XVI IMEKO World Congress
Measurement - Supports Science - Improves Technology - Protects Environment ... and Provides Employment - Now and in the Future
Vienna, AUSTRIA, 2000, September 25-28

FROM THE SENSOR TO THE RESULT OF MEASUREMENT

H.-J. Dubrau
Zelz 11a, 03159 Jerischke, Germany

Abstract: Presented is an uniform function scheme of the measuring process with the elemental functions

- Selection of unities of measurement
- Storage of comparison quantities and comparison values
- Comparison and control unit for comparison
- Registration of the measured values and presenting the results.

This function scheme describes both analogous as well as digital gauges and measuring devices. From it an universal block scheme is developed for all gauges and measuring devices. This functional description of measuring allows fundamental statements to measuring errors. There are two possible quantisating errors. These appear both at analog as well as digital gauges and measuring devices.

Keywords: IMEKO, World congress, IMEKO 2000 topic, measuring, measure, quantisating error, measuring comparison, measuring embodiment, measuring algorithm, measuring scheme

1 Introduction

For the description of the measuring process the measuring chain is used up to now almost exclusively according to the German recommendation VDE/VDI 2600 (Fig. 1). Thereby a multitude of variations is to be met.

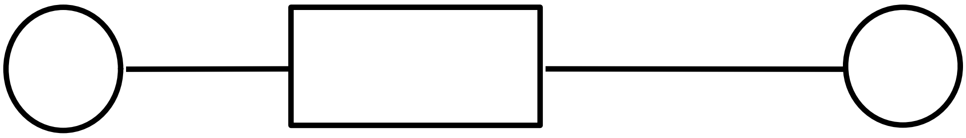

Figure 1. Measuring scheme from VDE/ VDI 2600

The measuring chain is interpreted often as an information transfer canal by Shannon. This is however wrong. There is at least two groups of schemes, which are not compatible:

1.1 Functional schemes

To this kind belong f.i. circuit diagrams, true to scale drawings or force graphs. They present connections mathematically exactly. Thus they make possible the calculation of each other depending quantities, like which voltages and currents of a network at alleged network elements or the plains and volumes of geometric objects. The diagram of the information transfer canal by Shannon with source, canal and sink belongs likewise to this class, since it make possible the exact calculation of it information transfer characteristic. That is not possible for the measuring chain.

1.2 Order schemes

Order schemes present spatial, temporal or other connections without an exact mathematical description exists. To it belong sketches of products, program term plans, direction structures, ancestral trees and also the measuring chain by VDE/ VDI 2600 as well as their variations in textbooks and publications.
Fig. 1 states only, that from the entrance structure a measuring device (sensor/ gauge) a measuring quantity is transfered to the measuring output. Thus remain two questions open.

Where does the element most essential for a measuring device be found, the measure embodiment?

Where is the reason operation of each measurement undertaken, the comparison?
Causes of these obscurities is evidently the fact, that these questions were not put and not answer.
The man can do comparisons with sufficient precision only for few qualities directly:

- visual comparisons of lengths, brightness and colors
- acoustic comparisons of pitches and sound intensity

His abilities to the comparison of forces, temperatures, times and electric quantities allow only very crude statements. For magnetic and many other quantities owns he quite no sense organs. On the other hand required trade and technology, science and medicine always more exact measurements. Thus the development of the mankind is joined with the development of measuring processes and dvices narrowly. The first measuring processes emerged empirically already in prehistoric time, but only in the last years was successful to formulate an uniform measuring theory. /1//2//3/

2 MEASURING AS COMPARISON WITH MEASURE EMBODIMENTS

The reason operation of each measuring process is the **comparison**. Compare leave itself only quantities the same kind of quantity, like two lengths or two voltages. As result of a comparison are only the both statements „both quantities are each other equal" or „both quantities are unequally possible each other". The latter result can still completed become can around the statement: „Quantity A_m is larger (or smaller) than quantities A_c".

Comparing becomes to the measuring, if for one of the with each other compared quantity the relatiomship to the corresponding unity of measurement, their measuring value, known is. These known quantity is marked as **comparison quantity A_c**. It is always an element of an object, like the mass of a weight, the length of a yard-stick or the oscillations of a quartz generator. The numerical value forms along with the statement the kind of quantity the **comparison value S_c**, like the designations „5 cm", „3 kg" or „16 Ghz".

An object, by which a comparison quantity A_c uses for a comparison and its comparable value S_c can be read or recorded automatically, is called **monovalent measure embodiment**. An object, by which several A_{ci} are used for comparisons and its comparison values S_{ci} can be readread or automatically recorded is named **polyvalent measure embodiment**. Monovalent and polyvalent measure embodiments for quantities, whose comparison a man can undertake, are the simplest gauges. So is a right angle a monovalent measure embodiment and simultaneously gauge for the angle 90°. A stroke measure of 30 cm length with scale of millimetres is a polyvalent measure embodiment for 300 units of length of 1 mm to 300 mm and a linear measure for this area.

A **measurement** results now in that from the quantity $\{A_c\}$ is selected the providing the comparison quantity A_{ci}, which has the least difference to the quantity to be measured, the measuring quantity A_m. Therefore becomes the complex comparison

$$|A_{c(i-1)} - A_m| \quad |A_{ci} - A_m| < |A_{c(i+1)} - A_m| \tag{1}$$

accomplished.

This complex comparison can be presented as a conjunction of two simple comparisons:

$$(|A_{c(i-1)} - A_m| > |A_{ci} - A_m|) \,\&\, (|A_{c(i+1)} - A_m| > |A_{ci} - A_m|) \tag{2}$$

Equation (2) describes the fact, that at a measurement is ascertained, whether a measuring quantity has overstepped the lower threshold of the interval of quantisation, in which the comparison quantity A_{ci} is found, but the upper threshold was reached not. So that is ascertained, that A_{ci} and A_m within the chosen interval of quantisation are equal. For the display of this fact we have the sign $=_q$ (speak: quantisates immediately) introduced, whereby that for the equations (1) and (2) also can be written:

$$A_m =_q A_{ci} \tag{3}$$

Are the distances between the individual A_c constant, so emerge linear scale divisions. There can be undertaken however also exponential or logarithmically scale divisions. Accordingly there are different variations of the formula sign with the kinds „linearly quantisates immediately", „logarithmically quantisates immediately" or „exponential quantisates immediately". In the existing paper is understood $=_q$ always as linearly quantisates immediately. Furthermore it is pointed here already to, that each quantity have a beginning and an end, therefore two comparisons for the determination of one value are necessary.

3 MEASURING ALGORITHM

The measuring algoritm has two steps. The first step is the selection the comparison quantity A_{ci} according to equation (3). In the second step conclude s from the fulfillment of the equality (3), that also the relationship

$$S_m =_q S_{ci} \tag{4}$$

true. The man can examine the accuracy of the comparison (3) directly at the measuring device. He is not able examining the accuracy of the comparison values Sci for them Aci without the use of normals . The exact connection between the equations (3) and (4) guarantees thus the state metrology.
The comparison values S_c are always quantisated. An analogous measuring value is not possible. Each measurement leads to a quantisation. It emerges always an **error of quantisation D** S_q, which is contained implicit in equation (4). If one wants to expel it separately, so can equation (4) also in the form

$$S_m = S_{ci} \pm \mathbf{D}\, S_q \tag{5}$$

written will. The value of $\mathbf{D}\, S_q$ is chosen according to the necessary measuring precision. His minimal value should not remain below the technically meaningful dissolution. For $\pm \mathbf{D}\, S_q$ the designation has 1 LSB (least significant bit) taken root with the establishment (see also eq. (1))

$$A_{c(i+1)} - A_{ci} = A_{ci} - A_{c(i-1)} = \pm \mathbf{D}\, S_q = 1\ \mathrm{LSB} \tag{6}$$

4 THE MEASURING COMPARATOR

In the current completions the central meaning of the comparison was explained when measuring. Thereby it is to be ascertained, that the assignment of the functions remained measure embodiment and comparison to the elements of measuring devices until today particularly at analogous gauges unclear. There is used the diffuse idea „deflection process“, which is applied partially even for digital measuring devices.

However each measuring device has for the task „storage of comparison quantities and values“ the funktion unity **measure embodiment** and for the „comparison“ the function **measuring comparator**. Thereby there is a fundamental difference between analogous and digital measuring devices:
- At all analogous measuring devices becomes the comparison always through the man undertaken He realizes **visually** the function measuring comparator. At a moving-coil instrument occurs a comparison of two angle positions. The scale marks of the gauge are a polyvalent measure embodiment for angle degrees. Measuring quantities, like current or voltage, are transformed proportionally to their intensity into a torque, whose quantity causes due to the resetting force of the feather a proportional pointer deflection. Visually the man associates these pointer deflection to a scale value. Thereby he undertakes the comparison.
- All digital measuring devices contain a **technical measuring comparator**, which executes along with a measure embodiment and a controller the comparison according to the equation (3) and (4).

Whether now a man undertakes the comparison (analogous measurement) or a technical measuring comparator (digital measurement), always is determined a digital measuring value, which thus also an quantisation error produces. Since analogous gauges reach only two-or three-digit dissolution $10^{-(2\ldots3)}$ their quantisation error much larger, than which high-resolution of digital measuring devices $10^{-(3\ldots16)}$.
Independently of it, whether a measurement is executed analogously or digital, two different situations emerge for the comparison excist. Pragmatically seen they have a beginning and an end. The problem exists now therein, that the beginning of the measuring quantity with the beginning the comparison quantity must be compared and the end the measuring quantity with the end of the comparison quantity. Each measurement requires thus two comparisons.

In some cases measuring and comparison quantity can be brought on it equal starting point. Examples for it are the directing level at length measurements, the electrical connection between voltmeter-zero and object-zero or two empty pans of a balance. We mark this linking of the begins of measuring as **referential comparator**. Thereby an equality at this side can be achieved, which is essentially more exact, than which respective quantisation is (Fig. 2). On it not linked side of measuring- and comparison-quantity results always a quantisation owing to a **quantisation comparator**. Cause for these quantisation is the fact, that for economic reasons only a final amount can be provided by. Besides is only a final precision possible, .Moreover is only a final precision possible, so that no interval of quantisation is meaningful, if their interval width within the measuring uncertainties lie.

The often set up assertion, that at analogous gauges is working continuously and be achievable thus an arbitrarily high dissolution, can not be supported. At each stroke measure or each circularity scale a numerical value is determined at the reading always direct or through interpolation and thus the concerned quantity quantisates. As from Fig. 2 on the left shown has a **measuring comparator type A** on the one side the comparison quantity a referential comparator (Fig. 2 below on the left), which error of quantisation no causes, and on the other side a quantisation comparator (Fig. 2 above on the left). The measuring comparator type A causes thus only **the simple error of quantisation** the quantity 1/2 LSB (least significant bit).

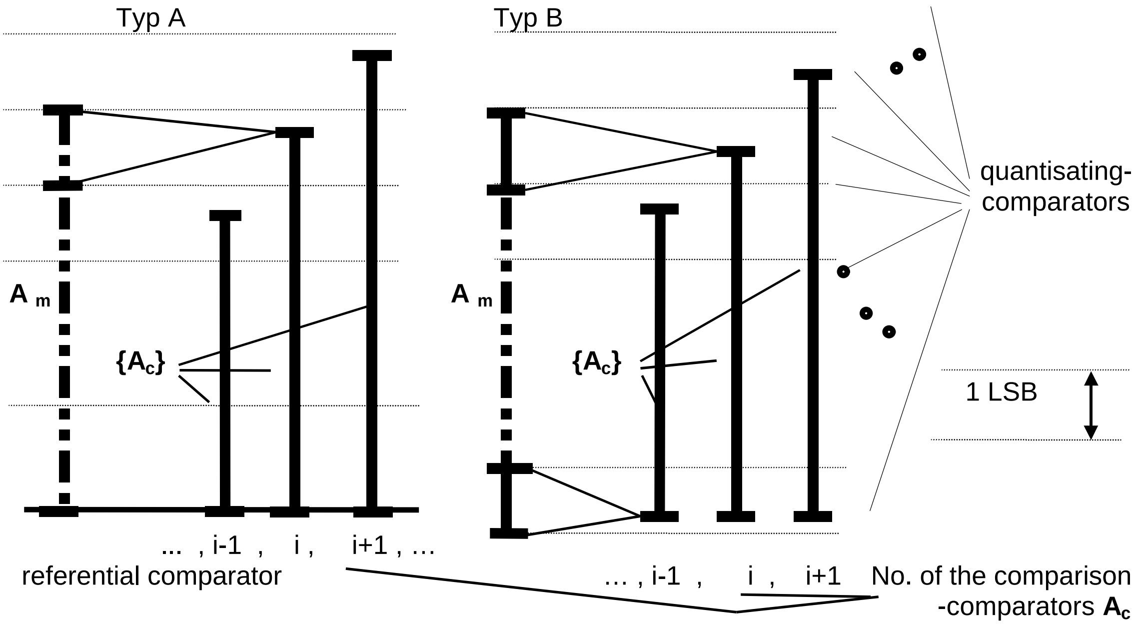

Figure 2. Measuring comparators of the types A and B
Type A is composed of 1 comparison comparator and 1 referential comparator
it has the simple quantisation error 1/2 LSB
Type B is composed of 2 quantisating comparators, it has the double quantisation error 1 LSB

However is not at all measurements a referential comparator realizable. If a time or frequency measurement is undertaken on the basis of the world time or a quartz generator, so exists a stiff screen of time strokes. The start for the times or frequencies to be measured results however often independently from this measuring screen. Thus beginning as well as ending of the measuring time must be determinate by means of a quantisation comparator (Fig. 2 on the right below and above). With it emerges a **measuring comparator type B**. Herewith the measuring quantity emerge both in the beginning as well as at the end of the quantity A_m a quantisation error 1/2 LSB. Altogether the comparison with a measuring comparator type B leads to the **double error of quantisation** of 1 LSB. Falsely this kind of error under the designation „digital remainder error“ is associated often only digital measuring devices. Today all ADC with measuring comparators work however with the type A. On the other hand a whole series of analogous gauges have measuring comparators type B. They yield therefore a digital residual error.

If one explores the technical possibilities of the comparison of quantities through measuring comparators, so strikes, that a few only in the measuring technology are inserted:

Length, angles, torque , electric voltage and time, in rare cases still the electric current and the lighting intensity. Direct comparisons of temperatures, masses, forces or magnetic quantities are not to be met. Similarly it looks at the measure embodiments. At the analogous gauges lengths-and anglescales, mass units (wights), pendulums and balances dominate as well as electric resistance, in the digital measuring technology almost exclusively voltage sources and quartz generators.

5 MEASURING TRANSFORMERS

To record the entire width of measuring devices both between measuring quantityies and measuring comparator as well as between measure embodiments and measuring comparators transformers are inserted. There are scale transformers and dimension transformers.

Scale transformers do not change the kind of quantity. They have constant or in steps changeable transfer elements between their entrances and exits. Typical examples for scale transformers are in the mechanic levers and crooked plane, in the optic lenses and in the electrical engineering voltage divider or amplifiers. So one derives from a standard cell precise d.c.voltage in the area of microvolt up to many volts. For the adjustment of scale transformers no etalons are required.There suffice generally reproducible processes, like which twofold or halving of quantities.

Dimension transformers have clear connections between different kind of quantities. Among this count thermocouples, strain gauge, feathers and pressure membranes, bimetal elements or phototransistors. Thermocouples guarantees a problem-free temperature measurement, although it neither temperature measure embodiments gives nor temperature comparators. While scale transformers adjusted become without connection at a Normally be able to do requires one for dimension transformers per an etalons both for the entrance quantity and the exit quantity.

In rare cases is the dimension transformer themselves a measure embodiment, like which electric resistance R= U/I. In such cases is for the standardization only one etalon necessary.

Generally one must presuppose for a dimension transformer only, that it owns a monotonously climbing characteristic with an unique connection A'= f (A).

For the simplification of the matter subsequently is indicated always a multiplicative connection in the form A'= k A. Thereby is between the analogous connection $k_{ma}= A_m'/ A_m$, which is marked as change function, and his digital value $k_{md}= S_m'/ S_m$, the transformation faktor, to distinguish.

For the comparison under inclusion of measuring and comparison quantity transformers (see fig. 3) emerges the relationship according to eq. (3)

$$A_m' =_q A_{ci}' \qquad (7)$$

respectively. with $A_m' = k_{ma} \; A_m$ und $A_c' = k_{ca} \; A_c$

$$k_{ma} A_m =_q k_{ca} A_{ci} \qquad (8)$$

just as resolved to A_m :

$$A_m =_q (k_{ca} / k_{ma}) A_{ci} \qquad (9)$$

The passage of the quantity to the values yields ultimately

$$S_m =_q (k_{cd} / k_{md}) S_{ci} \qquad (10)$$

Scaling is at the employment of measuring transformers no more only by the selection different comparison quantities possible but also by variation the change of conversion factors in the measuring and the comparison canal. The comparison quantity change function k_{ca} suits especially. It enters linearly in the result S_{ci}. Changes of k_{ma} are used mostly to the decadic measuring area changes, since an inverse influence exists to the measuring value.

As example for a scaling by selection of the measure embodiment A_{ci} is given here the balanced beam. The adjustment is affectef by variation of weights. In contrast to it in the balance with sliding weight the measure embodiment A_c is constant. The scaling results by variation of the measuring transformer, the lever length k_{ca} .

6 MEASURING DEVICE

Fig. 3 shows that general function diagram of all gauges and measuring devices. It is the technical convert of the equations (9) and (10).

Each measuring device is made accessible the measuring quantity A_m of a measuring object. It contains always a measure embodiment. This produces the comparison quantity A_c (monovalent measure embodiment) or them A_{ci} (polyvalent measure embodiment). Both as well as can be conveyed quantity transformers. Their exit quantity A_m‘ and A_c’ arrive at the measuring comparator. The comparison quantity is varied as long as, until the measuring comparator recognizes $=_q$ and is fulfilled thus equation (9). By this time the pertinent values of the transformers and the measure embodiment are recorded and the measuring value according to equation (10) calculated. At analogous measuring devices become both undertaken the comparison ($=_q$) as well as the variation of measure embodiment and/ or comparison transformers and measuring quantity transformers by the man. He calculates also the measuring value according to eq. (10), how at the moving-coil instrument was demonstrated.

Digital measuring devices contain:

- a controller and a measuring comparator, whose signals ≠ or $=_q$ are determined by the controller,
- from the controller controllable arrangements for the variation of comparison quantity transformers and measuring quantity transformers as well as, if present, for the selection of the required comparison value from a polyvalent measure embodiment.

The controller realizes after comparison the dataacquisition and measuring value calculation as well as also the output.

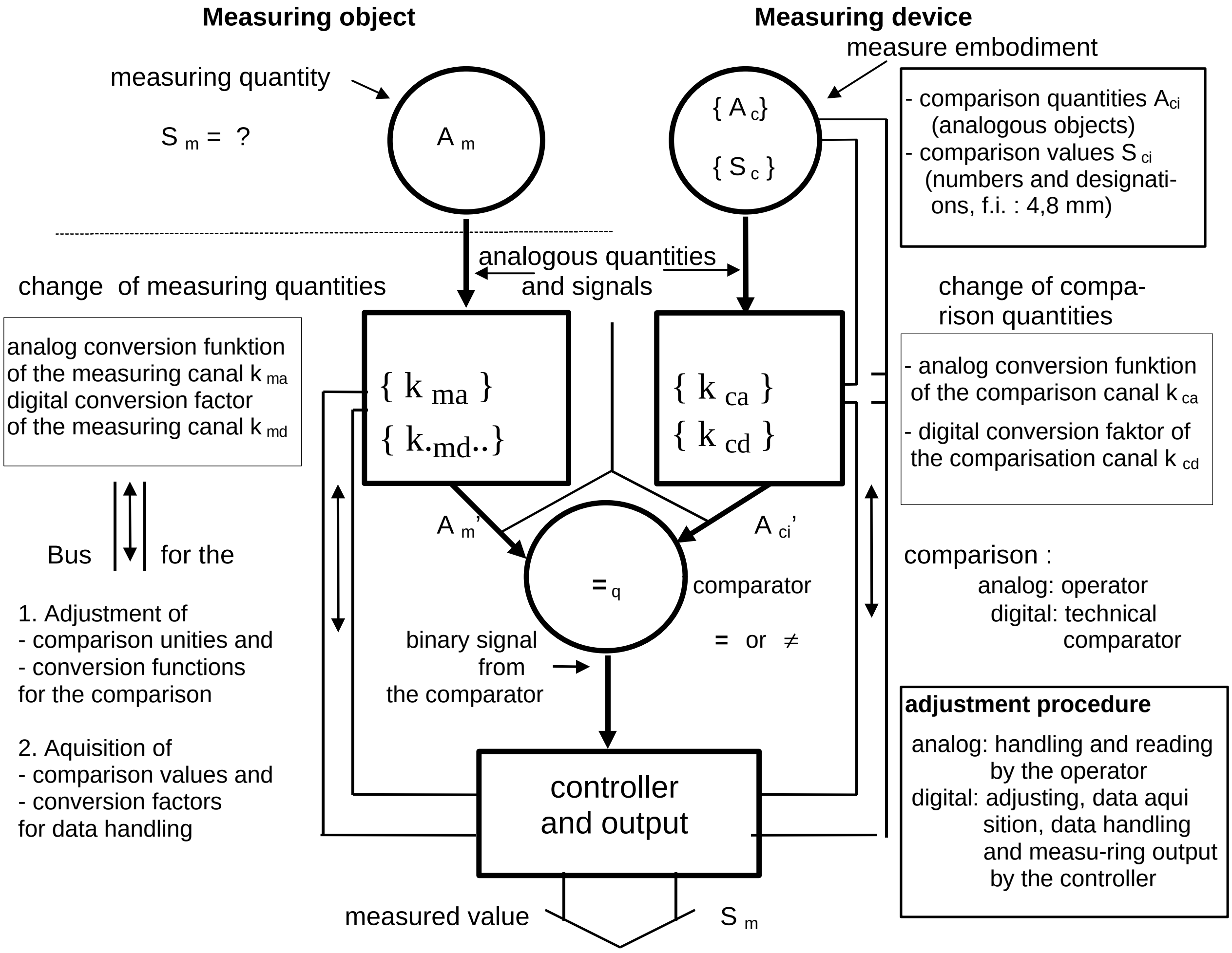

Figure 3. Scheme of measuring devices

REFERENCES

[1] Dubrau, H.-J.: Unitary block scheme for measuring devices. 5th International IMEKO Symposium TC 7 „Intelligent measurement“, June, 10-14, 1986Jena GDR
[2] Dubrau, H.-J.: Hybrid memories of measures in meters and measuring devices.3rd International IMEKO Symposium on theoretical Metrology. October, 15-17,1986 Berlin GDR
[3] Dubrau, H.-J.: Vom Sensor zur Meßwertausgabe - ein einheitliches Funktionsschema des Meßprozesses. IV. Meßtechnisches Symposium. Rheinisch-Westfälische Technische Hochschule. Oktober, 10-11, 1991, Aachen FRG

AUTHOR: emeritus Prof. Dr. Hans-Joachim DUBRAU, Zelz 11a, 03159 Jerischke, Germany
Phone/Fax : ++49 35600 22560