On the Information Flow of Measuring Systems and the Influence of Self-Calibration

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Abstract: For the design of smart sensors and measuring systems the information flow of measurement systems is of increasing importance. Therefore the maximum information flow of some systems and especially of some measuring systems with self-calibration is examined. The special information flow problems of self-calibration are regarded.

1. Introduction

The maximum information flow is an important parameter to characterize telecommunication systems. In modern systems different intelligent components e.g. of measurement, of compu-ting and of telecommunication applications collaborate. There is mostly to realize a voluminous exchange of information between their components . Therefore the interface conditions and especially the information flow between these systems is of high importance. In this paper, the information flow of measuring systems will be regarded and consequences for its optimization will be derived.
The objective of the paper is to analyze different groups of intelligent measuring systems concerning to their channel capacity and the influence of the self-calibration algorithms on their resulting information flow.

2. Theoretical Base

The given examinations base on a general system structure similar to that shown in fig. 1. This structure is valid for smart measuring systems and sensors. The maximum available information flow – similar to the channel capacity - gives the possibility to analyze measuring units and the computer structure by a common theoretical base.

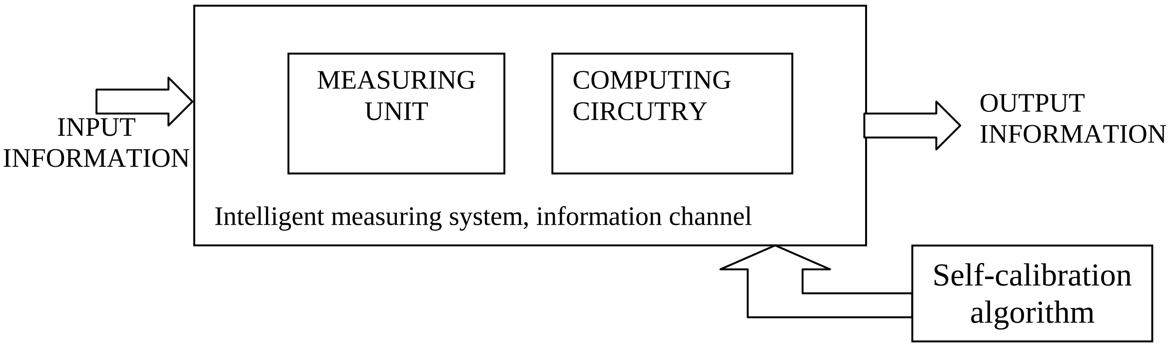


Figure 1 General intelligent measuring system

Generally, calculators and measurement systems are characterized by different parameters. Especially the number of operations per time, the length of words, the clock frequency, and additionally the characteristics of the memory are of special importance for the computer circuitry. The measuring deviations, the resolution, and the number of decision classes are the main parameters of measuring units. Further, rise and fall time, conversion time and e.g. measurement frequency are also used.

The channel capacity C characterizes the information flow of the intelligent systems:

$$C = Q_i \max$$
$$Q_i = \frac{1}{T_M} \text{ ld } m \quad \text{Bit s}^{-1} \qquad (1)$$

with: T_M time between two measurements
m number of classes

The main problem is to find the relevant number of classes and the total needed time of the measurement procedure, depending on the structure and on the algorithm of the self-calibration.

The relation between the absolute and the relative measuring error e_m respectively F and the range of measurement x_{max} - x_{min} is given by

$$F = \frac{e_m}{x_m} = \frac{e_m}{x_{max} - x_{min}} \qquad (2)$$

In the case of |F|<<1, a linear divided scale with steps of s = $2e_m$, of an equal probability for all x_E in the region from x_{min} to x_{max} , the information flow Q_i is finally given by equ. 3[2 etc.]:

$$Q_i = \frac{1}{T_M} \mathrm{ld} \quad m = \frac{1}{T_M} \mathrm{ld} \left(\frac{1}{2F} + 1 \right)$$

$$Q_i \approx \frac{1}{T_M} \mathrm{ld} \quad \frac{1}{2F} \qquad \text{Bit s}^{-1} \qquad (3)$$

The gain of information flow $G_i = Q_{i1}/Q_{i2}$ and the difference of the information flow $D_i = Q_{i1} - Q_{i2}$ allow to compare the different systems:

$$G_i \quad = \quad \frac{T_{M2}\, \mathrm{ld} \quad 2F_1}{T_{M1} \mathrm{ld} \quad 2F_2} \approx \frac{T_{M2}}{T_{M1}} \left[1 - 2(F_1 - F_2) \right] \qquad (4)$$

$$D_i = \frac{1}{T_{M1}} \mathrm{ld} \quad 2\, F_1 \; - \; \frac{1}{T_{M2}} \mathrm{ld} \quad 2F_2 \qquad \text{Bit s}^{-1} \qquad (5)$$

(with ld x ≈ 1-x for x<<1)

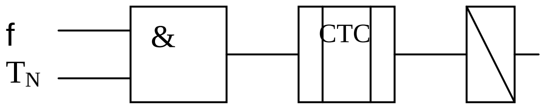
The corresponding relations for the communication systems and for the computers may be estimated from the number of symbols per clock, worth length and the number of operations per time in a similar way. This relations give the possibility to evaluate and to optimize the information chain sensors – transmission line– computer.

3. Information Flow of Systems

3.1 System 1(Counter)

In the case of the counting measuring systems it is shown, that the information flow is given by two typical terms (equ.3), one mainly depending on the measuring time and the other depending on the accuracy of the hardware components. This gives criterions to optimize the system concerning to its information flow or its accuracy.

Figure 2: Counter (Basic variant), CTC counter circuit



For frequency measurements two different methods are used:

<u>Variant A:</u> Direct Frequency Measurement (conventional counter)

With $T_N = T_M$ gate time, shortest time between two measurements
$F_Z = 1/z_{max}$ digital system error, there are no other errors assumed,
$z_{max} = m$, number of classes

The information flow is given by:

$$Q_{iA} = f_x \frac{ld\ 2z_{max}}{z_{max}} \quad \text{Bit s}^{-1}$$

<u>Variant B:</u> „Inverse” Frequency Measurement System (computing counter). The gate time T_N is formed by N periods of the measurand f_x. The counter registers the number of pulses of the reference frequency f_0 during the gate time $T_N = N\,T_x$. With $T_x = 1 / f_x$ and $T_N = z_{max} / f_0$ follows

$$Q_{iB} = f_o \frac{ld\ 2z_{max}}{z_{max}} \quad \text{Bit s}^{-1}$$

The gain of information and the difference

$$G_i = Q_{iA}/Q_{iB} = f_x/f_0 \qquad (6)$$

$$D_i = \frac{ld\,2z_{max}}{z_{max}}(f_x - f_0) \quad \text{Bit s}^{-1} \qquad (7)$$

show that the method A is more favorable than method B in the case of $f_x > f_0$ for the same resolution ([2],[4] etc.).

3.2 System 2 (General System with self-calibration)

Fig. 3 gives the structure of the regarded system including the self-calibration and an offset correction. x_s represents the offset, k characterizes the transfer factor of the smart sensor or of the measuring system.

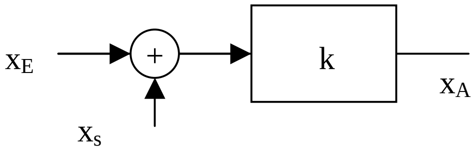


Figure. 3. Exemple 2

a) Without self-calibration it follows from: $x_A = (x_s + x_E)\,k_0\,(1 + F_k)$
the maximum error: $F_{A0} = |F_E| + |F_k|$ with $F_E = x_s/x_E$ (14)

b) With self-calibration the following algorithm will be used
under the conditions:

x_0 reference of high long-term stability
F_0 maximum error of x_0
T_M time for measurement of x_1, x_2, x_3 and for calculation of x_E
$T_{Mges} \approx 4\,T_M$, total measuring time
$F_1 = F_2 = F_3 = F$ maximum measuring error

- Measurement 1 $x_1 = k\, x_s$
- Measurement 2 $x_2 = k\,(x_s + x_0)$
- Measurement 3 $x_3 = k\,(x_s + x_E)$
- Calculation of x_E

with :

$$x_E = \frac{x_3 - x_1}{x_2 - x_1}\, x_0$$

$$F_{Am} = |F_0| + 2|F| \qquad \text{(maximum error)} \qquad (15)$$

c) Comparison:

Without self-calibration: $Q_{io} \approx -\frac{1}{T_M}\,\mathrm{ld}\,2F_{Ao}$ Bit s^{-1}

With self-calibration: $Q_{im} \approx -\frac{1}{4T_M}\,\mathrm{ld}\,2F_{Am}$ Bit s^{-1}

Corresponding to equ.(4) and (5) one receives using equ. (14) and (15):

$$G_i \approx 4[1 - 2(F_E + F_k) + 2(F_0 + 2F\ )] \qquad (16)$$

$$D_i = \frac{1}{4T_M}\,\mathrm{ld}\,\frac{2(F_0\ + 2F\ )}{2^4(F_E + F_k)^4} \quad \text{Bit } s^{-1} \qquad (17)$$

The comparison of the information flow between the to regarded systems shows two special regions with $Q_{im} > Q_{io}$ and $Q_{im} < Q_{io}$. Fig. 4 gives an explications for the fact, that it is generally very difficult or expensive to reach the same information flow in systems with self-calibration as by systems without any self-calibration.

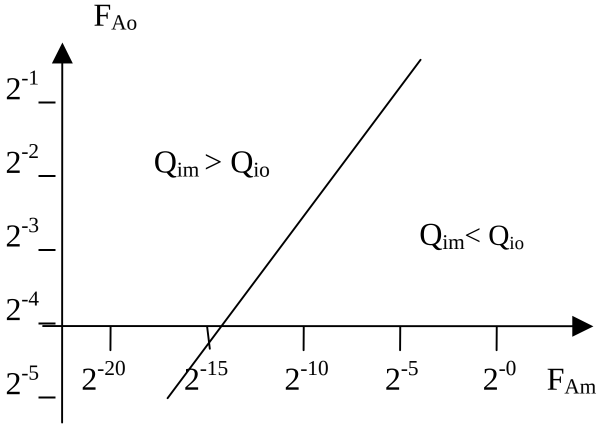


Figure 4. Comparison of system A with system B

3.3 System 3 (Depth measurement)

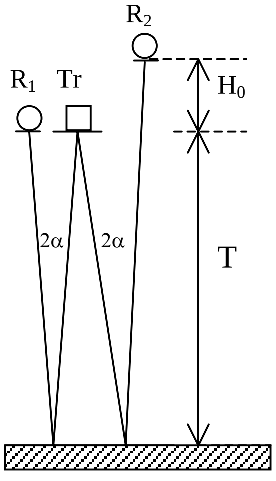


Figure.5 Measurement of depth T

Fig. 5 shows an ultra-sonic measuring system for the depth of a boiler. R_1, R_2 are the two receivers of the pulses generated by the transmitter Tr. In this case the depth measurement is reduced to the measurement of the pulse transit time between the transmitter and both receivers under the following conditions:

$$\alpha < 1, \ \cos\alpha \approx 1 - \frac{\alpha^2}{2} \ ; \quad H_0 << T;$$

- $F_{fo} << 1$ error of reference frequency f_0 of the counter
- $F_z = 1/z$ digital system error of time measurement
- short time stability of f_0 and c (sound velocity) assumed

a) Reference system (System without self-calibration)

The depth measurement is reduced to the pulse transition time measurement on the way Tr-R1 and contains no self-calibration . The depth T_o and its error F_{T0} may be calculated by the following expressions:

$$T_o = \frac{c(1-\frac{\alpha^2}{2})z_1}{2f_0} \quad \text{and} \quad F_{To} \approx F_c + 1/z_1 \qquad (18)$$

These measurements are essentially influenced by the changes of the sound velocity depending on variations of the gas concentration and of the gas temperature.

b) Depth measurement with self-calibration: Assuming only a short time stability of f_0 and the sound velocity c the measured depth T_m and the errors F_{Tm} are given by:

$$T_m = \frac{H_0}{2}\frac{z_1}{z_2 - z_1}$$

$$F_{Tm} = \frac{z_2}{z_2 - z_1}\left[\frac{1}{z_1} + \frac{1}{z_2}\right] + F_{H0}$$

There z_1 and z_2 represent the counting results of the parallel executed digital measurements of the transit time T_M between $Tr\text{-}R_1$ and $Tr\text{-}R_2$ and T_{M1} is near T_{M2}.
Introducing the process parameters λ, c, and f_0 it follows:

$$F_{Tm} \approx \frac{c \ \cos\alpha}{H_0 f_0}\left(\frac{4T - H_0}{2T}\right) + F_{H0}$$

$$F_{Tm} \approx \frac{2c}{H_0 f_0} + F_{H0} \qquad (19)$$

c) comparison: Comparing both systems and taking in account the relation $T, H_0 >> \lambda = c/f_0$ we receive corresponding to (4) and (5):

$$G_i \approx \frac{ld2F_{Tm}}{ld2F_o} \approx [1 - 2(F_{Ho} - F_c)] \qquad (20)$$

$$D_i \approx \frac{1}{T_M}\left(ld\frac{F_{Ho}}{F_c}\right) \qquad Bits^{-1} \qquad (21)$$

4. Summary

Generally. a measurement system acts as a part of an information channel (fig.6). Therefore, the information flow of such a system is an important unity to characterize the system and its components. But, the optimization of its technical structure needs of course the knowledge of the parameters in the physical plane. Additionally, the knowledge of the expected information flow is an important part for the design of the different interface planes and processes, for data processing and handling. It starts with the incoming information flow (output of the measuring object) and end at the measuring system's output. In this connection the relation between the accuracy and the needed measuring time is of special importance. This was discussed for several classes of systems /sensors in chapter 3.
It was shown, that the information flow is generally more influenced by the measuring time than by the accuracy of the system (equ. 3, 4, and 5) With self-calibration it is possible to increase the accuracy of a measurement system or to reduce the effort concerning to the long-term stability of its components (example 3.3). But, self-calibration needs additional measuring procedures. This means, that special efforts concerning to the system structure, the measuring procedure and algorithm have to be done. Only by an essential reduction of the needed time between two measurements a sufficient high information flow will be reached. This is possible by an

essential change of the measurement procedure and in consequence of the system structure. One possible way is a parallel working system as it was discussed in chapter 3.3b . In this way an increase of the information flow is reached and at the same time the accuracy will be essentially improved (example 3.3). But, naturally, the expenses increase.

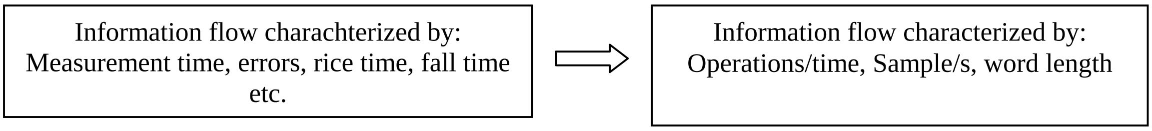


Figure 6 Measuring chain, information channel

On the other hand one can conclude, that there is no strategy to optimize Q_{imax} nd F_{min} at the same time at a low level of technical requirements. In the worst case, the optimization of a measuring system has to take in account two possible extremely different strategies, depending on its application : to maximize the available accuracy or to maximize the available information flow.

The main advantage of self-calibration is, that the long-term-stability is reduced to that of only a small number of components, mainly to a low-cost reference and its environment. Special correction algorithms lead in measuring systems to a high accuracy but they reduce additionally the information flow. The reduction of the resulting information flow by self-calibration is remarkable (chapter 3, factor of $10^{-2}..10^{-3}$) and it is only to avoid in the above mentioned way.

Generally, the regarded problems are valid for analogue and for digital systems or sensors. ADC-structures show a similar behavior ([2] etc.), too.

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