TECHNOLOGICAL AND METHODOLOGICAL

ADVANCES IN MEASUREMENT

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DATA PROCESSING AND SYSTEM ASPECTS

General Editor

PROF. GY. STRIKER

Editors

KAROLINA HAVRILLA
JUDIT SOLT
DR. T. KEMÉNY

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VOLUME III

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Plenary Lectures

Transmission, Modeling and Stochastics

Diagnostics and Fault Localization

Systems

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PLENARY LECTURES

NEW DEVELOPMENTS IN SYSTEMS THEORY WITH CONSEQUENCES TO THE TECHNIQUE OF MEASUREMENTS

by

M. PESCHEL—W. MENDE
Academy of Sciences of the GDR
1119 Berlin-Adlershof, Rudower Chaussee 5, GDR

L. KÖHLER—G. ECKARDT
Technical Highschool of Karl-Marx-Stadt, Section of Automatisation
90 Karl-Marx-Stadt, Reichenhainer Str. 20, GDR

In new developments in system theory we observe the tendency to more unified system-concepts also for nonlinear systems on one hand and on the other hand a trend to more qualitative kinds of behaviour descriptions characterized by pattern recognition methods. This is consistent to the achievements in modern microelectronics offering the possibilities to realize more complicated processes of measurement within the sensors immediately at the sources of measurement data.
In the paper two approaches are described taking into account these tendencies: the concept of describing nonlinear behaviour by Volterra equations and the hardware-orientated concept of adaptive measurements transformer.

Integrated measurements, Volterra equations, pattern recognition

INTRODUCTION

We are reflecting real world phenomena with the help of system theory. In history the evolution of our understanding of processes in nature with the help of physics, mechanics, chemistry, biology, ecology etc had always an important impact on developments in system theory and vice versa. As long as preferably deterministic thinking was ruling arisen from Newtons laws those parts of system theory dealing with ordinary and partial differential equations were of high importance.
Uncertainties observed in particle motions as for example Brownian motion, met in quantum mechanics and Boltzmanns laws in thermodynamics forced the development of stochastic system theory.
The necessity to observe large scale production processes forced to take into account the decision-making behaviour of people, this opened the path for artificial intelligence in system theory.

But without a sufficient and reliable measurement technique system theory is completely useless, is then only another branch of natural philosophy. We need sensors for all important variables within our models for the description of real phenomena. The criterion of truth is practice, our models must be linked by sensors with real systems.
That means, there is a dependency of system theory on the possibilities of measurements.
Reversely the possibilities of measurements are always depending on the state of evolutions in system theory. The main objective of this paper is to stress especially this point of view, to demonstrate the possible influence of system theory on measurement technique.
In practice we meet a hierarchy of levels for the penetration of real processes by system theory, which can be roughly characterized by the denominations hardware, software, brainware and orgware.
We shall point out the common role of system theory and measurements technique on the different levels of this hierarchy.
The classical role of measurement technique consisted in the design of hardware sensors for gaining primary information for single physical variables as temperature, pressure, elongation, voltage, current, velocity, acceleration etc. transforming the original physical variable into a scale variable by the hardware properties of the sensor itself.
The quality of the sensors were evaluated by objectives like accuracy, resolution, lower and upper limit frequency, and so on.
If we don't regard the dynamic transformation properties of every sensor already as a signal preprocessing property, a data processing in the real sense of words did not take place.
On the software level the primary information is transformed into a secondary information according our aims.
Here signals can be transformed into frequency representations (for example Fourier - or Walsh representation) or using different signals compound features can be computed, for example correlation functions and spectral power densities, respectively.
The spectrum of reasonable demands from measurements practice is described in more detail in /8/.
For these procedures of signal computations aids by corresponding software tools are necessary.
These tools can be situated in process control computers remote from the sensors positions, but with the help of integrated modules of microelectronics and microprocessors, respectively, it is suitable to perform these signal processing operations immediately within complex sensors. This brings a lot of advantages: the amount of transferred information can be reduced, the necessity to communicate signals with very high frequencies will be avoided.
We think that the unifying concept for nonlinear system theory using representations by Volterra equations can be very useful for this software level of information processing.

The main task of the software level of information processing is the determination of integrated or aggregated features of primary measurement signals.
They serve supervising aims of the processes or are signal or process models parameters helping to analyse the properties of the corresponding real system. Model-building itself is an activity belonging to the brain-ware level of information processing.
Every model needs a system-concept, that means a framework for our present knowledge about the system under study, knowledge from realiable theory and experiences, a framework too for hypothetic properties of the system, which we want to understand better with the help of our systemanalytic study. Today it is already possible more or less complicated models to integrate immediately into a sensor. This is then a sensor for a multivariable measurement with the model parameter vector as the corresponding measurement vector. In the present usually models of a complicated process are driven remote from the real process with distances of some hundred meters. In the automatisation of experiments physics had a pioneer role together with control engineering in the establishment of this brainware level.
We have to differentiate between two different kind of models, quantitative and qualitative models.
Quantitative models are given by deterministic relationships between the values of variables over time and in space. State-space equations of linear multivariable control systems

$$dx/dt = Ax + By$$

with y the input vector and x the state vector or Navier-Stokes equations in hydrodynamics, Maxwell equations in electrodynamics are famous examples for quantitative models.
Qualitative models are given by relations between sets.
In cases of rough resolution we don't distinguish single values of a variable from each other, but we decompose the whole feasable set, on which the given variable is defined, into a finite number of clusters (intervals for example) considering different values of the variable belonging to the same cluster as not resolvable.
This can be done with all input and output variables of a real system. The behaviour of the system can be modelled in such a case by a (static or dynamic) relation between clusters of input and output variables.
This is the famous pattern recognition approach in system theory. In the brainware level man plays more or less the role of a passive observer or supervisor of the real process, he uses his knowledge in designing the system-concept for the model and adapting the parameters of the model with the help of planned experiments.
The active role of man is well expressed on the orgware level. The orgware level is characterized by the usage of linked technical devices, by computer networks and the access to data-bases.
The automatisation of measurements on the orgware level must continuously update the content of data-bases, aggregated

information must be exposed to the operators, control actions must be automatically applied or sequences of control actions are proposed to the decision-makers.
On the orgware level in high degree mental properties of men are to be substituted by intelligent programs.
The newest results of artificial intelligence in all directions as for example in classification, automatisized diagnosis, problem-solving, question-answering, image-processing are on the orgware level introduced in large-scale automatisized systems and there must be a very efficient communication between the operators and decision-makers and the intelligence already installed in the system.
For the measurement techniques on the orgware level the compatibility with digital signal communication and digital computation is very important. Digital properties are to be introduced into the sensors to synchronize their work with the work of the whole system.
The considerations of this paper shall be concentrated on the consequences of system theory on measurement technique up to the brain-ware level.
Basic for the understanding of measurement technique is the thesis: 'EVERY MEASUREMENT IS ESTIMATION'
There is always a difference between the real value of a variable and the value recognized by a measurement, the measured value is only a model of the real value.
Fluctuations in the real system or from the measuring process, dynamic properties of the sensor, restriction of the sensor hardware and other influences hinder us to identify the real value. We use different approaches to fight with all these disturbances. We perform nonlinear scaling corrections, compensation of the dynamic properties of a sensor, repetition of measurement to smooth out purely stochastic variations etc.

All these measures are nothing else as a seeking process for the real value of the measured variable, in which we make use of all informations at hand and all our strategic possibilities on the base of our knowledge of the properties of the source and the sensor.
This situation is quite similar to what we meet in statistics, where we try to filter out stochastic variations only on the base of our knowledge of the probability distribution law.
In this sense every measurement process is an estimation process.

NEW DEVELOPMENTS IN SYSTEM THEORY

The concept of rate-coupled systems and Volterra equations

The concept of Taylor expansion is very famous in system theory. It is based on the usual assumption, that 'the degree of change of a dependent variable x is proportional to the degree of change of the independent variable y'

$$\Delta x = K \Delta y$$

If x and y are in the relationship $x = f(y)$, then obviously $K = df(y)/dy$. We are mostly interested in time-dependent processes, therefore in our considerations the independent variable y shall always be the time t.
In this case our axiom leads to

$$dx/dt = K$$

In the simplest case this describes a uniform motion in Newton sense.
But in real life we very often meet quite another type of proportionality. The degree of change of a dependent variable x is proportional to the variable x itself **and** to the degree of change of the independent variable y'

$$\Delta x = K x \Delta y$$

If x and y are in the relationship $x = f(y)$, then we put

$$\ln x = \ln f(y) = g(y)$$

Then we have $K = dg(y)/dy$
For the special case of time-dependent processes we have

$$dx/dt = K x$$ (radioactive radiation, pressure decay, temperature decay)

This is a motion in the form of an exponential function.
In applications very often a global instationary motion $x = f(t)$ is substituted by a sequence of local motions in the support point t_i.
In the Taylor-concept we choose as local motions straight lines $dx/dt = K_i$, in the exponential concept we choose as local motions exponentials

$$dx/dt = x K_i$$

both as approximations to the given instationary process in a certain neighbourhood of the supporting point.
There is always a dualism between structure and function. That means, it is not enough to design only a functional model in a blackbox form.
To get a relevant picture of a real process we have always to design a model of the structure and a model of the function, both models in mutual dependence from each other.

Very often we meet chain structures (control, reaction kinetics, encymology etc).
After the Taylor concept chains should consist of linear modules with the equations

$$dx_i/dt = K_i + x_{i+1} \quad \text{for} \quad i = 0,1,\ldots,N$$

with the normalising initial condition

$$x_i(0) = 0$$

If $x_o(t) = x(t)$ is a given function of t, then the coefficients K_i can be uniquely determined by

$$K_i = p^i x(t)\big|_{t=0} \quad \text{with } p = d/dt$$

and the chain structure then represents the wellknown Taylor-expansion of the function x(t) up to the member N.
After the concept of Exponential chains the chain should be build up from nonlinear modules with the equations

$$dx_i/dt = K_i x_i x_{i+1} \quad \text{for } i = 0,1,\ldots,N$$

with the normalising conditions

$$x_i(0) = 1$$

If $x_o(t) = x(t)$ is a given function of t, then under general conditions it can be expanded into an Exponential chain as an alternative to Taylor expansion and the coefficients K_i of the Exponential chain can be uniquely determined by

$$K_i = p^i \; x(t) \big|_{t=0} \quad \text{with } p = \; d \ln / dt$$

Taylor-chain and Exponential chain are special cases of a general concept for structural design based on chain structures. This structural design concept is taken from experiences with complex ecological systems, but it fits very well to the hardware concepts of microelectronics as mentioned below.

We try to find a structure for a given complex dynamic and in general nonlinear system, which in a not very precise sense fulfils the following objectives.

1. The structure shall mainly consist of chains or closed cycles (hyper-cycles in the sense of P. Schuster and M. Eigen) based on a basic operator F.
2. Within a basic structure (chains or cycle) shall exist only a small number of internal feedbacks.
3. Between different basic structures (chain or cycles) shall exist only a small number of interconnections.

Governed by this general wishes we propose the following Structure Design Rules.

R 1.: On any intermediate signal x_i in the Structure Design Process we apply the basic operator F, producing thus an arithmetic expression A_i

$$F\; x_i = A_i$$

R 2.: In A_i we identify signals already known and new signals never met up to now.
We connect the signals already known by feedback links from the place of first occurrence with the arithmetic expression A_i.

R 3.: For the new signals in A_i we introduce names. There is a certain ambiguity to do this leading thus to degrees of freedom in the design process and in the consequence to different structures for a given signal or system fulfilling our general design demands. Is u such a new signal. Then we apply new our whole design concept on u trying to find a realising structure for u.

R 4.: The design process stops, if after a finite number of design steps we meet only arithmetic expressions consisting completely of signals already known. If we stop the process ourselves after some design effort, then we get an approximation of the behaviour of the given real system fulfilling our general structure imaginations.

If we choose as basic operator F = d/dt, the ordinary differentiation, then we get structures with chains based on Taylor-expansion, and using multiplication of signals in the arithmetic expressions besides addition and multiplication with constants (amplifiers).
If we choose as basic operator F = dln/dt, the logarithmic derivation, then we get structures with chains based on Exponential chain expansion without multiplication of signals in the arithmetic expressions.
If we introduce for the denomination of the output signals of the basic modules F the identifiers x_i then all descriptions of the behaviour of such systems are unified, we meet as a general form of description the famous Volterra equations

$$dx_i/dt = x_i(e_i - \sum_j g_{ij}x_j)$$

e_i are the ressource constants and g_{ij} are the constant interaction coefficients. If we develop a signal x(t) satisfying a nonlinear ordinary differential equation of order N into a Volterra representation with our Structur Design Principle then we meet a set of Volterra equations with order $N' \geq N$. Different equivalent Volterra representations of a given system can have different orders N', the smallest order of all equivalent Volterra representations we call the Volterra order. The Volterra order can be considered as a certain complexity measure of a given system from the point of view of rate-coupled systems.
There are equivalence transformations between different Volterra-representations of a given system, if we assume, that the systems behaviour can be realised in the positive cone $x_i \geq 0$, for all i, in the state-space of the Volterra-system.

By these equivalence transformations it can be shown, that the nonlinear system theory of Volterra representations is a generalisation of Kalmans theory of multivariable linear systems.