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Systematic and computer-assisted design of measurement systems

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Abstract

In this paper, a new approach is presented for the user guided automatised design of measurement systems. Two concepts are presented: an adapted concept for describing a measurement system and a new concept for the design of a measurement system. For the design concept, a heterarchical implementation is proposed. The applicability of our approach is illustrated with an example from practice.

Keywords: Measurement system; System design; Computer-aided design

1. Introduction

Designing a measurement system is quite a difficult task. This has (among others) the following reasons:

- The 'client' often does not have a clear view of the task of the system and of its specifications with respect to quality, physical dimensions and costs.
- The number of possible solutions in most cases is overwhelming because almost every physical phenomenon is suitable as a principle for a measurement system.
- On every level of design it has to be decided whether off the shelve components can be used, or a custom design should be carried out.
- The number of available sensors is overwhelming too. Besides, some sensors are only transducers while others consist of complete measurement systems including hard and software for signal processing, sometimes with everything on one chip.
- Evaluating the total quality of a solution requires weighing criteria on different areas, like robustness, accuracy, physical dimensions and costs.

The Measurement Laboratory has been involved with the design of several smaller and larger measurement systems [1–4]. One common problem concerning these projects was that every new design had to be carried out from scratch. This happened because circumstances between the different projects varied so widely that during a project, people could not use

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the results of previous projects in a satisfactory way. Therefore, it was decided to start a new activity, searching for methods to design measurement systems in a consistent, systematic and computer assisted way [10]. These methods are to be realizable in a (computerised) design system. Moreover, they should offer a design procedure that is:

- Faster and on demand
- Better, using optimisations based on specifications
- Cheaper, because of less experiments and less failures

This paper discusses the elements, required for a methodology for measurement system design. In the first place, a suitable measurement system concept is required, indicating which functional elements are necessary for a measurement system. Organising these elements leads to a basic structure of a measurement system. Such a concept is presented in Section 2. Based on this concept, measurement systems can be designed. In order to systemise and automatise this design, also a proper concept for the design of a measurement system is needed. This will be presented in Section 3 where also an inventory of the elements required for this concept will be made. In Section 4, the design method will be illustrated using a specific measurement problem.

2. Modelling a measurement system

2.1. Basic concept

According to Ref. [5], 'a measurement is the process of empirical, objective assignment of numbers to the attributes of objects and events in the real world, in such a way as to describe them'. These numbers only have a meaning if they can be interpreted. This requires a model of the objects and events. Thus, the above-cited definition of a measurement is in fact a definition of 'model based measurement'. In our view, modelling the world (as far as relevant) and the measurement process should be made explicit for a number of reasons:

- Modelling the world, that is the environment in which the measurands occur, specifies the nature of these measurands. Also, actuators may modulate the environment, in order to enable observation of the measurands.
- Intelligent and robust observations can be done, using as much prior knowledge as possible.
- The use of explicit models may reveal implicit assumptions, made by the designer. During a performance analysis of the measurement system, the correctness of these underlying assumptions can then be investigated.

Therefore, as happens in Ref. [2], we start with a description of the system under consideration (SUC) as a dynamical system, characterised by a set of measurands $\vec{m}$ that has to be determined. See Fig. 1. According to system theory, the time-dependent behaviour of any system can be described by:

$$x(t) = f(x(t),u(t),t)$$
$$y(t) = g(x(t),u(t),t) \tag{1}$$

where $x(t)$, $y(t)$ and $u(t)$ are the system state vector, the output vector and the input vector, respectively.

The measurands to be determined may be state variables from the state vector $x(t)$, but may also be parameters occurring in $f(.)$. They are collected in a measurand vector $\vec{m}(t)$. Some of the inputs $\{u_1^n(t), \ldots, u_N^n(t)\}$ are 'natural' in the sense that they would be there without a measurement system. However, inputs $\{u_1^a(t), \ldots, u_M^a(t)\}$ can be added as a result of the actions of some actuators $\{A_1, \ldots, A_M\}$

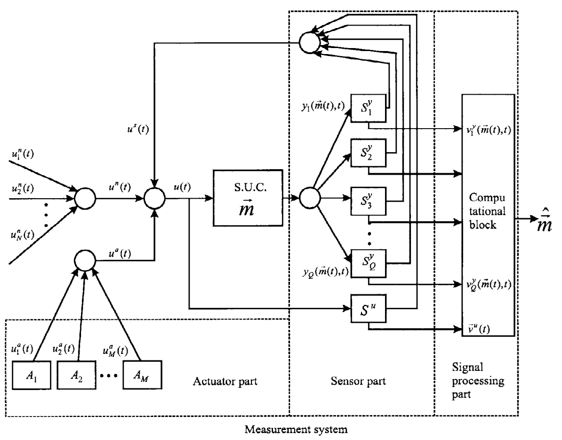

Fig. 1. Scheme of the measurement system concept in this paper.

being part of the measurement system. Thus the environment may be modulated to enable measurements. The outputs, $\{y_1(\vec{m}(t),t), \ldots, y_Q(\vec{m}(t),t)\}$, are stored using the sensors $S^y = \{S^y_1, \ldots, S^y_Q\}$ yielding a signal vector $\vec{v}^y(\vec{m}(t),t) = (v^y_1(\vec{m}(t),t), \ldots, v^y_Q(\vec{m}(t),t))^T$. Also the input is determined by a number of sensors collected in S^u, yielding a signal vector $\vec{v}^u(t)$. The signals $(\vec{v}^u(t),\vec{v}^y(\vec{m}(t),t))^T$ are combined in $\vec{v}(\vec{m}(t),t)$ containing all measurement values. Finally, the sensors may feed back energy to the SUC In most cases such interaction is undesirable, but it cannot always be prevented. It is represented by an additional input term $u^s(t)$, added to the input of the SUC

The signal-processing block estimates the measurands $\vec{m}(t)$ from the signals $\vec{v}(\vec{m}(t),t)$.

2.1.1. Discussion

A clear distinction has been made between the system under consideration to be observed and the measurement system that should carry out the observation. It offers the opportunity to use actuators to evoke responses from the system. No one to one relation is foreseen between a measurand and a specific sensor. There is only a general relation between a set of parameters and a set of signals, allowing a free form of sensor fusion. The only requirement is that the parameters $\vec{m}(t)$ are observable from the measurements $\vec{v}(\vec{m}(t),t)$. In this approach we agree with Ref. [2]. In system theory observability is a well-known concept [7].

The scheme may be implemented in a hierarchical way. The sensors and actuators can be modelled as dynamical systems themselves. As an example, a sensor can be modelled as a state system with an input and an output. An additional actuator may be used to evoke a response from this sensor, which leads to the concept of the modulated sensor [12]. As a consequence of this hierarchical view, the SUC together with the measurement system can be regarded as one dynamical system, for which a model is required. Below a framework is proposed to enable this modelling task in an efficient way.

2.2. Dynamic system modelling

Dynamic system theory [9] systematises the description of systems in various domains (electromagnetic, optical, mechanical, thermodynamic etc.). Specifically, power and energy flows are considered. In terms of these concepts the above-mentioned domains can be described quite analogously, obtaining generic models. Therefore, several elements are defined that model the various parts of a system. We have (among others):

- Energy sources, that deliver energy to the system
- One-ports defining a relation between an effort and a flow variable
- Multi-ports defining relations between several effort and flow variables, allowing the transformation of energy from one domain to another

These elements can be connected modelling the exchange of power and energy. A graphical representation of such a system is called a bond graph. The schematics in this paper are kept somewhat simpler to keep the reader from feeling uneasy with the bond graph views. The arrows in a scheme indicate the positive direction of the power flow.

The power in an element can by definition be written as the product of an effort and a flow variable. Typical effort variables are voltage and mechanical force. The flow variables being power conjugated to these efforts are, respectively, current and speed. The product of effort and flow gives a power quantity:

$$P = e \cdot f \tag{2}$$

As indicated in Ref. [6], if the effort or the flow can be neglected, then there is no power transport. The non-neglectable variable only transports information and can be considered to be a signal.

One-ports come in three flavours: *C*-type (capacitance), *I*-type (inertia) and *R*-type (resistance). For the *C*-type element the constitutive relation is:

$$\begin{aligned} e &= e(q) = e\left(\int f\,\mathrm{d}t\right) \quad \text{(general case)} \\ &= \frac{q}{C} = \frac{1}{C}\int f\,\mathrm{d}t \quad \text{(linear case)} \end{aligned} \tag{3}$$

where C is the capacitance and q is the generalised displacement, which is the integral over the flow variable f.

Eq. (3) should be understood as to contain an initial condition, still to be determined. Differentiating Eq. (3), linear case, with respect to time we obtain:

$$f = C\,\frac{\mathrm{d}e}{\mathrm{d}t} \tag{4}$$

Thus a linear C-type buffer implements a first order differential equation in one dimension. In the same way the constitutive relation for an I-type buffer is:

$$\begin{aligned} f &= f(p) = f\left(\int e\,\mathrm{d}t\right) \quad \text{(general case)} \\ &= \frac{p}{I} = \frac{1}{I}\int e\,\mathrm{d}t \quad \text{(linear case)} \end{aligned} \tag{5}$$

with I the inertia of the port and p the generalised momentum, which is the integral over the effort variable.

To conclude, for the R-type one-port we have:

$$\begin{aligned} e &= e(f) \quad \text{(general case)} \\ &= fR \quad \text{(linear case)} \end{aligned} \tag{6}$$

with R the resistance.

Note that these one-port elements have a realisation in almost all domains.[1] To give an example, while a capacitance in the electrical domain is realised with a capacitor, in the mechanical domain it is realised with a spring.

A two-port defines two relations between two pairs of efforts and flows. For a C-type two-port we have:

$$\vec{e} = \vec{e}(\vec{q}) \tag{7}$$

with:

$$\vec{e} = \begin{pmatrix} e_1 \\ e_2 \end{pmatrix}, \ \vec{q} = \begin{pmatrix} q_1 \\ q_2 \end{pmatrix} = \begin{pmatrix} \int f_1\,\mathrm{d}t \\ \int f_2\,\mathrm{d}t \end{pmatrix} \tag{8}$$

Often the relations between the original effort and flow variables are non-linear. To analyse the behaviour of the system variables, a linearisation around a working point can then be necessary. For a C-type two-port we obtain in the linear (or the linearised) case:

$$\vec{e} = C^{-1}\vec{q} = C^{-1}\int \vec{f}\,\mathrm{d}t \tag{9}$$

with C the capacity matrix.

Two-ports with linear relations between efforts and flows are the transformer with:

$$\begin{aligned} e_1 &= n \cdot e_2 \\ f_2 &= n \cdot f_1 \end{aligned} \tag{10}$$

and the gyrator with:

$$\begin{aligned} e_1 &= g \cdot f_2 \\ e_2 &= g \cdot f_1 \end{aligned} \tag{11}$$

A source is a one-port, having a special constitutive relation. An effort source has a fixed effort, while the flow is left free (which means that the flow depends on the other elements in the model). A flow source has a fixed flow, while the effort is left free. A source is modulated if the fixed quantity produced by the source is influenced by an external signal.

Junctions (Fig. 2) are three-ports connecting three elements like buffers and energy sources. There are two types. In the case of a 0-type junction, the efforts at all the ports are equal, while all the flows add to zero (including the sign). In the case of a 1-type junction it is just the other way around.

2.2.1. Discussion

Dynamic system theory models the physical world according to general concepts that occur in every domain. Its merit is that a vast number of physical systems can be modelled, based on only a small number of basic elements that can be implemented easily in a computer system. Two-port elements offer the opportunity to couple physical systems in different domains. The result of an analysis according to the elements in this section can be expressed in a state space model, consisting of a set of differential equations. Thus, a system description according to

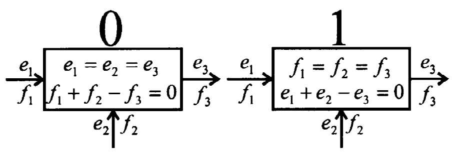

Fig. 2. Zero-type (left) and one-type junction (right). The arrows indicate the positive direction of the power flow.

[1] In the material and thermodynamic domain no generalized momentum can be defined.

Eq. (1) can be obtained, which can be investigated with respect to observability of the states and parameters.

Two limitations should be mentioned. The approach described here only yields model descriptions with lumped parameters and state variables. Models of systems governed by parameters or state variables that spatially vary in a continuous way, are therefore only approximately correct. A more accurate final model may be necessary for these systems. Also, two-ports are often non-linear in the transformation variables. This may necessitate a linearisation in order to analyse their behaviour during simulations.

3. A concept for measurement system design

3.1. Background and basic concept

Design already has a long history. An inventory has been given in Ref. [13], in which four types of design are distinguished:

1. Intuitive design, in which the art of design is taught in a master apprentice situation. This type of design was (is) applied mainly in art.
2. Industrial design, in which the intuitive design is applied in creating functional useful products.
3. Engineering design, in which the design is supported by advanced tools for simulating system behaviour based on scientific knowledge. The basic attitude to design is still the know-how, contained in the minds of people and acquired through long experience.
4. Formal design, in which the design process is carried out according to a number of formal steps. These steps have been formulated after an investigation of the necessary activities during the design process. Thus the management of the design process is concerned.

This paper is about a formal design method, for which we want to present a concept. The advantages that we expect from designing products in a formal way are threefold:

- The learning curve of designers will be steeper if they can learn to design following clearly formulated fixed steps.
- The design process can be supported and parts can even be taken over by the computer. This can save much time, while resources from everywhere in the world can be used.
- As performance prediction and analysis also will be formalised, the end user will obtain a better insight into the functionality and the quality of the product.

To start with, design can be divided into two major steps. The first step is to formulate unambiguously the requirements to the product (measurement system) to be created. This step is certainly non-trivial, as end users often have only a vague impression of what their product should do. The second step is to find elements that may contribute to a solution and to assemble them to a product satisfying the requirements. This step can be regarded as a search problem that might be carried out completely by a well-equipped computer system. In practice it will be impossible to perform such an exhaustive search. It will therefore have to be guided by the designer.

Taken together, we propose a concept for the design of measurement systems, enabling human designers to design products in cooperation with a computer system. The concept is depicted in Fig. 3. The design of a measurement system will consist of the following phases:

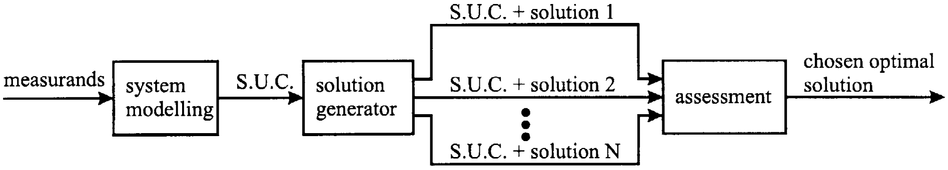

Fig. 3. Simple serial scheme of the proposed concept for designing measurement systems.

Modelling the system under consideration starts with making an inventory of the relevant measurands. In order to appreciate their meaning, these measurands should be a part of a model describing the system under consideration in which they appear. This may compel the designer to reconsider his statements about what has to be measured. Thus, an explicit model gives a clear meaning to the measurands and it offers a clue to a particular measurement method.

While *generating measurement solutions*, transducer models are created and connected to the SUC such that their outputs make the measurands in the SUC observable. The final outputs will be electrical signals, for instance voltages. Therefore, finding a measurement solution means: searching for one or more conversions between the physical domain of the measurand and the electrical domain.

During the *assessment of the solutions*, the solutions are rated on various aspects, like accuracy, robustness and costs. Based on this assessment, the best solution is chosen and carried out. As many different criteria will be used, optimisation in this multidimensional space is not a trivial process.

3.2. Levels of abstraction

The design of a product always passes different levels of abstraction. First, a general design is made on a high abstraction level. The elements are described into more detail at a lower abstraction level. The reason for this hierarchy is the desire to keep the search process as simple and short as possible. Considering the SUC and the measurement system we distinguish the following levels:

The *generic level* is the dynamic system level discussed in Section 2.2. The models are mathematical without physical background. The combination of the SUC and the measurement system will be modelled at this level first. The models consist of a chain of sub-models connected by two-ports, which define an energy conversion.

At the *energy level*, the physical domains of the different parts of the generic model with their energy types are selected. If these domains have been chosen, also the energy conversions of the two-ports are known. It can then be investigated if these conversions are physically realisable.

At the *physical level*, explicit physical parts are selected to implement the elements of the generic level. These include the two-ports defining the energy conversions. Thus, the transducer principles are determined.

At the *hardware level*, the physical models are converted into components that can be bought or made in the shop.

3.3. Heterarchical implementation

The design concept in Section 3.1 has to be implemented using the four levels of Section 3.2. At each level, solutions will have to be sought. This could lead to a combinatorial explosion, which can only be prevented by cutting the search tree as often and as early as possible. Therefore, at all moments, an assessment of solutions should be possible, so that some solutions can be accepted for further investigation, while others can be rejected or put on a reserve-list. The most flexible architecture seems to be a multilevel description of the SUC, built on a blackboard, together with a number of measurement solutions. Agents, a modelling agent, a solution-generating agent and an assessment agent, can add to this description at any moment. Also a human operator may act as an agent to guide the design process. This blackboard architecture is also used in Ref. [8]. A scheme of this concept is shown in Fig. 4.

Measurement solutions are searched in two steps.

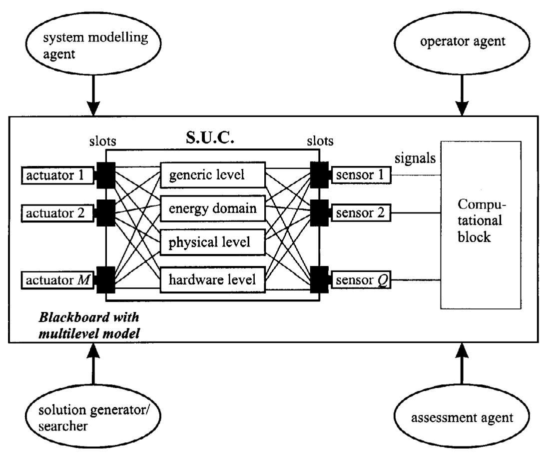

Fig. 4. Heterarchical implementation in a blackboard architecture. Note that the sensors and actuators are to be modelled according to the same hierarchical framework as the SUC.

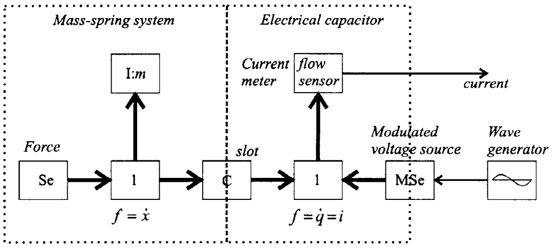

Fig. 5. Creating a slot and connecting a sensor to it.

First, slots are created in the SUC, representing places where sensors or actuators can be connected to the SUC. Then sensors and actuators are actually put into these slots. This generation process will first start at the generic level. Consider a mass-spring system, actuated by a force. The bond graph scheme is sketched in the left part of Fig. 5 ('Mass-spring system'). Slots can be created, by:

- Replacing the C-port by a two-port
- Replacing the I-port by a two-port
- Adding a connection to the one-type junction with a new element

The first possibility is worked out in Fig. 5. To the C-type two-port representing the slot, a bond graph is connected representing an electrical capacitor with an AC voltage source and a current meter.

Thus the two-port should connect the mechanical spring with an electrical capacitance. Whether this is possible will depend on the type of spring used. This is described in the underlying physical model of the SUC. From this example it can also be observed that a transducer is itself a system, to be modelled according to the same hierarchy as the SUC. Thus, modulating transducers can be modelled in a similar way.

A real world measurement problem with its solution is described in Section 4.

4. An example: modelling a wind velocity sensor

4.1. Introduction

In this section, a case of a real world measurement is discussed. The problem has also been solved in a conventional way. In Section 4.2, the original design is described. In Section 4.3, it will be discussed how this result could have been obtained using the method of this paper. Also the generation of an alternative will be considered. We will restrict ourselves to the three upper levels of abstraction. The physical realisation will not be considered in this paper. Neither an explicit assessment of the solutions will be given.

The case has been taken from a project, concerning the development of a wind velocity measurement set-up [1]. The requirements to the sensor were the following:

- The sensor should be connected to the Smartec universal transducer interface (UTI) [11], which interfaces a variety of capacitive sensors
- No moving parts are allowed
- The measurands are wind speed and direction
- It should be low cost

Currently the problem has been partially solved by the realisation of a capacitive force sensor, which will have to measure the forces exerted by the wind on a spherical object placed on a stand.

4.2. The design

Fig. 6 sketches the design of the velocity measurement set-up. Two circular plates are rigidly connected to each other at the boundaries. The stand with the sphere will cause a deflection of the upper

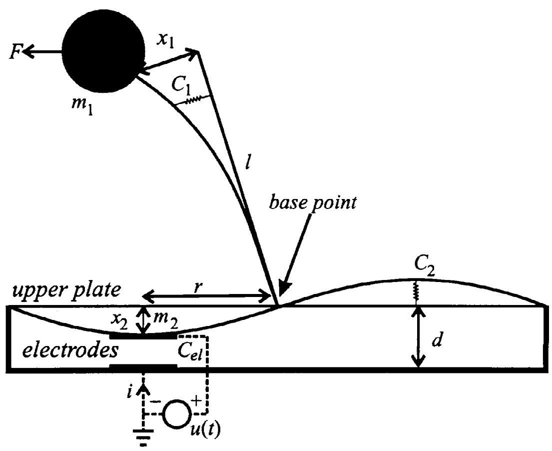

Fig. 6. Sketch of the measurement set-up.

plate, which causes a change of the capacitance constituted by the plates.

The motion of the stand consists of a rotation around its base point (point of connection with the upper plate) and by a deflection, according to a spring constant C_1. It is assumed that the mass of the stand can be neglected or is concentrated near the spherical object. Also the mass of the upper plate is assumed to be concentrated near the electrodes. In both cases a 'lumped parameter' model is obtained. The force by the wind on the sphere causing the deflection is modelled to be:

$$F_w(t) = Bv^2(t) \tag{12}$$

where B is a parameter depending on the size of the sphere.

The displacement of the upper plate consists of a deflection, according to a spring constant C_2, resulting in a wavelike deformation. The connection of the stand to the upper plate is assumed to be stiff. Both the upper and the lower plate contain electrodes constituting an electrical capacitance. It is measured using current measurements corresponding to voltages from a voltage source.

The equations of motion of the plates can be shown to satisfy (for the symbols see Fig. 6):

$$m_1 \frac{d^2x_1(t)}{dt^2} + C_1\left(x_1(t) - \frac{l}{r}x_2(t)\right) - F_w(t) = 0 \tag{13}$$

$$m_2 \frac{d^2x_2(t)}{dt^2} - C_2x_2(t) + C_1\left(x_1(t) - \frac{l}{r}x_2(t)\right)\frac{r}{l} + F_{el}(t) = 0 \tag{14}$$

$$\frac{q(t)(d - x_2(t))}{\epsilon A} - u(t) = 0 \tag{15}$$

where $q(t)$ is the charge on the plates and:

$$F_{el}(t) = \frac{q^2(t)}{2\epsilon A} \tag{16}$$

is the electrical force on the upper electrode arising from the voltage across the capacitor

To be able to compute the wind velocity it is assumed that the voltage $u(t)$ varies quickly, compared with the wind velocity variations. Also no energy feed back from the electrical to the mechanical subsystem is assumed. In that case $x_2(t)$ will vary only slowly compared with $q(t)$ (quasi-static approximation). From Eq. (15) we obtain:

$$\frac{d - x_2}{\epsilon A} q(t) - u(t) = 0 \tag{17}$$

where x_2 is taken to be a constant with respect to $q(t)$.

Taking the Laplace transform of (17) we get:

$$\frac{\hat{q}(s)}{\hat{u}(s)} = C_{el} \tag{18}$$

or:

$$\frac{\hat{i}(s)}{\hat{u}(s)} = Y(s) = sC_{el} \tag{19}$$

where:

$$C_{el} = \frac{\epsilon A}{d - x_2} \tag{20}$$

and $\hat{i}(s)$ and $\hat{u}(s)$ are the Laplace transforms of the current $i(t)$ and the voltage $u(t)$, respectively.

Thus, $x_2$can be computed from impedance/admittance measurements (Eq. (19)). The result can then be used as an input $x_2(t)$ to solve Eq. (14) for $x_1(t)$ and finally Eq. (13) for the force by the wind $F(t)$. This is the 'classical' method followed in Ref. [1].[2] The bond graph of this design is sketched in Fig. 7.

4.3. The design according to the new approach

In the previous paragraph, a wind velocity meter has been presented, designed in a classical way by an inspired designer. In this paragraph the design of the wind velocity meter is redone using the formal approach of Section 3. The environment consists of an air mass moving with a certain velocity $\vec{v}$. As no specific circumstances are specified, there is no explicit model describing the behaviour of the air. At the generic level, the air is therefore described as a flow source producing a velocity $\vec{v}$ according to Eq. (12). The only option for a measurement is to add a connection and an element. A gyrator is chosen, transforming the velocity to an effort (Fig. 8). Now, on the energy level, a domain should be chosen. In

[2]In Ref. [1] four electrodes are used to measure components of the wind velocity. This will not be worked here.

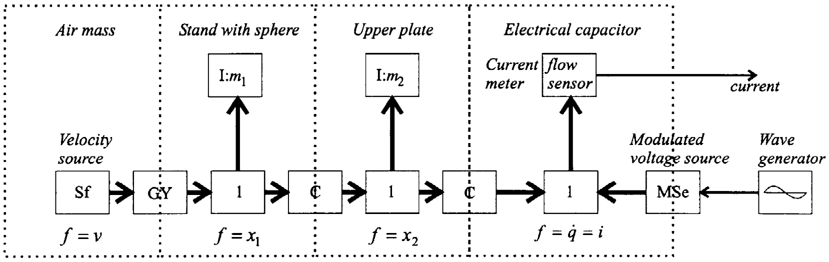

Fig. 7. Final design of the wind velocity meter.

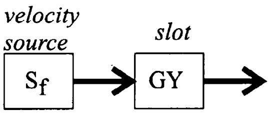

Fig. 8. Environment, consisting of a flow source with slot.

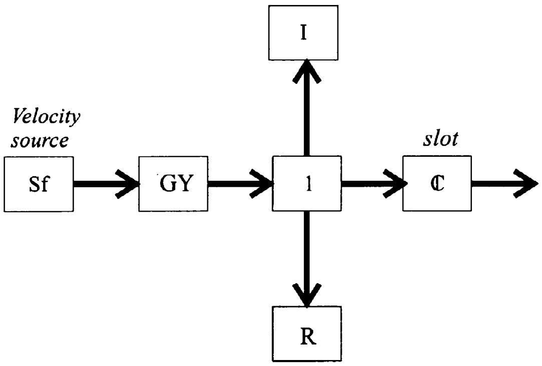

Fig. 9. Extension of the generic model.

the electrical domain, the effort is a voltage. As we do not know a direct conversion from velocity to voltage, this seems not an option. An option is to choose the mechanical domain. Then the gyrator converts the velocity to a force.

The effort may drive a system, consisting of an inertia, a generalised capacity and a resistance. In this system replacing the capacity with a capacity two-port again creates a slot. The result is seen in Fig. 9. The right side of the capacity two-port can be incorporated in a new system, containing an inertia, a capacity and a resistance, together with an effort source. Again considering the energy domain, it can be observed that indeed a capacity two-port exists, containing a mechanical and an electrical port. This is an electrical capacitor with variable plate distance. Thus, the new system can be an electrical system.

The first provisional design of the wind velocity meter is shown in Fig. 10. In this model the mechanical system consists of two plates connected with a certain stiffness, described with a spring constant. The force directly works on one of the capacitor plates. It may be expected that the capacity change from the wind velocity will be very low. Therefore the mechanical system is split up into two systems, allowing an object to catch the wind. Also, this allows working with torques so that the forces may be amplified. Thus the final design of the

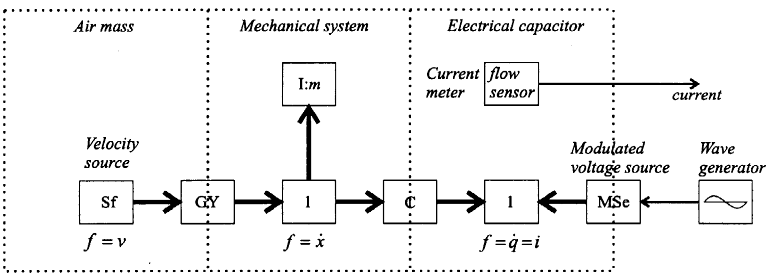

Fig. 10. First provisional design of a velocity flow meter. A friction element, a resistance and an inductance have been left out, being non-essential.

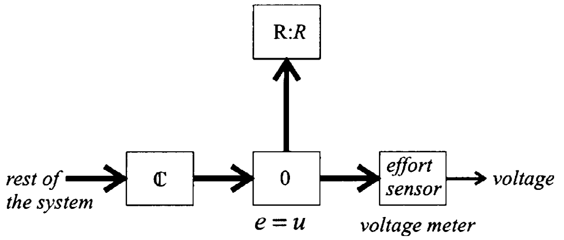

Fig. 11. Generic model of an alternative measurement principle.

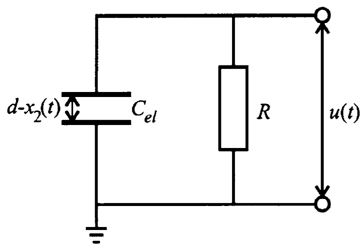

Fig. 12. Alternative measurement circuit.

system described in Section 4.2 is obtained as sketched in Fig. 7.

4.4. An alternative

As an illustration of the possibility to generate several measurement solutions, an alternative is generated by replacing the electrical part in Fig. 10 by the bond graph scheme of Fig. 11. It is realised by the electrical scheme of Fig. 12, in which a resistance is placed in parallel to the capacitor and the voltage across both is measured. Eq. (15) transforms to:

$$R\frac{\mathrm{d}q(t)}{\mathrm{d}t}+\frac{q(t)(d-x_2(t))}{\epsilon A}=0 \qquad (21)$$

Without the voltage source, $u(t)$ is now taken to be the voltage across the resistance and the capacitor. Eliminating $q(t)$ in Eq. (21) for $u(t)$ we have:

$$u(t)+R\frac{\epsilon A}{d-x_2(t)}\frac{\mathrm{d}u(t)}{\mathrm{d}t}=0 \qquad (22)$$

From the measurements $u(t)$, $x_2(t)$ can be computed according to:

$$x_2(t)=d+\frac{\epsilon AR}{u(t)}\frac{\mathrm{d}u(t)}{\mathrm{d}t} \qquad (23)$$

Note that in order to determine $x_2(t)$, $u(t)$ must be unequal zero. Thus, a bias voltage across the plates is required, corresponding to a bias charge on the plates.

4.4.1. Discussion

Our final objective is to obtain computer programs, generating the design of a measurement system during an interactive process with a user, guided by certain constraints. A first small step to attain this goal has been made in Section 4 with a description of the design of a measurement system, carried out following a number of formal rules. We demonstrated how measurement solutions can be generated, using available options. The benefit from this approach, implemented in a real computer program will be that the computer can suggest many measurement solutions and that these solutions can be assessed, so that the best one can be chosen. Thus, with a systematic approach a better solution might be obtained than without such an approach.

In our opinion it will be possible to create an information system, containing knowledge about measurement solutions and about available hardware. The big challenge will be the management of the search for measurement solutions, to be guided by the user and by constraints, obtained from specifications.

To implement the approach of this paper in a computer system, a large number of questions will have to be answered. Without being exhaustive we mention the following:

In order to obtain the final measurement solution, it is not enough to formulate the forward model. Also a model inversion is required, yielding the measurands as a function of the measured quantities. In Section 4, the assumption that the plate distance would vary only slowly, was necessary to find Eq. (17). This expression relates the plate distance to the current measurements and from there the wind velocity is found using Eqs. (14) and (13). This example shows that obtaining a measurement principle from the physical model may not be trivial.

The generic models only contain ‘lumped’ parameters. Lumped parameters only approximate continuously varying variables. Therefore, real systems can only be modelled in an approximate way.

The distinction between designing and selecting a sensor is not sharp. Designing here means assembling a system form smaller subsystems. Selecting means to find a sensor (system) as a whole from a database. Often a choice has to be made between choosing an off the shelve sensor and making a custom design.

Sensors, being the basis of a measurement solution must be specified unambiguously and sensor suppliers should adhere to standards concerning these specifications. Setting up such specification schemes is subject for further research.

5. Conclusions

This paper presents a new approach for the interactive computer assisted design of a measurement system. It has the following features:

- The user carries out the design in an interactive process with a computer design system.
- The user has to explicitly define his measurement problem in terms of a description of the system to be measured at and the measurands that appear.
- During a user guided search process, the computer generates a set of measurement solutions and performs an assessment of their quality, based on user-defined criteria. Thus an order is defined between the solutions, enabling the user to do a soundly based choice.

As a basis for this approach, two concepts are presented.

A measurement concept from the literature is extended, modelling the interaction between the system under consideration and the measurement system. It allows sensor fusion and the use of dedicated actuators to evoke a response from the system. The solution of the measurement problem is defined as the situation when all measurands are observable.

Next a concept for the design of a measurement system is presented, in which two hierarchies are defined:

1. A hierarchy containing the different processes to be completed during the design
2. A hierarchy containing the different levels of description of the SUC together with the measurement system.

A heterarchical implementation is proposed, allowing maximum freedom during the search for solutions. This freedom is necessary to guide the direction of this search in an efficient way.

Our approach is illustrated with a real world measurement problem that originally was solved in a conventional way. It has been demonstrated that this solution could have been obtained using the formalism of our approach and that alternatives can be generated so that a choice between them is possible.

Although only part of the design process could be illustrated in this paper, we have shown that our approach is realistic. Also, we have demonstrated that automation of the design process can be based on such an approach. To conclude, we believe that this automation will be necessary in order to satisfy the ever-increasing demands for dedicated high quality measurement systems.

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