerned by the naked eye. It does not take much discriminatory power for the inductive reasoner to distinguish between the three operational modes of the system. The example was chosen only since it had been previously discussed in the VSS literature (Strömberg *et al.*, 1993).

## Electric Circuit

The second example is much more involved. It is much more difficult for the inductive reasoner to correctly identify the various structural modes, and to know when a transition from one node to another takes place. It is therefore proposed as a benchmark for structure identification. The system consists of an electric circuit containing three binary switches as shown in figure 4. Consequently, the system can be in any of eight different structural modes depending on the switch positions. The resulting eight structural modes exhibit behavioral patterns that are different enough to be characterized, yet similar enough to make their correct identification a difficult problem.

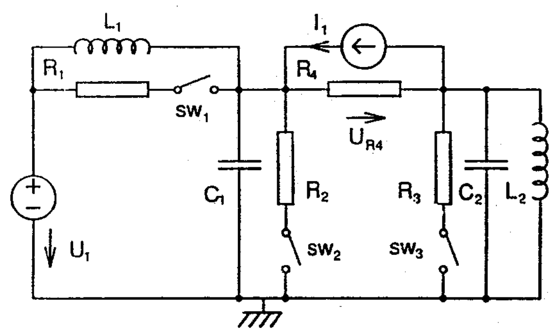


Figure 4: Electric circuit VSS.

The system has two inputs, $U_1$ and $I_1$, and one output, $U_{R4}$. The quantitative circuit model has been built using Dymola (Elmqvist, 1993; Elmqvist *et al.*, 1993) generating an ACSL (MGA, 1986) simulation model. The model is presented below.

```
model Circuit
  submodel (CSource)    I0
  submodel (VSource)    V0
  submodel (Resistor)   R1(R = 50.0), R2(R = 10.0)
  submodel (Resistor)   R3(R = 100.0), R4(R = 50.0)
  submodel (Capacitor)  C1(C = 10.0E-6), ->
                        C2(C = 10.0E-6)
  submodel (Inductor)   L1(L = 6.0E-3), ->
                        L2(L = 3.0E-3)
  submodel (Switch)     Sw1, Sw2, Sw3
  submodel Common

  input  u1, u2, o1, o2, o3
  output y
  node   n0, n1, n2, n3, n4, n5, n6

    connect ->
      Common  at    n0, ->
      V0      from  n1 to n0, ->
      R1      from  n1 to n2, ->
      Sw1     from  n2 to n3, ->
      L1      from  n1 to n3, ->
      C1      from  n3 to n0, ->
      R2      from  n3 to n4, ->
      Sw2     from  n4 to n0, ->
      I0      from  n5 to n3, ->
      R4      from  n5 to n3, ->
      R3      from  n5 to n6, ->
      Sw3     from  n6 to n0, ->
      C2      from  n5 to n0, ->
      L2      from  n5 to n0

  V0.V0 = u1
  I0.I0 = u2

  Sw1.OpenSwitch = o1
  Sw2.OpenSwitch = o2
  Sw3.OpenSwitch = o3

  y = R4.u
end
```

In a first experiment, the switch positions were frozen in one of the eight possible position, and the two inputs were excited with binary random noise to collect data (1000 data points) for characterizing the behavior of the system in that particular mode. The experiment was repeated for all eight switch positions. Using the FIR methodology, eight different qualitative models were obtained, each one with its own FSM and its own set of landmarks.

In a second experiment, the numerical model was rerun, this time including a mechanism to change the switch positions once every 50 sampling intervals. By going through the eight different stages, 400 data points of variable structure circuit simulation were obtained to be used as the "real" data for identifying the structural mode the circuit is in at any point in time.

The 400 data points collected from the variable structure simulation were recoded (fuzzified) eight times using the specific landmarks (i.e., borderlines between neighboring discrete classes) obtained for the eight qualitative models. Using the previously obtained qualitative models, it was now possible to forecast the system behavior eight times over the entire period using the eight different qualitative models. It was hoped that each of the eight qualitative models would produce a decent prediction during the time span when the real model was operating in the corresponding structural mode, and a poor prediction during all other times.

This problem is much tougher than the two–tank problem. Several of the eight modes lead to input/output behavior that is almost indistinguishable. At least by simply looking at the data, it is not obvious that they were generated from different structural modes. It is thus interesting to check whether the FIR methodology "has a better eye" than we humans do.

Figure 5 depicts a transition from mode 001 (switches 1 and 2 are in the closed position whereas switch 3 is in the open position) to mode 000 (switches 1, 2, and 3 are all in the closed position). The continuous line represents the true trajectory behavior of the system, whereas the dashed line represents the FIR forecast of the system using the qualitative 001–mode model, whereas the dotted line represents the FIR forecast using the qualitative 000–mode model.

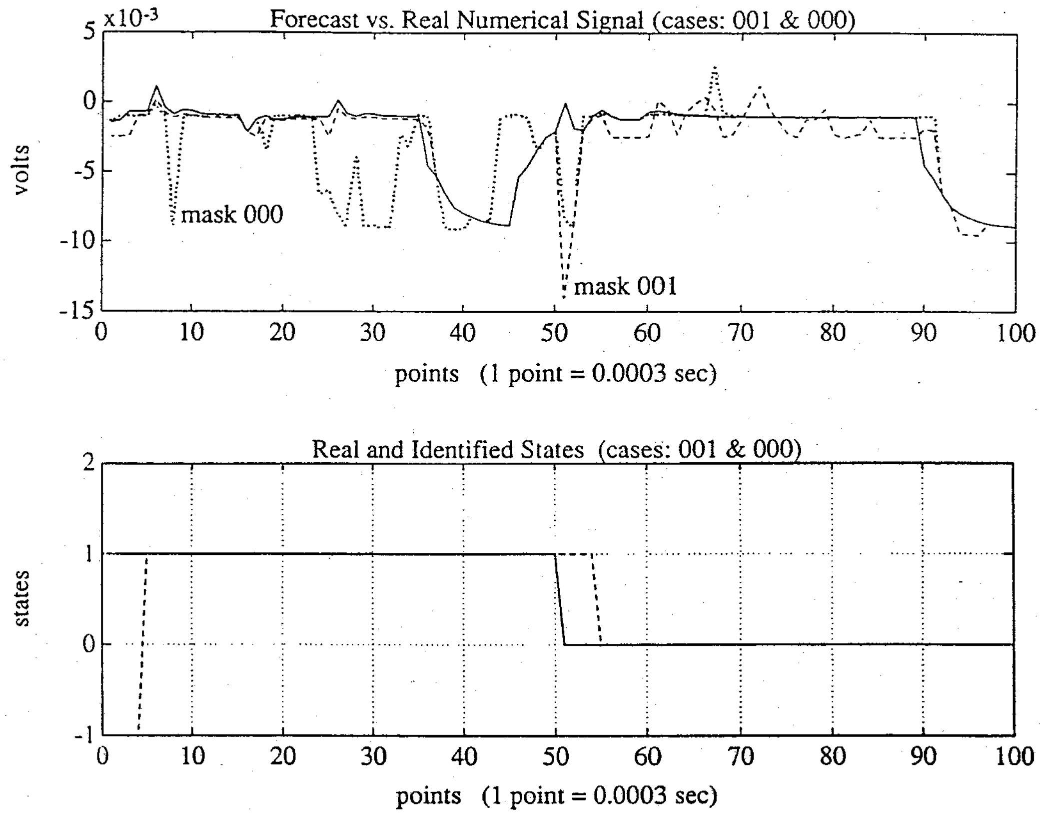


Figure 5: Forecast of two very similar structural modes.

The structural mode change occurs at sampling point 50. Due to the transient taking place immediately following the switching event, and due to the lag behavior of the error filter, it takes five sampling periods, before the mode selector switches from mode 001 to mode 000. Notice that the FIR mode detector was capable of unambiguously identifying the correct mode, although the input/output behavior of the system looks indistinguishable to the human eye. Figure 6 shows the identification results obtained for the 400 points of VSS simulation. The mode number shown on figure 6 is a decimal encoding of the binary (three bit) mode pattern. The solid line represents the true mode, and the dashed line denotes the mode identified by the FIR method.

Every 50 data points, the system changed from one mode to another. As can be seen, the FIR methodology was able to identify the correct mode in which the system is operating in six out of the eight cases. From points 251 to 300, corresponding to mode 010 (switches 1 and 3 closed, and switch 2 open), the FIR toggled between two plausible modes, the correct mode 010 and the very similar mode 111. In this case, the similarities between the two modes were so strong that the FIR was not able to discriminate between them. From points 351 to 400, corresponding to mode 101 (switches 1 and 3 open, and switch 2 closed), the FIR was not able to identified anything. In this case, the wrong identification has a different cause, namely an incorrect characterization of the 101 mode. Some structural modes presented more difficulties than others for their characterization due to the effects of the excitated input signals on the single output signal of the system. It might be possible to overcome this problem by varying the type of excitation during the mode characterization phase.

Of course, it is possible to make the structure identification problem less hard by adding additional output signals to the circuit, so that the FIR method obtains redundancy in determining the right mode. However, it was decided to keep the problem as hard as it is, and present the results as they were obtained. This is a really tough problem, and other researchers are invited to try their own structure identification approaches on it to see whether they can do better than the FIR methodology. However, the FIR performance may be hard to beat.

## CONCLUSIONS

This paper demonstrated that the FIR methodology is a powerful tool for structure characterization in variable structure systems. Two examples have been presented, the (fairly simple) two–water–tank problem, and an electric circuit model containing three switches. The latter example is very tough, and it is therefore proposed as a benchmark

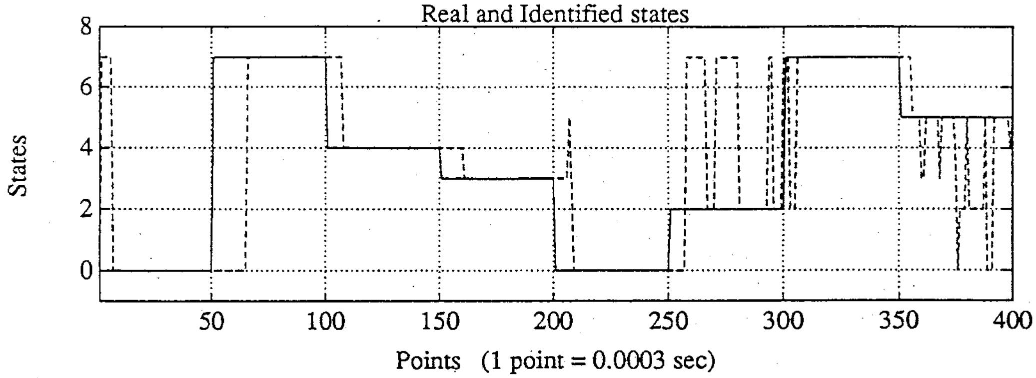


Figure 6: Real vs. identified modes.

problem for structure identification algorithms and codes.

## ACKNOWLEDGEMENTS

This research has been supported by CICYT, under project TIC93-0447. The authors wish to thank Dr. Rafael M. Huber from the Institut de Cibernètica for his continuous support.

## REFERENCES

Cellier, F.E. (1991), *Continuous System Modeling*, Springer-Verlag, New York.

Cellier, F.E. and F. Mugica (1992), "Systematic Design of Fuzzy Controllers Using Inductive Reasoning," *Proc. IEEE Intelligent Control Conference*, Glasgow, Scottland, U.K., August 11–13, pp. 198–203.

Cellier, F.E., A. Nebot, F. Mugica, and A. de Albornoz (1992), "Combined Qualitative/Quantitative Simulation Models of Continuous-Time Processes Using Fuzzy Inductive Reasoning Techniques," *Proc. SICICA'92, IFAC Symposium on Intelligent Components and Instruments for Control Applications*, Málaga, Spain, May 20–22, pp. 589–593.

de Albornoz, A., and F.E. Cellier (1993a), "Qualitative Simulation Applied to Reason Inductively About the Behavior of a Quantitatively Simulated Aircraft Model," *Proc. QUARDET'93, IMACS Internat. Workshop on Qualitative Reasoning and Decision Technologies*, Barcelona, Spain, June 16–18, pp. 711–721.

de Albornoz, A., and F.E. Cellier (1993b), "Variable Selection and Sensor Fusion in Automatic Hierarchical Fault Monitoring of Large Scale Systems," *Proc. QUARDET'93, IMACS Internat. Workshop on Qualitative Reasoning and Decision Technologies*, Barcelona, Spain, June 16–18, pp. 722–734.

Elmqvist H. (1993), *Dymola: Dynamic Modeling Language — User's Guide*, Dynasim AB, Lund, Sweden.

Elmqvist H., F.E. Cellier, and M. Otter (1993), "Object-Oriented Modeling of Hybrid Systems," *Proc. ESS'93, European Simulation Symposium*, Delft, The Netherlands, October 25–28, pp. xxxi–xli.

Emelyanov, S.V. (1970), "Design of Variable Structure Systems With Discontinuous Switching Functions," *Eng. Cybern.*, 1, pp. 156–160.

Hung, J.Y., W. Gao, and J.C. Hung (1993), "Variable Structure Control: A Survey," *IEEE Trans. Industrial Electronics*, 40(1), pp. 2–22.

Mitchell & Gauthier Assoc., *ACSL: Advanced Continuous Simulation Language — User Guide and Reference Manual*, Concord, Mass.

Sira-Ramirez H. (1990), "Dynamical Discontinuous Feedback Control of Nonlinear Systems," *IEEE Trans. Automatic Control*, 35(12), pp. 1373–1378.

Slotine, J.J.E. (1984), "Sliding Controller Design for Nonlinear Systems," *Internat. Journal of Control*, 40(2), pp. 421–434.

Strömberg, J.E., U. Söderman, and J. Top (1993), "Bond Graph Supported Estimation of Discretely Changing Parameters," *Proc. ICBGM'93, Internat. Conference on Bond Graph Modeling*, San Diego, Calif., January 17–20, pp. 47–52.

Utkin, V.A. (1977), "Variable Structure Systems Within Sliding Mode," *IEEE Trans. Automatic Control*, 22(2), pp. 212–222.

Utkin, V.A. (1984), "Variable Structure Systems: Present and Future," *Automation and Remote Control*, 44(9), pp. 1105–1120.