Measurement concepts: from classical transducers to new MEMS

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Abstract

In this paper a formalization of the measurement concept (mc) is presented. Based on this formalization, a classical measurement concept (cmc) supported by classical transducers is derived. Restrictions and inconveniences of the cmc are exposed when the evaluation of more characteristics is concerned (the so-called multi-measurement process). Using a new measurement concept (nmc) developed in this work, the main drawbacks of the cmc can be removed. The core of the nmc is an actuator–sensor structure. Some basic principles regarding the design of this new structure as a MicroElectroMechanical System (MEMS) are also mentioned. Developing a state-space representation of the classical transducer and the new structure, the practical implementations of both concepts are compared and the superiority of the nmc is proven. Finally, the nmc is illustrated with an example concerning the determination of fluid and flow parameters using MEMS.

Keywords: Measurement concept; Transducer; Actuator–sensor structure; MEMS

1. Introduction

From the early civilization of human being, measurement and instrumentation have played an important role in natural science, industry, commerce, defence, health, safety, protection of environment, etc. Measurement science has undoubtedly evolved from the origin of mankind, and there is no reason to assume this evolution has come to an end.

The last two decades showed important progress in the development of measurement science. In this framework, some key subjects are: intelligent measurement systems [3], formal metrological concepts [4], semantic aspects of the measurement [5], quality of the measurement and measuring systems [6], and processorless smart sensors [7].

In all the application fields of measurement there is an increasing demand for improvement and advance. In natural sciences modern investigations demand ever more sensitive, accurate and fast measurements and provide a widening spectrum of physical and chemical measurands. Human systems become ever more complex, and rational approaches to this complexity call for better understanding of the foundational concepts of measurement. In all industrial and scientific activities the demand for higher quality of products, for cost effectiveness and the overcoming of the deficiencies of human
operators, calls for better measurement and instrumentation. To meet these demands, modern technology provides increasing opportunities for enhancement of the capabilities of instrumentation [8].

Therefore, not only from a theoretical but also from a technological point of view, measurement science still experiences substantial progress. At present, microelectronics is the major driving force for most advances in the field.

**MicroElectroMechanical Systems** (MEMS) are electro-mechanical devices manufactured using the same techniques developed for the manufacturing of integrated circuits. Although most MEMS today are fabricated on silicon wafers which makes them relatively simple to integrate with silicon-based control electronics, MEMS are not limited to these materials [9].

Even though products manufactured using MEMS have already been successfully established on the market, the field as a whole is still in a state of ‘emergence’, at the transition to ‘growth’ and far from ‘ripeness’, as shown in [10].

W.S. Trimmer, the first Editor-in-Chief of the Journal of Microelectromechanical Systems, in an overview on MEMS, showed that ‘science and metrology of small devices should be developed’. A. Umeda of the National Research Laboratory Metrology in Japan aptly stated the need for uniform and well-defined ways to measure micro phenomena, namely “if there is no measurement standard – it is speculation” [11].

Therefore, there is still a considerable time gap between new technological achievements and measurement science in the domain of MEMS. This is a fundamental problem for the present, especially in the cases where the evaluation of more characteristics is concerned. By presenting a new measurement concept (nmc) applicable for MEMS, this paper intends to bridge this gap.

To reach this target, the authors follow the lines mentioned briefly hereafter. The paper begins with a formal description of the measurement concept (mc), defining its main elements. It is exemplified with an application from the area of fluid mechanics. Next, the typical implementation of this concept, using classical transducers, is described. The restrictions and limitations of this concept designated as the classical measurement concept (cmc), are exposed.

From this perspective, a nmc is introduced, and a comparison with thecmc is given. This new concept is illustrated with an implementation using MEMS, namely with an application for determination of fluid and flow parameters. The paper concludes with some other important items for future research on the nmc and its implementation for MEMS.

### 2. Measurement concept

In this section we present a formal description of a general measurement concept. To get acquainted with the formal definitions and notations given next, we start with a simple example: the measurement of some fluid and flow properties. It is organised as a bridge between the non-formal and formal description.

The measurement object under consideration is a fluid in laminar flow through a pipe. The operator likes to determine its velocity and thermal diffusivity, so he likes to get two numbers associated with two specific measurement units. These two numbers are essential pieces of information for the operator in exploring the measurement object.

To achieve this objective, the operator should perform two activities: first, he has to define the measurement object as a distinctive part of the environment and secondly the measurement process as consisting of the actions for getting those two numbers should be outlined.

We start by defining the fluid in a laminar flow as a measurement object.

The fluid and its flow are characterised by a number of characteristic properties, such as the physical and chemical characteristics of the fluid, the flow velocity and the geometry of the pipe. This set of properties, that uniquely defines the fluid and flow under consideration and in relation with the environment, is formally denoted as a feature (feat). In consequence, a feature consists of one or more characteristic properties, formally denoted as characteristics (denoted as char). Surely, the operator defines the feature in a way as to characterize the measurement object at the present situation.

In a dynamic situation, the measurement object may change, and so may the composition of the feature. As a consequence, time should be included
in the formal description. Concerning our example, over time, the composition of the feature defining the fluid in a laminar flow may change as follows.

Starting the measurement at a time \( t_1 \), the operator notices intuitively the characteristic properties as mentioned before. It means that at \( t_1 \), the feature is built up from the physical and chemical characteristics of the fluid, the flow velocity and the geometry of the pipe: \( \text{feat}_1 \). This situation may last for a period of time starting from \( t_1 \).

At a time \( t_2 \), the fluid may change its general appearance or behaviour, for instance by an increase in its temperature due to an actuator placed inside or outside the pipe. Therefore, the same fluid has got an additional \( \text{char} \) (namely the temperature) that must be added to the previous set for building up a new feature: \( \text{feat}_2 \). Although it is still considered to be the same fluid in a laminar flow, the operator is obliged to define a different feature because he notices a major change in the behaviour of the fluid from time \( t_1 \).

It is mentioned that both velocity and thermal diffusivity (as a physical characteristic of the fluid) are included in \( \text{feat}_2 \) as well as in \( \text{feat}_1 \).

The dynamic behaviour of the measurement object can be considered as a mapping from the time moments to the pairs (time moment, feature). This mapping is formally denoted as \( \text{thing} \). Therefore, by defining \( \text{thing} \), a formal description of the measurement object is obtained.

Next, we define the second activity to be performed by the operator for getting the two numbers associated with two specific measurement units as numerical representations of the velocity and the thermal diffusivity.

A measurement action comprises the assignment of a number associated with a measurement unit, formally denoted as \( \text{dimensional number (dino)} \), to a certain \( \text{char} \) at a certain time moment. These are, in our example, the velocity and thermal diffusivity, expressed in numbers with units \( \text{m s}^{-1} \) and \( \text{m}^2 \text{s}^{-1} \), respectively.

A measurement process is built up basically from many measurement actions, namely from all assignments of a certain \( \text{dino} \) to each \( \text{char} \) from every \( \text{feat} \) in accordance with the time moment. Therefore, the result of a measurement process is a set of dimensional numbers, denoted as \( \text{symbol (symb)} \), assigned to the particular \( \text{feat} \) and time moment under consideration.

This mapping for defining the measurement process, namely from the pairs (time moment, feature) to the symbols is formally denoted as the \( \text{attribution mapping (attr)} \). Therefore, the definition of \( \text{attr} \) mapping synthesises the formal description of the action done by the operator who is evaluating the velocity and thermal diffusivity of the fluid.

By having defined both the measurement object and the measurement process, described, respectively, by \( \text{thing} \) and \( \text{attr} \) mapping, the operator has described globally the \( \text{measurement} \) he is aiming at. It is synthesised by the compound mapping between \( \text{attr} \) and \( \text{thing} \), formally denoted as \( \text{measurement mapping (meas)} \). This mapping, describing the operator’s target, assigns a set of dimensional numbers to each time moment under consideration. Concerning our example, \( \text{meas} \) mapping assigns a numerical value expressed in \( \text{m s}^{-1} \) for the fluid velocity and another numerical value expressed in \( \text{m}^2 \text{s}^{-1} \) for the thermal diffusivity of the fluid, corresponding to each time moment considered by the operator.

The formal description of the measurement concept is developed next, following the milestones presented above. The outline of this development is shown in Fig. 1.

2.1. Formal description

Measurement is currently conceptualized and formalized in terms of the so-called representational model. In this framework, for describing objects of the real world, two symbolizations have been considered. One of them is the numerical measurement (generally obtained by electronic processing) which provides an objective quantitative description of the objects, and another one is the linguistic measurement (generally obtained by interrogation of users) which provides a subjective qualitative description of the objects [12].

Using the general ideas concerning the representational model, we derive in this section an appropriate formal description of the \( \text{mc} \) for the case of the numerical measurement, underlaying the role of the transducer and its implications as well as its restrictions in the measurement.
The starting point of this description is the following definition from [13]: “Measurement is an empirical operational procedure of assignment of numbers to members of some class of aspects of characteristics of the empirical world according to a well defined rule.” In a similar manner, the term measurement is defined in [14], as the assignment of numbers or other symbols, by an objective, (or) empirical process, to attributes of objects or events of the real world, in such a way as to describe them.

The motivation for developing a formal description of the measurement concept presented herein is Finkelstein’s affirmation from [15] that “measurement is a special case of representation by symbols in which a measure together with the scale of measurement, represents information about measurand”. Some ideas presented already in [1,16] are used as a general framework for this development.

As outlined before referring to Fig. 1, an entity as an object, a process, or an event is characterised at any time by the fact that it owns a certain feature, i.e. while keeping its own individuality during time, it can continuously change something of its appearance and behaviour. Such an entity, denoted here as thing, is formalized as a vectorial mapping of a time set \( \text{T} \) to the Cartesian product of \( \text{T} \) and the power set of a feature set \( \text{FEAT} \) denoted as \( \mathcal{P}_{\text{FEAT}} \).
Because it is frequently used next, we remind that the set of all subsets of a given set $U$ is called the power set of $U$ and is written $\mathcal{P}_U$ [17].

Therefore, $\text{thing: } \text{TIME} \rightarrow \text{TIME} \times \mathcal{P}_{\text{FEAT}}$, so that the pair $(t, \text{feat}) = \text{thing}(t)$ symbolises the feature of $\text{thing}$ at time $t \in \text{TIME}$. The entity $\text{feat} \subseteq \text{FEAT}$ is a subset of the $\text{FEAT}$ set that contains all necessary and sufficient elements of $\text{FEAT}$ for the individualisation of the value corresponding to the given mapping $\text{thing}$ at time $t$. These elements are considered as the characteristics of the feature and are denoted as $\text{char}$. The union of all characteristics corresponding to $\text{thing}$ over the $\text{TIME}$ set builds up the $\text{FEAT}$ set. Therefore, the pairs composed of a time moment and a feature express then the ‘time versions’ of $\text{thing}$. The union of all these pairs corresponding to $\text{thing}$ is the range of $\text{thing}$ denoted as $\mathcal{R}_{\text{thing}}$. Obviously, $\mathcal{R}_{\text{thing}} \subseteq T \times \mathcal{P}_{\text{FEAT}}$.

From the measurement science point of view, all (or at least some) characteristics (e.g. length, frequency, temperature, pressure) of a certain feature corresponding to $\text{thing}$ are subject to evaluation.

The ideal target of a measurement is to obtain the full knowledge of $\text{thing}$. In the case of a numerical measurement, this is equivalent with the numerical evaluation of all characteristics of all features corresponding to $\text{thing}$, at each time moment from $\text{TIME}$. This action is formalized as the vectorial attribution mapping of $\mathcal{R}_{\text{thing}}$ to the power set of a symbol set $\text{SYMB}$ denoted as $\mathcal{P}_{\text{SYMB}}$. Therefore, $\text{attr: } \mathcal{R}_{\text{thing}} \rightarrow \mathcal{P}_{\text{SYMB}}$, so that $\text{symb} = \text{attr}(t, \text{feat})$ symbolises the result of the numerical evaluation at a certain moment of a particular feature. Because each feature contains a certain number of characteristics, the result of this evaluation is a subset of a symbol set $\text{SYMB}$ that contains the evaluations of all characteristics of that feature, so that $\text{symb} \subseteq \text{SYMB}$. The evaluation of the characteristics are materialized by numbers, associated with certain measurement units. For this reason, we call them dimensional numbers, denoted as $\text{dino}$. In fact, the $\text{attr}$ mapping associates a certain $\text{symb} \in \mathcal{P}_{\text{SYMB}}$ to each $\text{feat} \in \mathcal{P}_{\text{FEAT}}$ at a certain moment $t$. Hence, the $\text{attr}$ mapping associates a certain $\text{dino} \in \text{symb}$ to a certain $\text{char} \in \text{feat}$ at each time moment $t$.

We note that the term ‘characteristic’ is used to refer to quantities in the general sense (e.g. the concept of velocity in itself), but the term ‘dimensional number’ is used to refer to quantities in the specific sense (e.g. 1.23 $\text{m s}^{-1}$).

Composing these two mappings results in $\text{attr} \circ \text{thing: } \text{TIME} \rightarrow \mathcal{P}_{\text{SYMB}}$. It symbolises that at the time $t$, the $\text{attr}$ mapping has been evaluated on $\text{thing}$, and the obtained value is $\text{symb}$, namely $\text{attr}(\text{thing}(t)) = \text{symb}$. In fact, this compound mapping is just the vectorial measurement mapping denoted as $\text{meas}$, therefore $\text{meas} = \text{attr} \circ \text{thing}$.

The establishing of the features is an intuitive action, based on the practical experience of the specialist involved in the measurement.

The particular situations presented by Fig. 1 requires some remarks.

We assume that for the same thing, each feature has at least one characteristic in common with at least one other feature, otherwise if there is one feature disjunct with all the other features, we define another thing.

The constituents of each feature are chosen so that each feature contains the necessary and enough characteristics for the individualisation of that feature.

Further, it is noticed that $\text{thing}(t_1) = (t_1, \text{feat}_a)$ and $\text{thing}(t_2) = (t_2, \text{feat}_b)$, so the feature of the analysed thing is the same at the time moments $t_1$ and $t_2$. Also, $\text{meas}(t_1) \cap \text{meas}(t_2) \neq \emptyset$, but $\text{meas}(t_1) \cap \text{meas}(t_2) = \emptyset$, which means that some identical dimensional numbers are possible to be obtained at different time moments, as might occur in the measurement.

The measurement on $\text{thing}$ at a certain time, described by $\text{meas}$ mapping, is a practical action for recovering the feature of $\text{thing}$ at that time. It means that a measurement implies evaluation of a certain feature (that consists of a set of characteristics) of $\text{thing}$. The result of this evaluation is a symbol consisting of a set of dimensional numbers.

The above formal construction is denoted as the measurement concept (mc).

### 2.2. Exemplification of the mc

A visualisation of this formal description of the mc is given in Fig. 2. Here, $\text{thing}$ consists of a fluid in laminar and incompressible flow through a pipe. We consider that at time $t_1$, the feature is uniquely determined by the following characteristics: $u$ (ve-
locity of the fluid), \( g \) (geometrical characteristics of the pipe) and \( f \) (physical and chemical characteristics of the fluid). Therefore, \((t_1, \text{feat}_a) = \text{thing}(t_1)\), where \( \text{feat}_a = \{u, g, f\}\). At another time \( t_2 \), the feature is determined by the characteristics \( u, g, f, T_f \) (temperature of the fluid) and \( T_p \) (temperature of the pipe surface), because in this situation the fluid enters the pipe at a temperature different from the temperature of the pipe surface. In this case, \((t_2, \text{feat}_b) = \text{thing}(t_2)\), where \( \text{feat}_b = \{u, g, f, T_f, T_p\}\). The evaluations of these two features are denoted by \( \text{symb}_1 \) and \( \text{symb}_2 \), respectively. The components of these two subsets are dimensional numbers, indexed relatively to the respective symbol.

As seen in this example, the characteristics defining the feature could be either space dependent or space independent. To avoid further difficulties, if a characteristic is space dependent, we consider one different characteristic for each spatial point instead of that space dependent characteristic. Therefore, each characteristic is considered as space indepen-
dent. In the previous example we can initially consider that \( u, g, T_f \) and \( T_p \) are space dependent characteristics, but \( f \) is a space independent characteristic.

Different manners for building the attribution mapping imply different practical implementations of the \( mc \). The attribution mapping is the only entity with a large freedom during the practical implementation of the \( mc \). Therefore, the development of the attribution mapping is discussed in the next section.

3. Development of the attribution mapping

The target of a measurement process is to evaluate all or part of the characteristics of a feature at a certain moment. The result of this evaluation is a symbol consisting of a set of dimensional numbers. As we saw before, \( \text{meas} = \text{attr} \circ \text{thing} \), but the \( \text{thing} \) mapping is a priori imposed, so the construction of the \( \text{meas} \) mapping depends on the development of the \( \text{attr} \) mapping.

From a practical point of view, it is necessary to study the development of the attribution mapping of the previous formal construction because this is the current operation made by an operator when he is performing a measurement action. Therefore, the analysis and design of the attribution mapping is the core of the measurement.

A common practical implementation of the formal description of the \( mc \) developed previously is represented in Fig. 3, as a functional scheme corresponding to the \( \text{meas} \) mapping.

Assume \( \text{thing} \) being a work process with input \( u(t) \) and output \( y(t) \). Its corresponding characteristics, at a certain time, grouped in the \( \text{feat} \) set, are being evaluated as \( \text{symb} \). This task is fulfilled by an attribution mapping implemented practically by the attribution block \( \text{attr} \) in the figure.

The functional scheme of the \( mc \) shown in Fig. 3 is a typical industrial implementation of the formal description of the \( mc \) described in Section 2.1 and exemplified in Section 2.2. The two mappings whose composition defines the \( \text{meas} \) mapping are pointed out.

Note that part of this functional scheme, namely the \( \text{thing} \) mapping, is partially unknown to the
Development of the functional scheme of the \textit{cmc}

Usually, the design of the \textit{attr} block is based on a classical \textit{transducer}.

In the framework of the \textit{cmc}, the \textit{attr} block is divided in a number of transducer blocks.

Theoretically, this number equals the number of characteristics to be evaluated. In practice, this number is smaller than the number of characteristics for evaluation, because the operator is not always interested in the evaluation of all these characteristics.

Therefore, each transducer is designed for materializing only one association between one element \textit{char} $\in$ \textit{feat} and one element \textit{dino} $\in$ \textit{symb} as part of the \textit{attr} mapping at a certain moment. Finally, the number of transducers equals generally the number of characteristics for evaluation.

The functional scheme of the \textit{cmc}, represented in Fig. 4, is a well-known development of the functional scheme of the \textit{mc} from Fig. 3. Each transducer corresponds to one component of the vectorial \textit{attr} mapping and gives a dimensional number according to this component.

In all representations shown in this paper, thin arrows are used for the case when the respective item is a scalar, and thick arrows in the case of a vector.

For detailing the manner in which the components of the \textit{attr} mapping are defined, we consider, in this paper, the case when at a certain moment $t$, the feature is \textit{feat}$_{\alpha}$ = \{\textit{char}$^{a}$, \textit{char}$^{b}$, \ldots, \textit{char}$^{k}$\}. For this case, in the situation of the \textit{cmc}, the vectorial \textit{attr} mapping is developed as:

\begin{align*}
\text{attr}(t, \text{feat}$_{\alpha}$) &= \text{attr}(t, \{\text{char}$^{a}$, \text{char}$^{b}$, \ldots, \text{char}$^{k}$\}) \\
&= (\text{attr}^{a}(t, \text{char}$^{a}$), \text{attr}^{b}(t, \text{char}$^{b}$), \ldots, \\
&\quad \text{attr}^{k}(t, \text{char}$^{k}$)) \\
&= (\text{dino}$^{a}$, \text{dino}$^{b}$, \ldots, \text{dino}$^{k}$).
\end{align*}

It is noticed that each component of the vectorial \textit{attr} mapping depends on only one of the characteristics for determination. The practical implementation of this condition is a difficult task and also is an important restriction in the framework of the \textit{cmc}. We will refer to these aspects later.
4.2. State-space representation of the transducer

As a consequence of the functional scheme of the \textit{cmc} in Fig. 4, the state-space representation of the transducer, shown in Fig. 5, is discussed in this section. For clarity, we consider the state-space representation of transducer\textsuperscript{a} from Fig. 4.

Bold characters are used for some notations in connection with the state-space representation presented in this and following sections. The reason is to underline the difference between the static items implied by the functional scheme and the dynamic items implied by the practical development of the attribution block shown as state-space representation.

The static character of the functional scheme is determined by the target of the attribution blocks as for evaluation of the characteristics of a feature at a certain moment. The dynamic character of the practical attribution block is determined by the internal mechanisms of this block (as is the case in which this block is formed with a classical transducer). Analogous remarks are also valid for the case of the \textit{nmc} presented in the next section.

Some transducers (namely the modulating transducers) may need an input. This possible input, denoted as \textit{in}, is known a priori. It could be generally a time-variable scalar.

The state of the transducer, denoted as \textit{x}, is
generally a time-variable vector whose dimension is much smaller than the dimension of feat, because of the design conditions of the transducers.

It is considered that the characteristic char at feat, corresponding to the moment t, has to be evaluated.

A design condition is that the initial state of the transducer, denoted as x(t), must include char as a component, namely the characteristic to be evaluated by means of that transducer.

Properly speaking, the initial state of the transducer contains many elements of feat, one of them being the characteristic char for evaluation. Thus, a component of the initial state of the transducer is the characteristic to be evaluated.

We notice the contrast between the frequent approach (in which the characteristic for evaluation is considered as an input for the transducer) and our approach (in which the characteristic for evaluation is considered as part of the initial state of the transducer). This specific choice is determined by two main reasons:

• a better delimitation between the meanings and effects of char (as a component of the initial state) and in (as the possible dynamic input) upon dino (the dynamic behaviour of the dimensional number which is the result of the numerical evaluation);
• the building of a convenient framework for a future development of the ideas concerning the evaluation of characteristics using the results about the observability from the system theory. It is known that the concept of observability implies an ability to determine the initial state of the system from knowledge of the input and the output over an arbitrary time interval [18]. As we are looking for the evaluation of the initial state or part of it, the use of the results concerning the observability should be a promising field of research for problems like the determination of conditions in which such evaluations are likely to be fulfilled.

Analogous remarks are also valid for the case of the state-space representation of the actuator–sensor structure presented in the next section.

The output of the transducer, denoted as dino, is generally a time-variable scalar, because the transducer is designed in such a way that only a particular characteristic is evaluated. Thus, the output is known a posteriori, containing the result of the evaluation.

From the above it follows that a transducer can be considered as a nonlinear, time-varying dynamic system, described by the following state-variable equations:

$$\frac{d}{dt} x(t) = p(x(t), in(t), t)$$

(1)

$$dino(t) = h(x(t), in(t), t)$$

(2)

where p and h are mappings of the state x, the input in and time t [19].

It is stressed, to avoiding any possible confusion, that Eqs. (1) and (2) describe the dynamics of the transducer, not the dynamics of the work process. Also, it is noticed that the last argument is the time, denoted by t, its origin being the certain moment (e.g. t) when a certain characteristic (e.g. char) has to be evaluated. Therefore, when another characteristic has to be evaluated, the origin of time is changed accordingly.

Even if the input is presented generally here as a time-variable item (being determined by the practical setup where the transducer is used), it is a constant item in many practical situations. The results presented herein are not influenced by certain particular situations.

Now, we may consider that at the initial moment t, the state of the transducer reproduces ‘at a small scale’ the analysed feature, because its initial state contains some characteristics of this feature. This state is modified in a dynamic manner, as Eq. (1) shows, but is ‘focussed’ on a certain characteristic for evaluation, because the transducer is built such that its output depends strongly on only that characteristic.

 Everywhere in this paper it is considered that the dynamics of the work process is much slower than the dynamics of the transducer, justifying the formal considerations concerning the characteristics as items defined at a certain moment. Some of them are going to be evaluated. In fact, as presented before, the characteristic for evaluation is a time-invariant item because it is defined at a certain moment, so the dynamics of the transducer is determined only by its
input. When the evaluation of a characteristic is involved, this characteristic is always associated with a certain time moment, so if the moment is changed, another evaluation of the same or of another characteristic must be fulfilled. A similar discussion applies in the case of the \textit{nmc}.

Hence, the design of the transducer is made so that its output \textit{dino}^a, described by \textit{h} mapping, is a scalar item and depends only on one component of the vectorial item \textit{x}, denoted as \textit{char}^a. This component describes the dynamics (determined by the transducer behaviour) of the characteristic that must be evaluated. Otherwise, when the output of the transducer depends on many components of \textit{x}, an undesirable effect known as cross-sensitivity appears.

Thus, Eq. (2) becomes

\begin{equation}
\textit{dino}^a(t) = \text{\textit{h}}(\text{\textit{char}}^a(t), \text{\textit{in}}(t), t)
\end{equation}

where

\begin{equation}
\text{\textit{char}}^a(t_1) = \text{\textit{char}}^a
\end{equation}

is the characteristic for evaluation of the feature \textit{feat}_n.

From Eqs. (3) and (4), the output of the transducer is

\begin{equation}
\text{\textit{dino}}^a = \text{\textit{dino}}^a(t_1) = \text{\textit{h}}(\text{\textit{char}}^a, \text{\textit{in}}(t_1), t_1)
\end{equation}

This situation corresponds to an ideal case because the operator gets the result \textit{dino}^a exactly in the moment \textit{t}_1 when the transducers are connected to the measurement object. This is known as measurement in transitory state [20].

Practically, this situation is very difficult to be fulfilled although some promising theoretical results concerning new measurement methods are available [21]. Consequently, the dynamic process modelled by Eqs. (1) and (2) is necessary to be developed in the transducer. Its design is realized in such a way that a stationary state is reached at the moment \textit{t}_1, that can be considered the final moment of the measurement process whose initial moment is \textit{t}_i. The output of the transducer at this moment is recorded from Eq. (3) as

\begin{equation}
\text{\textit{dino}}^a(t_1) = \text{\textit{h}}(\text{\textit{char}}^a(t_1), \text{\textit{in}}(t_1), t_1)
\end{equation}

Since the output of the transducer, namely \textit{dino}^a(t_1) from Eq. (6), is different from the expected output \textit{dino}^a(t_1) from Eq. (5), a lot of effort must be done in transducer design to make \textit{dino}^a(t_1) depending in a simple way (generally a proportional relation) on \textit{dino}^a(t_f).

Thus, finally, the operation of the transducer is based on a relation between \textit{char}^a and \textit{dino}^a(t_f) through Eqs. (1), (5) and (6). Many difficulties are involved in obtaining a proportional relation between \textit{char}^a and \textit{dino}^a(t_f). This problem is analysed, from a practical point of view, in some papers as [22].

From the above considerations, it is noticed that the conditions imposed on the design of transducers used in connection with the \textit{cmc} are rather restrictive. The most common cross-sensitivity in a classical transducer is with temperature [23]. In order to minimize cross-sensitivity effects, some special hardware precautions has to be considered, regarding the transducer in the framework of the \textit{cmc}. When temperature is involved, it is comparatively easy to evaluate temperature independently and to provide correction either on a standard correction associated with the transducer type or on calibration measurements [24].

Summarising, the main inconveniences of the \textit{cmc} are:

- for each characteristic of the feature for evaluation, a specific part of the \textit{attr} block is built around a classical transducer;
- technical solutions must be developed to arrive at a transducer that provides the proper evaluation of only one characteristic.

5. New measurement concept

5.1. Development of the functional scheme of the \textit{nmc}

Because of the restrictions implied by the \textit{cmc}, it is interesting to find a possibility for relieving them. An efficient way is the renunciation of dividing the \textit{attr} block (Fig. 3) in separate blocks, as proposed in a recent work [2].

The main idea of the \textit{nmc} is the design of the \textit{attr} block as an entity for the simultaneous evaluation of more characteristics of that feature, and not only one at each moment. The practical implementation of this block is based on an object named \textit{actuator–sensor...}
structure (briefly structure) for reasons which are detailed later.

The functional scheme of the nmc is represented in Fig. 6. It is a new development of the functional scheme of the mc from Fig. 3. Its analysis is similar to that of the functional scheme of thecmc.

Ideally, the structure is designed for materializing all associations between the elements char \in feat and the elements dino \in symb, in fact for the entire attr mapping. Practically, the structure is designed for materializing of only that part of the attr mapping which is interesting from an applicative point of view.

For the nmc, the vectorial attr mapping is developed as:

\[
attr(t_1, \text{feat}_n) = attr(t_1, \{\text{char}^a, \text{char}^b, \ldots, \text{char}^k\}) \\
= (\text{attr}^a(t_1, \text{char}^a, \text{char}^b, \ldots, \text{char}^k)) \\
\]

It is noticed that each component of the vectorial attr mapping may depend on all characteristics. This dependence is more likely and more easy to be fulfilled from a practical point of view, being a natural dependence.

To obtain this operation, a structure can be defined as an ensemble of \(m\) actuators (of the same physical nature) and \(n\) sensors (of the same physical nature) placed together as close as possible (to ensure the space independence of the characteristics for evaluation in the vicinity of the structure), and controlled by a computational block. We detail the actuator–sensor structure in the next section.

5.2. State-space representation of the actuator–sensor structure

As parts of the actuator–sensor structure, each actuator needs a certain input, known a priori. For some sensors, an input known a priori, could also be necessary. The inputs of this first type are denoted as a time-variable vector \(\text{in } I\). These inputs of the structure play a central role for deriving the dimensional numbers corresponding to the characteristics of the feature for evaluation.

The inputs of the second type are denoted as a time-variable vector \(\text{in } II\). These inputs of the structure are similar to those used in the case of modulating transducers in the framework of thecmc, so they play a secondary role.

Since these two groups of inputs have different functions in the case of the actuator–sensor structure, they are shown separately in Fig. 7, where the state-space representation of the actuator–sensor structure is displayed.

The actuators are used to modify slightly the feature whose characteristics are evaluated, so that some new characteristics, named supplementary characteristics, must be added. Their dynamics (produced by actuators) are evaluated by sensors as shown in Fig. 7 through the winding lines. Using these dynamics and also some a priori information (e.g. the theoretical relations between the dynamics of the supplementary characteristics and the characteristics for evaluation, the inputs of the structure),
Fig. 7. State-space representation of the actuator–sensor structure.
the computational block derives the characteristics for evaluation.

We note that the sensors of the structure are used for the evaluation of the supplementary characteristics (on the same physical nature), not of the characteristics of the feature (on different physical nature) as the situation is in the framework of the \textit{cmc}. Surely, in some practical situations, it is possible to consider some sensors of the structure which are able to evaluate directly some characteristics. Therefore, in the general case, it should be possible to divide the structure in two parts. One of them consists from typical sensors, being analysed in the framework of the \textit{cmc}, as done before. Another one consists in actuators and sensors, as Fig. 7 shows, being analysed in the framework of the \textit{nmc}. To avoid further complications, we consider in the following only the case when the entire structure looks as in Fig. 7 being analysed in the framework of the \textit{nmc}.

In the following, a detailed description of the actuator–sensor structure is included.

As mentioned previously, the input of the actuator–sensor structure consists of two time-variable vectors. One of them is optional, known a priori, denoted by \textit{in II}, and having the same significance as in the case of the classical transducer.

Another component of the input is obligatory, known a priori, denoted by \textit{in I}. The constituents of this vector have the same physical nature. They act upon the actuators, that are also of the same physical nature. More precisely, the actuators produce a slight alteration upon the feature $\textit{feat}_a$ whose characteristics have to be evaluated. Therefore, the \textit{in I} component of the input causes, through actuators, a slight enlargement of $\textit{feat}_a$ with some supplementary characteristics grouped in the supplementary feature denoted as $\textit{feat}_a$s.

At the state-space level of the structure, the slight enlargement of $\textit{feat}_a$ is mirrored in the appearance of other components for the state of the structure. They are collected in a time-variable vector denoted as $\textit{x}s$. The dimension of the state vector is generally smaller than the dimension of $\textit{feat}s$ depending on the practical achievements.

Thus, the structure is built so that its initial state contains many components belonging to $\textit{feat}_a$s.

The development of the output of the structure, generally a time-variable vector whose components are denoted as $\textit{dino}^a$, $\textit{dino}^a$, ..., $\textit{dino}^a$, has to be made so that they derive the evaluations of $\textit{char}^a$, $\textit{char}^a$, ..., $\textit{char}^a$. These evaluations are obtained using the dynamics of some components of $\textit{xs}$, denoted as $\textit{char}^{s_1}$, $\textit{char}^{s_2}$, ..., $\textit{char}^{s_n}$ corresponding to the supplementary characteristics $\textit{char}_1^{s_1}$, $\textit{char}_2^{s_2}$, ..., $\textit{char}_n^{s_n}$. These dynamics are produced by the actuators of the structure and are evaluated by the sensors of the structure.

Thus, the problem is reduced from the determination of some characteristics of $\textit{feat}_a$ (of different physical nature as discussed previously) to the determination of some characteristics of $\textit{feat}_a$s (of the same physical nature).

From a technological point of view, the superiority of this approach consists in using the same type of actuators (e.g. heaters) and of the same type of sensors (e.g. temperature sensors).

Also it is customary that actuators and sensors belong to the same physical domain.

Therefore, based on the evaluations of $\textit{char}^{s_1}$, $\textit{char}^{s_2}$, ..., $\textit{char}^{s_n}$ (achieved by the sensors of the structure) and on the relations between them and the characteristics for evaluation, the latter are derived by the computational block. These evaluations are collected in the $\textit{dino}$ vector constituting the output of the structure, as Fig. 7 shows.

Following the same procedure as in the transducer case corresponding to the \textit{cmc}, from a state-space representation point of view, an actuator–sensor structure can be considered as a nonlinear, time-varying dynamic system, described by the following state-variable equations:

\[
\frac{d}{dt} \textit{x}_s(t) = p_s(\textit{char}^i, \\
\textit{j} = a, \ldots, k), \textit{x}_s(t), \textit{in I}(t), \textit{in II}(t), t) \tag{7}
\]

\[
\textit{dino}_s(t) = h_s(\textit{char}^i, \\
\textit{j} = a, \ldots, k), \textit{char}_s(t), \textit{in I}(t), \textit{in II}(t), t) \tag{8}
\]

where $p_s$ and $h_s$, $i = 1, 2, \ldots, n$ are mappings depending on the ‘$k$’ characteristics which must be evaluated, the state $\textit{x}_s$, the inputs $\textit{in I}$, $\textit{in II}$ and time $t$. In Eq. (8), $\textit{char}_s$ are the ‘$n$’ components of the vector $\textit{x}_s$, whose evaluations are done by the sensors of the structure.
The equation describing the functionality of the ‘computational block’ must be added at Eqs. (7) and (8), namely

\[
dino^i = r \cdot s^i ([\text{char}^i, j = a, \ldots, k], \{\text{dino}_s^i(t), \nonumber
\]

\[
i = 1, \ldots, n), \text{in}_1(t), \text{in}_2(t), t \in [t_1, t_j])
\]

(9)

where \( l = a, \ldots, k \), and \( t_j \) is the final moment when the observation of the dynamics of the supplementary characteristics stops. It is implicitly considered that the start moment is just \( t_1 \).

Thus, finally, the operating principle of the actuator–sensor structure is based on the relations between \{\text{char}^i, j = a, \ldots, k\} and \{\text{dino}^i, l = a, \ldots, k\} through Eqs. (7)–(9).

From a geometrical point of view, the actuators and sensors are usually zones, points and lines. Also, for a proper design of the structure, it is necessary to stress that the behaviour of the structure is affected by the choice of actuators and sensors (e.g. number, location and spatial distribution) [25].

Concerning the ‘computational block’ from Fig. 7, it is also noticed its action in deriving the evaluation of desired characteristics, using Eqs. (7)–(9), as shown before. For this action, some a priori information must be known, as:

• the mathematical model of the actuator–sensor structure (materialized in the knowledge of the mappings \( p_1, \{h_s^i, i = 1, \ldots, n\}, \{r_s^l, l = a, \ldots, k\}\));
• the knowledge of the time-varying inputs \( \text{in}_1(t), \text{in}_2(t) \).

Following discussions from Sections 4 and 5, the most important differences between the practical implementation of the \( \text{cmc} \) and \( \text{nmc} \) are summarized in Table 1.

It is noticed from Table 1 that the complexity moved from the hardware part to the software part.

At the end of this section it is remarked an apparent closeness between two subjects. One of them is the \( \text{nmc} \) and the actuator–sensor structure as its core, that are discussed previously. The other one is the area of intelligent transducers specifically for multi-measurement processes. As defined in [26], transducers incorporated with dedicated signal processing functions are called intelligent transducers or smart transducers. The roles of the dedicated signal processing functions are to enhance design flexibility of sensing devices and realize new sensing functions. Additional roles are to reduce loads on central processing units and signal transmission lines by distributing information processing in the sensing systems. In the case when the multi-measurement processes are concerned, the problem is traditionally solved in the framework of the \( \text{cmc} \), namely each intelligent transducer is used to evaluate a certain characteristic in an independent way. Consequently these two subjects are different in meaning and approach.

### 6. Implementation of the \text{nmc} for MEMS

As stated previously, the core element of the \( \text{nmc} \) is an actuator–sensor structure. It has to be designed
in such a way as to derive the evaluation of the desired characteristics.

A useful practical implementation of the \( nmc \) is developed in this section. It aims at the evaluation of a set of space dependent characteristics. Theoretically, all these characteristics correspond to a single spatial point.

We consider again the laminar liquid flow in a long duct. The liquid velocity (as a flow parameter) and the thermal diffusivity (as a liquid parameter) have to be estimated.

Therefore, the characteristics of the feature for evaluation are the velocity field and the thermal diffusivity of the liquid. The velocity field is considered as being determined by only the free-stream velocity.

Firstly, we examine the possibilities for solving this problem in the framework of the \( cmc \). Therefore, we detail separately the velocity evaluation as well as the thermal diffusivity evaluation.

Secondly, we examine a possibility for solving this problem in the framework of the \( mmc \). An actuator–sensor structure (realized as a MEMS) that is able to derive simultaneously both the velocity and the thermal diffusivity is detailed. The superiority of the second approach is underlined.

6.1. Velocity evaluation in the framework of the \( cmc \)

To reach this objective, transducers based on several different operating principles could be chosen. These operating principles consist of anemometer functions, physical deflections, temperature-dependent layers, and time-of-flight operation. The most commonly used principle is that of anemometers as shown in Fig. 8 [27].

A thermal anemometer refers to sensors that measure total heat loss. This heat loss is due to some heating element (such as a polysilicon resistor) heating up the fluid. The heat loss depends on the flow rate of the liquid and the operating mode for the anemometer.

The core of the anemometer is an electrically heated wire or film. Two modes are frequently used to measure flow called constant-current and constant-temperature, respectively. The first uses a constant current passing through the sensing wire. Variation in flow results in a changed wire temperature, hence a changed resistance, which thereby becomes a measure of flow. The second technique uses a servo system to maintain wire resistance, hence wire temperature. In this case, a change in flow results in a corresponding change in electric current.

When the anemometer is placed in a flow, heat will be transferred from the wire, primarily by convection. Radiation and conduction are normally negligible. The relation governing the dependence between temperature field inside the fluid and the free-stream velocity of the fluid is:

\[
\frac{\text{electrical power/unit length}}{\text{temperature difference}} = \frac{i^2 R}{T_w - T_a}
\]

\[
= A + B\sqrt{\rho V}
\]

(10)

where \( A \) and \( B \) are constants, \( i \) is the instantaneous current (A), \( R \) is the resistance of the wire per unit length (\( \Omega \text{ m}^{-1} \)), \( T_a \) is the ambient temperature (K), \( T_w \) is the temperature of the wire (K), \( V \) is the free-stream velocity (m s\(^{-1}\)) and \( \rho \) is the density of the liquid (kg m\(^{-3}\)).

A high absolute accuracy in calculated velocity, typically \( \pm 0.5\% \) of a reading, is achieved by calibration [28].

6.2. Thermal diffusivity evaluation in the framework of the \( cmc \)

Thermal diffusivity is the important thermophysical property used to describe heat conduction in a steady liquid. Some non-steady-state and steady-state measurement techniques are applicable [29].

The temperature oscillation technique is a non-
steady-state measurement technique that is simply described in the following.

The energy equation
\[ \frac{\partial T(x,t)}{\partial t} = \alpha \frac{T(x,t)}{x} \]  
(11)
describes heat conduction in a one-dimensional isotropic slab (solid or liquid) with constant thermal diffusivity, where \( L \) is the length of the slab (m), \( t \) is the time (s), \( T \) is the temperature (K), \( x \) is the distance along the slab (m), and \( \alpha \) is the thermal diffusivity (m\(^2\) s\(^{-1}\)).

The solution of Eq. (11) depends upon the specimen geometry and boundary conditions.

A slab is considered with two diathermic surfaces. On each side, periodic surface-temperature oscillations are generated with the same constant angular frequency \( \omega \) (s\(^{-1}\)), but with different amplitudes and phases.

Using the dimensionless coordinates
\[ \xi = x \left( \frac{\omega}{\alpha} \right)^{1/2} \]
and the dimensionless time
\[ \tau = \omega t \]
the mathematical formulation of this problem described by Eq. (11) is given as
\[ \frac{\partial^2 T(\xi,\tau)}{\partial \xi^2} = \frac{\partial T(\xi,\tau)}{\partial \tau} \]  
(12)
with the boundary conditions (subscript \( M \) indicates mean; subscript \( 0 \) indicates \( x=0 \); subscript \( L/2 \) indicates \( x=L/2 \); subscript \( L \) indicates \( x=L \))
\[ T(\xi_0, \tau) = T_M + u_0 \cos(\tau + G_0) \]  
(13)
\[ T(\xi_L, L^{1/2} \tau) = T_M + u_L \cos(\tau + G_L) \]  
(14)

The use of Laplace transform techniques yields the steady periodic solution of Eqs. (12)–(14). For convenience the complex solution is presented:
\[ T^*(\xi,\tau) = T_M + u_e e^{iG_e} + u_i e^{iG_i} \]  
(15)

Using Eq. (15), the complex amplitude ratio \( B^* \) between the points \( x=L/2 \) and \( x=L \) becomes:
\[ B^* = \frac{2u_e e^{iG_e} + u_0 e^{iG_0} \cosh \left( L \frac{\omega}{2 \alpha} \right)^{1/2} }{2u_L e^{iG_L} + u_0 e^{iG_0} \cosh \left( L \frac{\omega}{2 \alpha} \right)^{1/2} } \]  
(16)

The real phase difference \( \Delta G \) and the real amplitude ratio are expressed, respectively, from Eq. (16) as
\[ \Delta G = \arctan \left( \frac{\text{Im}[B^*]}{\text{Re}[B^*]} \right) \]  
(17)
and
\[ \frac{u_L}{u_{L/2}} = \left( \frac{\text{Re}[B^*]}{\text{Im}[B^*]} \right)^{1/2} \]  
(18)

From a measurement of the phase or the amplitude at two sides and in the centre of the slab the thermal diffusivity \( \alpha \) can be determined from Eqs. (16) and (17) or Eqs. (16) and (18), respectively.

The longitudinal section of the practical setup is presented in Fig. 9. The practical setup consists mainly of a small ‘silence room’ of a cylindrical shape obtained using a very narrow duct from the main duct where the fluid is moving in. The fluid is considered being in rest in the silence room which forms the slab whose thermal diffusivity is going to be evaluated.

The boundary conditions described by Eqs. (13) and (14) are realized practically with two heat sinks displayed at the both ends of the silence room. The

![Fig. 9. Thermal diffusivity measurement in the framework of the cmc.](image-url)
temperature of the fluid is measured in three points, at $x=0$, $x=L/2$ and $x=L$ using thermocouples located on the centerline.

The magnitudes of the measurement uncertainties of the slab thermal diffusivity are less than 2%.

6.3. Actuator–sensor structure for evaluation of velocity and thermal diffusivity in the framework of the nmc

Within the field of fluid flow, the characteristics of the feature for evaluation could be velocity field, pressure, density, viscosity, temperature, thermal diffusivity, chemical composition, etc.

All these characteristics could be evaluated separately, in the framework of the cmc, as we saw before. Some limitations appear in this case, as discussed in Section 4:

- a large number of transducers must be designed independently and special care must be taken to the mutual influence between transducers;
- some of the above characteristics depend strongly on each other, therefore the practical setup must be designed accordingly;
- from technological reasons it is not possible to evaluate characteristics corresponding to the same spatial point.

These limitations can be removed based on the nmc and using MEMS. As suggested previously, the structure is a MEMS tailored to derive the evaluations of all characteristics of interest. Because of its small dimensions, it is assumed to evaluate these characteristics simultaneously in a single spatial point.

The operation of the actuator–sensor structure, in this example, is based on the thermal flow sensing principle. The longitudinal section of the structure is sketched in Fig. 10. We notice its similarity to the general representation of an actuator–sensor in Fig. 7.

Its main part consists of a micro-channel made by bonding together two silicon or glass wafers, both containing an etched groove. Inside the micro-channel some heaters (as actuators) and some temperature sensors have been fitted. For convenience, only one heater and two temperature sensors are presented.

The heater is activated by an electrical circuit which is controlled by the computational block also used for data processing.

Note that, because of the operation in the same physical domain, a high malleability is available in the design and operation of both the actuators and sensors of the structure. As an illustration of the malleability, the same item could be used as a sensor or as an actuator.

The operation of the structure relies on the modulation of the temperature distribution in the micro-channel by the fluid medium [30]. The asymmetric temperature profile in the micro-channel is evaluated by the temperature sensors. This profile can be determined both by the fluid flow and flow parameters, and also by a suitable control of the heater.

We consider that the heat is emitted instantaneously in an infinite medium by a line source of strength $Q$ at $t=0$ parallel to the $z$-axis. The infinite medium moves uniformly with velocity $V$ parallel to the $x$-axis. The strength is the temperature to which the amount of heat liberated would raise a unit volume of substance. The transport of the heat generated by a line source through a fluid is governed by the energy equation [31]:

$$\frac{\partial T(x,y,t)}{\partial t} + VT(x,y,t) = \alpha \left( T_{xx}(x,y,t) + T_{yy}(x,y,t) \right)$$

where $Q$ is the strength of the line source (K m$^3$), $t$ is the time (s), $T$ is the temperature (K), $V$ is the
free-stream velocity \( (m \, s^{-1}) \), and \( \alpha \) is the thermal diffusivity \( (m^2 \, s^{-1}) \).

The analytical solution of Eq. (19) is [32]:

\[
T(x,y,t) = \frac{Q}{4\pi\alpha t} \exp\left(-\frac{(x-Vt)^2 + y^2}{4\alpha t}\right)
\]  

(20)

By measuring the time \( t \) at which the signal passes the sensors (placed at \( y=0 \)) having the top value, in other words differentiating Eq. (20) with respect to time, one can obtain:

\[
\tau = -\frac{2\alpha}{V^2} + \frac{(4\alpha^2 + u^2x^2)^{1/2}}{V^2}, \quad V \neq 0;
\]

\[
\tau = \frac{x^2}{4\alpha}, \quad V = 0
\]  

(21)

Let us consider two sensors at a distance \( x_1 \) and \( x_2 \) from the heater where the top times \( \tau_1 \) and \( \tau_2 \) are measured. With Eq. (21) we get:

\[
\alpha = \frac{x_1^2\tau_2^2 - x_2^2\tau_1^2}{4(\tau_2^2\tau_1 - \tau_1^2\tau_2)},
\]

\[
V = \left[ \frac{x_1^2}{\tau_2^2\tau_1} - \frac{x_2^2}{\tau_1^2\tau_2} \right]^{1/2} \]  

(22)

Using Eq. (22), the free-stream velocity of the flow and the thermal diffusivity of the fluid are determined.

Although Fig. 10 suggests that the fluid is moving, a set of valuable information about the fluid parameters can be obtained also when the fluid is in rest, using the temporal variations of the temperature evaluated by the temperature sensors when the heater is driven in a controlled manner.

A practical realization of this structure is displayed in Fig. 11. The frame of this structure is realised as a micro-channel on a \( \langle 100 \rangle \) Si wafer covered with a Pyrex wafer, both containing an etched groove. The heater as well as the temperature sensors consist of a thick metal film deposited on some \( Si_3N_4 \) carrier bridges. The length of the micro-channel is 3 mm, its width is 1 mm and its depth is 0.25 mm [33]. Therefore, this structure is able to evaluate a set of space dependent characteristics. The computational block can be integrated on the same chip together with the sensors and the actuators or can be built apart.

Briefly, the temperature of the fluid is locally perturbed in a controlled manner by the heater, and the response of the fluid at this perturbation is observed also locally as temperature variations of the fluid. This actuator–sensor structure is intended to evaluate the velocity and the thermal diffusivity of the fluid as shown before. These two characteristics are evaluated practically in the same geometrical point of the fluid.

The first practical evaluations show that the magnitudes of the measurement uncertainties are less than 5%, after calibration.

Another characteristic, namely the composition of the fluid can be derived using the same structure by means of an artificial neural network [34].

7. Conclusions

The formal description of the mc developed in the first part of the paper is the basis for the two mc detailed further, namely the cmc supported by the classical transducer and the nmc supported by the actuator–sensor structure.

Using a state-space representation of the classical transducer, the inconveniences of the cmc are underlined. Using these inconveniences, as a starting point, a nmc is defined and the actuator–sensor structure, as the core of this concept, is described both as a functional scheme and as a state-space representation.
The most important differences between the cmc and nmc are underlined, and the main advantage of the nmc, the fact that it moves the complexity from the hardware part to the software part, is stressed.

Firstly, from a formal point of view, the nmc modifies the fundamental approach of the measurement process mainly in the case when many characteristics have to be evaluated. Instead of using different transducers properly tailored for each characteristic (as is the case of the cmc), the nmc is using an actuator–sensor structure (containing actuators as well as sensors belonging to the same physical domain) for deriving evaluations of all characteristics of interest.

Secondly, the actuator–sensor structure is manufactured using MEMS technology (a growing technology). This technology is well suited to producing a class of micromachined sensors and actuators that combines signal processing and communications on a single silicon chip. It means that at the structure level, the characteristics are not space dependent.

The nmc and the actuator–sensor structure are promising ideas for the future of measurement science in connection with MEMS. An application concerning the determination of fluid and flow parameters is detailed in this paper.

Finally, the authors consider that using the nmc in connection with MEMS is a good alternative for the cmc supported by the classical transducers, from the points of view as cost, size, weight and measurement performances.

The limitations of using MEMS instead of classical transducers are caused by their low robustness in hostile practical conditions and the necessity for development of a detailed model of the actuator–sensor structure, which can be a difficult task in the case of nonlinear phenomena. Also, because of the special construction of the structure, the theoretical evaluation of the errors and uncertainty in measurement can be a difficult task.

The results obtained up to now have been encouraging, but a lot of research has still to be done. In particular, the derivation of the conditions for a proper design of the actuator–sensor structure (e.g. the analysis of the locations and types of the actuators and sensors) is an important item for future research, as well as the study of its metrological performance.

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References


