MODELING AND SIMULATION OF DYNAMIC SYSTEMS

Inge Troch and Felix Breitenecker
Vienna University of Technology, Austria

Keywords: System, Process, Model, Model of problem, Model of system, Modeling goals, Model structure, Model complexity, Equivalent models, Behavioral equivalence, Structural equivalence, Model simplification, Bottom-up modeling, Top-down modeling, Verification, Validation, Identification, Continuous-time simulation, Discrete-event simulation, Simulation experiment, Simulation run, Dynamic system, Static system, Deterministic system, Stochastic system, Continuous-time system, Discrete-time system, Discrete-event system, Hybrid system, State-events, Linear system, Nonlinear system, Parametric model, Non-parametric model, Time-domain, Frequency domain, Modeling concepts, Classification of systems, Classification of models, White-box, Black-box, Behavioral model, Structural modeling, Structured Analysis and Design Technique, Internal structure, Transition function, Semi-group property, Dynamical system, Simulation tools, Differential analyzer, Analogue computation, Hybrid computation, Feedback principle, Analogy of behavior, Principle of analogy, State-space concept, Input-output model, Input-state-output model, Cause-effect relationship, Manifest variables, Latent variables, Causal loop, Influence diagram, Credibility of results, Pseudo-random numbers, History of simulation

Contents

Summary

Models, especially mathematical models, are a powerful tool in automation and in analysis and design of control(led) systems. There are strong interconnections not only between the system, the modeling goal and the modeler but also between the model and the resulting solution for the industrial problem. The modeling process itself is examined from a rather general point of view highlighting especially those aspects which are important for automation and control. Further, simulation and simulation tools are discussed from the same point of view not only including topics such as model complexity, validation and verification but also numerical aspects. Important properties of systems, models and simulation tools such as e.g. *'continuous'* and *'discrete'* are not used in a unified way. Therefore, the most important pairs of properties are compared and reviewed briefly. Tools for modeling and simulation have become indispensable in automatic control. Their history is reviewed briefly together with the state-of-the-art with reference to subsequent chapters of this chapter which provide more details.

1. Introduction

Today, creation, improvement and running of automated systems are based on the use of computers and consequently, on models. Such models can be verbal, lists of actions to be taken, mathematical expressions or computer programs to name but a few. Computer aided analysis and design and, consequently, modeling and simulation are fundamental tools in automation and control engineering. Models are used during the various stages of the design process of a new system, be it a model for the procedure of creating a new automation system, be it a model of a system for which a controller has to be designed or be it a model for the investigation of a newly designed system or of an already existing control system which has to be investigated. In many situations models are used to demonstrate that a new system or a new controller will indeed do the job it was designed for.

However, both terms, *'model'* and *'simulation'* respectively, are used not only within the control community but by engineers of various disciplines and also in everyday speech due to the universality of the concepts behind the terms. Both notions are closely related to what is called today a *'system'* or *'process'*. Unfortunately, the triple *'system - model - simulation'* is not well defined and hence, scientists or engineers using one or the other of these terms in a discussion may use them with quite different meaning - a situation which is told to be rather frequent in philosophical discussions but normally unknown among scientists or engineers. Therefore, the various meanings and uses will be exploited in the sequel from a control engineering viewpoint together with - some - of the answers to *'WHY'* has modeling and simulation become so important in control engineering.

There exists a variety of types of systems and consequently many possibilities to model a system. The type of model to be used will depend not only on the system under investigation or to be designed, but also on the modeler's background and preferences concerning approach to be taken and tools to be used in order to achieve successfully the given goal. This can be seen easily when scanning the table of contents of the chapter on *Control Systems, Robotics and Automation of this Encyclopedia*. Modeling in general and especially modeling of systems for control or automation purposes is based essentially on the knowledge of those system properties that are important for the specific task. Proper identification of important system properties indicates which model classes will be useful and, which simulation tools will be appropriate. It is well known that a system with certain properties can be modeled in several ways and that its mathematical model is not uniquely defined but can be of various nature such as e.g. differential equations or describing functions. However, knowledge of the various classification concepts for systems and models respectively, is helpful for appropriate choice of model and tools for analysis and simulation. Therefore, the most important classification aspects will be discussed shortly. This provides at the same time some insight into use and abuse of certain terms which are used not only by control engineers but are rather common also in a more general setting.

Further, important aspects model building are discussed not only from the point of view of control but also from a more general point of view, providing thus also some insights into the reflections of scientists which were dealing with models and simulation either from a theoretic point of view or who worked in a different area of application. However, only those reflections, guidelines and results are presented in the following which are of interest for control engineering applications. Among them are general guidelines together with a discussion of appropriate model complexity, model structure and last but not least of relations between several possible models for one and the same system. Relations between models and the question of model equivalence is especially important in control engineering because there, many different description of one and the same system are often used in parallel - think e.g. on linear state space models and transfer function models or, on linear models derived by a special type of linearization or, on (linear or nonlinear) state space models of different order or different complexity etc. A detailed discussion of some of these aspects can be found in various places of the chapter on *Control Systems, Robotics and Automation*. Here, only the general aspects and the most important results will be presented which can - hopefully - lead to new theoretical investigations for various simplification techniques used in control applications.

It is to be noted that control engineers were among the first who used mathematical models for both for the analysis of plants and controlled systems and, for controller design. The same holds true for the more general setting of automation (of) systems. Analysis of a system, especially of a controlled one is based to a great extent on the evaluation of its future behavior under various disturbances.

A further question concerns the dependency of the system's behavior on changes of parameters i.e. questions of sensitivity and robustness. An analytic answer to these questions is often difficult to derive especially, if nothing about the system's behavior is known. Therefore, often a first investigation of these questions is given on the basis of extended simulation experiments which yield the time-histories of important system variables for various choices of parameters and disturbances respectively. Such simulations became a general accepted tool shortly after World War II - however by using neither the term *'simulation'* nor the equipment control engineers are accustomed to today. This leads to a short historical view on simulation and simulation tools which demonstrates at the same time what has been achieved and which developments are to be expected.

2. Systems, Processes and Models

As early as in 1954 Soroka wrote that *'engineering problems have increased continually in complexity as the fund of scientific knowledge and the store of engineering experience have accumulated. The rough approximations used in the past for design purpose are often no longer satisfactory as modern practice makes more stringent demands on materials, processes, and performance. Analytical solutions are often impossible without further advances in mathematics, while numerical calculations on desk calculators may become impractical because of the length of time required or the cost involved. If such problems are to be solved, one must have recourse to high-speed, high-capacity automatic digital computing machines, or else one must resort to some experimental method. Engineers always have tended to rely heavily on direct experimentation to obtain numerical results. It may be that such experimentation is at times impractical or impossible. Under such conditions an indirect experimental approach by means of an analog computer or simulator may well prove to be feasible and economical'*. Meanwhile half a century has passed and these statements have — with the only exception of the mentioned analog computer — not lost actuality.

Soroka states further, that *'the term 'analogy' means similarity of properties or relations without identity'*. And, this statement is one very appealing explanation of the characteristics of a *'model'*. A further — and also rather old — definition is due to Minsky: *'An object A is a model of the object B if an observer can use A to answer questions that interest him about B'*. Hence, a model is a representation of a system.

From the above follows that every model is related to an original i.e. to something what usually is called system or process and which is something *'real'* consisting of components and with boundaries which define what is to be included within a system and what belongs to the system's environment. Normally, it is assumed that the environment influences the system's behavior through inputs but, that there is no (or only negligible small) influence of the system on the environment. From this follows that - depending on the particular task and view on it — a controller may belong to what is called *'environment'* or, may be part of the system. The first view appears in controller design when plant and controller are viewed as two interacting but independent subsystems, the latter holds e.g. for stability or robustness analysis of the controlled system.

Reflections such as these indicate that the term *'system'* is not easily defined or explained. Ergo, there exist many explanations of it (some prefer process to indicate more clearly that there are changes as time passes). Rather common are descriptions like *'A system is a structured total of elements with well defined properties and with well established relations between these elements and with the environment'*. From the point of view of modern (computer-oriented) control engineering Cellier's favorite formulation, *'A system is a potential source of data'* is rather attractive. A goal-oriented exposition is given by Chorafas where a system is defined as a *'group of interdependent elements acting together to accomplish a predetermined task'*. Hence, a model is defined as the body of information about a system gathered for the purpose of studying, influencing or modifying etc. the system. Obviously, the purpose of the study will determine the nature of the information that is gathered. Hence, there is no unique model of a system.

Further explications of the two notions *'system'* and *'model'* can be found not only in many books on modeling and/or simulation but also in almost every encyclopedia. Among the more recent definitions of the term 'model' the one of Sage refers to the fundamental importance of mathematics for control engineers of today: *'A model is an image or abstraction of reality; a mental, physical or mathematical representation or description of an actual system.'* Engineers (no matter whether or not they were called by this name) are concerned with finding a realizable solution for a certain problem. Through centuries they used their imagination (i.e. mental models), more or less accurate sketches (i.e. visualization) or a physical model - often of reduced scale. Calculations were restricted mainly to static relations between a few quantities or, to rough estimates which often resulted from experience (rule of the thumb). It is important to note that the above concept of a model being the image of reality covers two aspects - the *'descriptive model'* of a really existing system and, the *'prescriptive model'* of a system which hopefully will exist and work satisfactory in the future.

However, demands have increased considerably and improvement of existing - industrial, engineering etc. - control systems or design of new ones is in most cases only possible, when appropriate mathematical models are used. A mathematical model is an abstract, simplified, mathematical construct related to a part of reality and created for a particular purpose. It is adequate if it is adequate for the goal in the mind of the modeler. It is important to note that *'a mathematical model is a symbolic representation composed of mathematical symbols. These symbols have precise mathematical meaning and the manipulation of symbols is dictated by the rules of logic and mathematics. A mathematical formulation becomes a model by relating its symbols to a system characterization'.*

Manipulation of variables contained in model need not be analytical. Often, a model is formulated as computer model and a solution is sought by experimenting with it, for instance by varying parameters. This was for long the case especially for discrete-event systems and led to a goal-oriented explanation *'A model is a description of some system intended to predict what happens if certain actions are taken'.*

So far, the arguments centered on a *'model'* which describes certain phenomena or - using control terminology - the plant and maybe some or all of the restrictions to be obeyed. If analysis of an existing - controlled or uncontrolled - plant is of concern then a model of the plant will be sufficient and appropriate for insight. But, whenever design is concerned, then a model for decisions is needed. In such situations not only the plant but also the task in question needs to be modeled. Such a 'complete' model will make the designer's task better defined and hence, somewhat easier. Moreover, application of design tools will become feasible. Such tools are certain mathematical methods such as e.g., optimal control design via maximum principle, dynamic programming or parameterization for which often computer support is available as e.g. in the various toolboxes of Matlab (Some information about this software tool is provided in Section 6, for more detailed information see *Software Development and Trends*) such as pole placement, LQG design, model predictive control, nonlinear control, optimization etc. Consequently, relations describing the various restrictions on plant variables should be included in the model as well as suitable formulations of all constraints on the controller(s), no matter whether these constraints result from physical, chemical etc.

properties or from economic, safety etc. considerations. Last but not least, also the various and often conflicting goals have to be modeled.

Today, it is common practice to view a system as a process that converts inputs over which the system has no direct control, to outputs i.e., one type of behavioral quantities to another. As long as interaction of a system or a subsystem with its environment (which may be one or several further subsystems) is concerned, a description of the relations between these two types of behavioral quantities would be sufficient. Such a description is called a *behavioral model* or *I/O-model* or *black-box model.* However, a system may react to one and the same input in quite different manners depending on its history. In order to model also these effects, the notion of state was introduced. The state is regarded as the most concise description of the system's past history. The current state and subsequent inputs determine the future states of the system. In the corresponding model, the state (if properly defined) contains all information needed to calculate future responses without reference to the history of inputs and responses. There are many ways that it could have gotten to the current value, but this history is irrelevant for the future responses. A mathematical model of such a system needs only the present state and future inputs to calculate future responses.

However, this input-output or input-state-output view of a system has also shortcomings and is no longer accepted unanimously. First, it is important to note that the choice of state variables for a particular system is not unique - most physical systems can be described with many different sets of state variables. Moreover - and maybe even more important - also the choice of inputs and outputs needs not be stringent. Electrical circuits are good examples in which the state-space concept has severe shortcomings and - as suggested by Jan Willems - the use of manifest and latent variables may be more appropriate for modeling dynamical systems.

3. Simulation

There are few terms that have changed so much their meaning and are used within so different settings as 'simulation'. Obviously, its roots are the Latin 'similis' and in every day life *'to simulate'* means (e.g. Webster's Collegiate Dictionary) 'to feign, to attain the essence of, without the reality'. Since long, simulation was connected closely with two areas, control engineering and the investigation of server/queuing systems. The models behind are quite different - for a long time only two types were used—differential equations in one area and models based on the use of probability distributions in the other. Meanwhile, systems and hence, also models are of great variety - events occur in many continuous-time systems either as state-events or as (random) stochastic events. Moreover, discrete-event systems have continuous-time subsystems. Therefore, boundaries have become weak and most simulations performed today are in one or the other sense 'hybrid'.

Nevertheless, it is useful to see how the term *'simulation'* can be defined and used. One rather commonly accepted definition of simulation dates back to Granino Korn and states: *'A simulation is an experiment performed on a model.'* However, this raises two further questions: “What is an experiment?” and “Why is it performed?”

Moreover, simulation is here closely related to the notion of a model. This holds true also for two further statements. The first was given by McLeod on the occasion of the founding of the journal 'Simulation': *'... as Editor of the Journal, I proclaim ..... simulation to mean the act of representing some aspects of the real world by numbers or symbols which may be easily manipulated to facilitate their study.'* The second statement stems from VDI-Richtlinie 3633, and reads as *'Simulation is the imitation of a dynamical process in a model in order to derive knowledge which can be transferred to reality.'* (The original German text reads*: 'Simulation ist die Nachbildung eines dynamischen Prozesses in einem Modell, um zu Erkenntnissen zu gelangen, die auf die Wirklichkeit übertragbar sind.'*) Again, we have a purpose behind simulation which (as stated by Mezencev) can be *'to draw conclusions about process properties'* achieved by *'driving a model of a system with suitable inputs and observing the corresponding outputs'*. This is rather close to Cellier's definition: *'An experiment is the process of extracting data from a system by exerting it through its inputs'* as background. This applies to many applications of simulation, be it analysis of an existing one (such as the plant) or a proposed system (e.g. a newly designed controller) or, design of a new system by a guess-and-test method or, prediction, what will happen under certain - normal or extreme - conditions or, information on what to do to allow for a smooth running during the system's whole life cycle. The last question is not as easily answered because it requires inclusion of the design process. This has led to a more general definition of the term experiment: *'An experiment is the application of a method to a model'*. As a consequence, not only time histories of inputs and corresponding outputs are experiments but also methods such as (optimal) controller design, stability analysis, linearization, statistical analysis of certain events etc.

Obviously, modeling and simulation are closely related. Perhaps, a statement by Ingels gives a suitable conclusion for the above discussions: *'Modeling is the development of equations, constraints, and logic rules, while simulation is the exercising of the model'*.

Control engineers were among the first to use simulation as an important tool for model development, for controller design and analysis of controller performance. However, at these early days, one did scarcely talk about continuous-time simulation but about analog computation and later on about hybrid computation. In these early days, the term *'simulation'* was more extensively used by people interested in the design of server systems (e.g. bank counter, fast food restaurant, taxicab flow) and other queuing systems such as renewal or repair processes. From this resulted the situation in which the term *'simulation'* was often used synonymously for *'discrete-event simulation'*. Gradually, terminology became more precise. Today, similar to modeling and as given in more detail in Section 4, simulation is usually (although not always) classified into four types

(1) continuous-time (differential equations)
(2) discrete-time (difference equations)
(3) discrete-event
(4) hybrid.

Last but not least, it should be mentioned that control engineers often confronted with the challenge to perform not only a simulation but to do it in real-time because hardware such as a newly designed controller, or human operator is to be part of the simulation system.

Well-known examples for the latter are flight simulators.

4. Classification of Systems and Models

As stated earlier, a system is a collection of one or more related objects which normally are physical entities with specific characteristics or attributes and, which can interact but need not to do so. Further, entities and the system may change with time. Aspects such as these together with the various types of changes are characteristics which lead to classifications of systems and models. Unfortunately, again these characteristics are used in the various scientific and engineering areas differently. Especially the property 'discrete' is often used without specification to which variable it applies. Depending on area and author it can denote discrete-time, discrete-event, discrete state or output variables respectively. Therefore, an overview of some of the most important characteristic features or, more precisely, characteristic pairs used for classification is given and their various uses are discussed briefly.

4.1. Properties of Systems and Models

The first group of pairs of properties relates to both, system and/or model (see General Models of Dynamic Systems):

dynamic - static: A system or model is called static, whenever the relations between all relevant elements of the system do not depend on time. There are only few types of possible and interesting models for static systems as indicated below. Dynamic formulation involves two types of variables, independent and dependent ones. Usually, at least one independent variable concerns time, either a sequence of instants (discrete-time, discrete-event) or values in an interval (continuous-time). A variety of models comes up depending on the other properties of the system. A short discussion follows at the end of this (incomplete) list of properties used for classification.

deterministic - stochastic: In many real-world problems demands (events) occur whose occurrence and lengths can, in general, be specified only probabilistically. Examples of such systems are computer systems, communication networks, inspection, maintenance and repair operations, industrial production processes, and inventory systems. The system is of random nature and called a stochastic system. Among them especially Markov processes are of interest and rather well understood. They can be discrete or continuous with respect to state or time, respectively. Exact prognosis (i.e. computation if all data is given) of future states is not possible. Moreover, a process can be stationary which means that its distribution function is invariant under time shift. Deterministic systems show in principle predictable behavior, if modeled exactly; the future behavior can be computed from its present state and the known influences on it. However, it must be noted that being deterministic does not necessarily result in what in every-day-life is called *'predictable'* behavior. Also deterministic systems and consequently, models (even very simple ones) may show a behavior where very small changes in one parameter lead to large and unexpected changes in the system's future behavior. The various behaviors are in principle computable (if all computations are indeed exact) but ad hoc prediction of long-term results of small parameter changes is impossible. The technical term for this is known as chaotic behavior of variables. Examples are beat of airplane wings, or the growth of certain insect populations. It should be noted that there are systems which - for the same goal - can be modeled in both ways e.g. weather forecast (for a detailed discussion of models for stochastic systems see *Models of Stochastic Systems*).

lumped parameter - distributed parameter: Both properties are related to systems of dynamic nature. The elements of it may change with time only or, may depend on time and space as the oscillations of a beam or BOD- and DO-values (BOD and DO stand for biological oxygen demand and dissolved oxygen respectively which describe water quality and hence, are important for its control) along a river. In the continuous-time case lumped parameter systems are described by ordinary differential equations whereas distributed parameter systems are modeled by partial differential equations. In the time-discrete case the simplest models for the latter are so-called 2D- or 3D-systems. Sometimes, distributed parameter systems (see *Some Basics in Modeling of Mechatronic Systems* and *Modeling and Simulation of Distributed Systems*) are called infinite-dimensional systems. However, the latter mathematical term includes also systems with (finite or distributed) dead lag i.e. differential-difference equations and integro-differential equations.

stationary (time-invariant) - time varying: A system is called stationary when it is invariant under arbitrary time shift. In the deterministic case such systems are modeled for instance by differential (difference) equations which do not depend explicitly on time (t, t_k resp.), in the stochastic case their distribution function is invariant under time shift.

continuous-time and discrete-time: This is not a precise contrast, because systems may change at discrete instants of time in a deterministic manner or, such changes may occur stochastically. Therefore, it is better to distinguish between three properties as follows:

continuous-time and discrete-time - discrete-event - hybrid: Systems which change continuously with time include very often a plant to be controlled. Among the most commonly used models are differential equations and bond graphs or, for linear systems only, transfer functions and frequency domain descriptions (operator models). Other systems change only at certain instants of time or during rather short intervals. Hence, one uses models (e.g. difference equations) which account for this fact. Moreover, certain operations (e.g. maintenance and repair, grinding, path welding) in industrial production processes appear randomly and/or have a duration which is of random nature. These systems are subjected to a sequence of countable events where it can be assumed that nothing of interest takes place between them which leads to the name discrete-event system or model, respectively. It must be mentioned that discrete-events of deterministic nature are also known. More precisely, one talks about state-events which normally appear in continuous-time systems as a switching between behaviors such as the switching between rolling and sliding of a car when aquaplaning takes place. This is one rather simple example of a hybrid system where both continuous time and (stochastic or deterministic) discrete-events are present. Continuous-time and discrete-time models are discussed in various contributions to the chapter on Control Systems, Robotics and Automation (see e.g. *Models for Discrete Event System* , *Modeling and Simulation of Large-Scale Hybrid Systems*, *Modeling of Hybrid Systems*).

continuous - discrete: This distinction dates back to the controversy between analog (= continuous) and digital (= discrete) simulation. Meanwhile, use of these two attributes without further precision should be avoided because this causes confusion. Both, dynamic systems and models have dependent and independent variables and one, several or all may change continuously or in a discrete way. It shall be mentioned that these qualities can be used also with a quite different meaning as in problems arising in continuum physics where discrete models may refer to models consisting of ordinary differential equations, whereas continuous models refer to partial differential equations.

linear - nonlinear: Linear systems have the nice property that the principle of superposition is valid. Therefore, they are - relatively - easy to understand and to handle (the latter only in the time-invariant case where several easy-to-handle descriptions are available). However, it is well-known, that real-world systems have essentially nonlinear behavior, and linear models are therefore always approximations which can be used only in a certain neighborhood of a working point etc. This dilemma between easy-to-handle and realistic has been formulated very nicely by Pindyck already in 1972: *'Our preoccupation with linear time-invariant systems is not a reflection of a belief in a linear time-invariant real world, but instead a reflection of the present state of the art of describing the real world'.*

-
-
-

Bibliography

Allgöwer F. and Zheng A. (Eds) (1991). *Nonlinear Model Predictive Control*, Basel: Birkhäuser. [This book address important theoretic topics, modeling aspects and applications from a control engineers point of view]

Atherton D. P. and Borne P. (Eds) (1992). *Concise Encyclopedia of Modelling and Simulation*, Oxford: Pergamon. [Modeling and simulation are addressed from a somewhat general point of view; however, as not only the editors but also many contributors are control engineers the focus is on aspects relevant for control systems]

Bender E. A. (1978). *An Introduction to Mathematical Modelling*, New York: Wiley. [An early undergraduate textbook with many simple examples]

van den Bosch P. P. J. and van der Klauw A. C. (1994). *Modeling, Identification and Simulation of Dynamical Systems*, Boca Raton: CRC Press. [This textbook on graduate level provides an overview for continuous-time and discrete-time (including stochastic) systems with emphasis topics relevant in control engineering]

Bossel H. (1992). *Modellbildung und Simulation*, Braunschweig: Vieweg. [Widely used textbook on undergraduate level, in German]

Breitenecker F. and Solar D. (1986). *Models, Methods, Experiments - Modern aspects of simulation languages,}* In: Proc. 2nd European Simulation Conference, Antwerpen, pages 195--199, San Diego: SCS. [Early reflection on what simulation means]

Brennan R.D. and Linebarger R.N. (1964). *A survey of digital simulation: digital analog simulator programs*, In: Simulation, 3(6): 22--36 [Early survey on digital simulation languages, of historical interest]

Cellier F. E. (1991). *Continuous System Modeling*, New York: Springer. [Widely read textbook/monograph on modeling which presents numerous modeling approaches and applications]

Chapman W. L., Bahill A. T. and Wymore A. W. (1992). *Engineering Modeling and Design*, Boca Raton: CRC Press. [Textbook written from a systems engineer's point of view]

Fowkes N. D. and Mahony J. J. (1994). *An Introduction to Mathematical Modelling*, Chichester: Wiley. [This textbook presents a general introduction in modeling, model analysis and problem solving with applications from many different areas]

Garzia R.F. and Garzia M.R. (1990). *Network modeling, simulation, and analysis*, New York: Marcel Dekker. [Easy-to-read textbook which covers also some more general modeling aspects]

Karnopp, D.C. and Margolis D.L. and Rosenberg R. C. (2000) *System Dynamics - Modeling and Simulation of Mechatronic Systems*, New York: Wiley, third edition. [Well-known textbook on modeling of multi-port systems with bond graphs]

Kheir N. A. (Ed.)(1996) *Systems Modeling and Computer Simulation*, New York: Marcel Dekker, Inc., 2nd edition. [Provides a survey on modeling and various types of models and of simulation including simulation languages, primarily from the point of view of (control) engineers]

Korn G. A. and Wait J. V. (1978). *Digital Continuous-System Simulation*, Englewood Cliffs, NJ: Prentice-Hall. [Description of the first digital simulation language, of historical interest only]

McLeod J. (1963). *Simulation is What?* In: Simulation, 1(1): 5--6. [Definition of simulation, of historical interest only]

Monsef Y. (1997). *Frontiers in simulation*, Erlangen: SCS - Society for Computer Simulation. [Textbook on modeling and simulation written primarily for computer scientists]

Murthy D. N. P., Page N. W. and Rodin E. Y. (1990). *Mathematical Modelling -- A Tool for Problem Solving in Engineering, Physical, Biological and Social Sciences*, Oxford: Pergamon Press. [A well readable introduction with many hints to the literature]

Polderman J. W. and Willems Jan C. (1998). *Introduction to mathematical systems theory*, New York: Springer. [Textbook which presents models for control systems which are not based on input/output considerations]

Schwerin R. von (1999). *MultiBody System SIMulation - Numerical methods, algorithms, and software*, Berlin: Springer. [An example for special purpose modeling and simulation software]

Shannon R.E. (1975). *Systems and simulation - the art and science*, Englewood Cliffs: Prentice-Hall, [Covers general modeling and simulation aspects which are still valid]

Soroka W.W. (1954). *Analog methods in computation and simulation*, New York: McGraw-Hill. [At its time a well-known textbook on continuous-time system simulation i.e. on analog computers and analog computation which provides also rather detailed information about the history of analog computation]

Spriet J. A. and Vansteenkiste G. C. (1982). *Computer-aided modelling and simulation*, London: Academic Press. [Presents theoretic and application oriented aspects of modeling and simulation together with a careful discussion of model equivalence, provides further a link between the engineer's point of view and the one of computer science.]

Thomson W. (1875-1876). *Mechanical integration of the general linear differential equation of any order with variable coefficients,* In: Proc. Roy. Soc. (London)} 24: 269-271. [Describes the discovery of the analog computer, of historical interest]

West B. J. (1985). *An Essay on the Importance of Being Nonlinear*, Berlin: Springer. [This book provides some reflections in a general setting]

Zeigler B. P., Praehofer H. and Kim T.G. (2000). *Theory of Modeling and Simulation - Integrating discrete event and continuous complex dynamic systems*. San Diego: Academic Press, second edition. [This book addresses these topics from computer science point of view]

Biographical Sketches

Inge Troch graduated (Dr.techn.) with a thesis in mathematics of control at the Vienna University of Technology. She is University Professor since 1974 and initiated courses and scientific work in Mathematics of Control, Modeling and Simulation at TU-Vienna. Her teaching comprises courses in these areas as well as on basic mathematics for engineering students and on differential equations at TU-Vienna, courses in robotics at the Universities of Linz and Bologna and for the Scientific Academy of Lower Austria at Krems. At present she is head of the Institute for Analysis and Scientific Computing at TU-Vienna.

She is Austrian delegate in IFAC Technical Committees (TCs) 'Optimal Control' and 'Linear Systems' and was chairperson for a four year term (and is still active member) of the VDI/VDE-GMA Committee on 'Modeling and Simulation in Automation' in Germany. She is chairperson of the IMACS-TC on 'Mathematical Modeling' and organizes successfully a series of triennial conferences on Mathematical Modeling (MATHMOD Vienna). She is senior member of IEEE.

Inge Troch is Editor-in-Chief of the *journal Mathematical and Computer Modeling of Dynamical Systems* and a member of the international editorial board of *Mathematics and Computers in Simulation* (MATCOM), *Systems Analysis, Modelling and Simulation*, *J. Intelligent and Robotic Systems* (JIRS) and *Surveys on Mathematics in Industry*). She was member of the editorial board of C-TAT (*Control -- Theory and Advanced Technology*), and was/is also a member of the IPC and/or session organizer of some 60 international symposia and congresses.

Inge Troch is a co-author of two books, co-editor of nine Proceedings, editor of several special issues of scientific journals, author or co-author of about 120 articles in scientific journals and books in the fields of mathematics of control (stability, systems theory, optimization), modeling, simulation and robotics.

Felix Breitenecker studied “Technical Mathematics” at Vienna University of Technology (VUT), finishing with Master of Technical Sciences (Dipl.-Ing.) in 1976 and graduated (Dr.techn.) with a thesis in Mathematics of Control in 1979. From 1976 on he worked as research assistant at the VUT Mathematics of Control and Simulation Group and from 1984 on, as associate professor at VUT for “Simulation and Mathematics of Control” engaged in teaching and RD in modeling and simulation. He was guest professor at University Glasgow, at Univ. Clausthal-Zellerfeld, Univ. Ljubljana, and Univ. Linz.

He is active in various modeling and simulation societies: president and past president of EUROSIM since 1992, board member and president of the German Simulation Society ASIM, member of INFORMS, SCS, UKSIM, etc. In 2004 he has been elected into the executive board of GI, the German Gesellschaft für Informatik. In 2001 he received as first European, the Distinguished Service Award of INFORMS, from the OR Society of USA.

He has organized and co-organized the European Simulation Congress Vienna (1995), ASIM conferences in Vienna, the conference series MATHMOD in Vienna, and Simulation Workshops in UK, Germany and Austria.

Felix Breitenecker covers a relatively broad research area, from mathematical modeling to simulator development, from discrete event simulation to symbolic computation, from numerical mathematics to object-oriented simulation implementation, from biomedical and mechanical simulation to workflow and process simulation.

He is involved in various national and international research projects and he is active in industry projects, e.g. with Daimler-Chrysler and EADS. In co-operation with ARCs, the Austrian Research Center Seibersdorf, he takes part in research and industry projects in biomedical engineering and in process engineering.

He has published about 210 scientific publications, and he is author of 2 books and editor of 16 books (Proceedings and Series). Since 1992 he is editing the journal Simulation News Europe, Editor-in-Chief since 1995, and he is co-editor of the SCS Series “Frontiers in Simulation” and “Advances in Simulation”.