Intelligent Sensors, the basics still apply.

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There is presently a great emphasis, in the scientific and engineering communities and the popular trade press, on intelligent or smart sensors. The terms "smart" or "intelligent" sensors refer to the inclusion of a microprocessor packaged with the transducer. This has enabled calibration and error analysis of the transducer and with the addition of digital transmission more information is available to the controller than just the transducer output. This extra information includes identification, calibration information and error reporting. With the emphasis on the "intelligence" and digital communications the transducer, the source of the information, may be ignored. In this paper the "traditional" methods of specifying transducer systems are revisited and discussed and the relationship of these techniques to the "smart" sensor revolution examined.

1 Introduction

Traditionally, in a measurement system, the term sensor referred to the element that is in contact with the variable being measured [1]. Typical examples of a sensor would be thermocouples, strain gauges or optical diodes. To convert the electrical signal from the sensor, to a level where it could be used for display or control purposes, a signal conditioning section would be required. This would include power supplies, amplifiers and possibly a communications interface. The combination of the these elements, normally in separate enclosures, was referred to as the "transducer". To complete the measurement system there would also be a signal processing element, data analysis and display or storage facilities which were again separate from the transducer.

With the development of microprocessors and large scale integration and miniaturisation of the individual components a trend developed to combine some or all of these different functions into a single enclosure or package with some form of digital communication. This brought about the terms "smart" or "intelligent" sensors or transducers and more recently "soft sensors". The definition of what does what is not clear with the debate ongoing [2, 3, 4, 5, 6]. The term "integrated" will be used in this paper to encompass all the definitions.

Designers and users of measurement systems using integrated sensors must guard against being insulated from the problems of the actual measurement by the ease of connecting and collecting data. The errors associated with the digitising of the signal and the digital communications also need to be considered when specifying or using a measurement system. The basics of specifying a measurement system are discussed with special emphasis on systems using integrated sensors.

2 Model of a Measurement System

Figure 1 shows a generalised model of a measurement system, as defined by Bently [1], accounting for both the static characteristics and the dynamic transfer function.

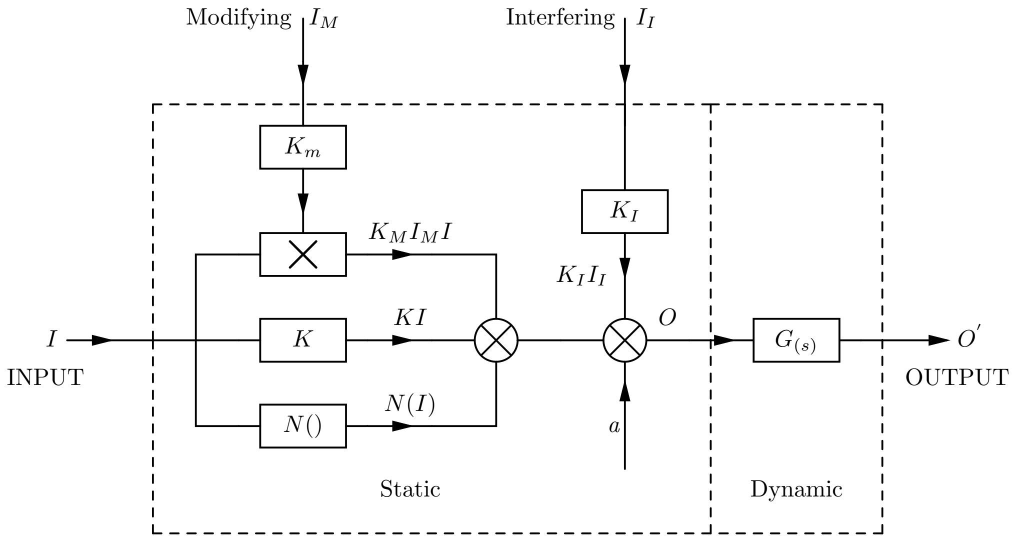

Figure 1: General model of a measurement system (After Bently [1])

This model will be used as the basis to analyse integrated measurement systems in terms of static, dynamic, error and noise characteristics.

2.1 Static characteristics

The static characteristics of a measurement can be defined by equation 1 [1].

$$O = KI + a + N(I) + K_M I_M I + K_I I_I \tag{1}$$

where

$$\begin{aligned}
I &= \text{Input of physical variable} \\
O &= \text{Output} \\
K &= \text{Gain} \\
a &= \text{Offset} \\
N &= \text{Non-linearity function} \\
K_M &= \text{Gain factor for the modifying input(s)} \\
I_M &= \text{Modifying input(s)} \\
K_I &= \text{Gain factor for the interfering input(s)} \\
I_I &= \text{Interfering input(s)}
\end{aligned}$$

The output (O) is defined in terms of the input variable (I) with respect to the gain, offset and non-linearity. In addition external conditions, such as change in power supply voltage or ambient temperature, are included in the modifying (I_M) and interfering (I_I) inputs. The modifying input(s) is defined as external influences changing the gain and the interfering input(s) as external influences changing the offset value.

The user of an integrated sensor, or measurement system, must consider this model when analysing the system in terms of the manufacturers data sheets, especially if the system is being marketed as a 'smart' sensor which may underplay the basic specifications.

A search for the basic information from various manufacturers of 'smart' sensors on the world wide web (www) revealed that this information was not available on the 'brochure' type data sheets [7]. It was found that it was necessary to download the operating instruction manual to obtain the basic data [8][1]. These are not always available to be downloaded and must be obtained from the manufacturer before any system is purchased. Table 1 shows the 'translation' between the inputs required by the model (figure 1) and the information supplied on the instruction manual [8]. The information for the model may have to be derived from more than one item on the data sheet as indicated.

Table 1: Translation of instruction manual information for the input to model

Model	**Instruction Manual**
Input (I)	Input range and Thermocouple type
Gain (K)	Input range and Thermocouple type
Offset (a)	Offset error
Non-linearity function (N_I)	not specified
Gain for the modifying input(s) (K_M)	Gain error
Modifying input (I_M)	Gain error (only related to temperature)
Gain for the interfering input(s) (K_I)	Offset error
Interfering input(I_I)	Offset error (only related to temperature)

Analysis of table 1 indicates that the user will have to carefully examine spe-

[1]Please note that the data sheets used in this paper were not chosen for any other reason than the ease of finding and downloading them.

cifications to extract the information required for the model to determine the limitations of the system. If the specifications are not complete the manufacturer must be contacted to supply the missing information, in this case the non-linearity of the system. It must not be assumed that a particular specification is perfect if it is not specified.

2.2 Dynamic characteristics

The determination and specification of the dynamic characteristics of an analogue measurement system is well documented in a number of text books including books by Bently [1] and Nachtigal et al [2]. The dynamic characteristics can be defined by using

- Linearisation and superposition
- Various transfer functions
- Transient response
- Frequency response

amongst others. The transfer function $G_{(S)}$ in figure 1 is defined as the ratio of the Laplace transform of the output ($\bar{f}o_{(S)}$) to the Laplace transform of the input ($\bar{f}i_{(S)}$) as shown in equation 2 [1].

$$G_{(s)} = \frac{\bar{f}o_{(S)}}{\bar{f}i_{(S)}} \tag{2}$$

Although the text books describe these methods to determine the dynamic characteristics of any system, data sheets do not normally give complete dynamic specifications and it is the responsibility of the user to determine if the measurement system, or components, meets the requirements. The instruction manual for an eight channel thermocouple input module [8] only gives the following specifications on the dynamic response.

- Update rate: 0,8 s per channel
- Input bandwidth: 3Hz

For this example, temperature measurement using thermocouples, the user will have to determine

1. the thermal inertia of the probe connected to the input module,
2. the bandwidth of the signal conditioner,
3. the sample rate of the analogue to digital (A/D) converter and
4. the transfer rate on the communication link or network.

This task may not be trivial and may require some form of experimentation on the whole measurement system, noting that under varying traffic conditions on the communication link or network the dynamic response may change.

2.3 Error analysis

Standard error analysis [1, 2] of the system still needs to be conducted even when using ‘smart’ sensors which include internal error correction. Miklovic [9] states *“The errors that can occur at different stages in the data acquisition process must be analysed, as they can add up to make the data meaningless”*. Care should also be taken not to interpret the accuracy of the output as being the same as the resolution of the display.

2.4 Noise

In a measurement system, noise is defined as any electrical signal present other than the the desired signal [10]. This noise may be coupled into the system through individual components or interconnecting cables. The mechanisms that introduce noise are defined by Bently [1] and Henry [10] and are

- Conductive coupling
- Common Impedance
- Capacitive coupling
- Inductive coupling
- Electromagnetic coupling

with standard methods described to reduce unwanted signals in a measurement system.

With integrated systems there are other noise sources to consider as the A/D conversion is done at the transducer and not at the controlling computer. This is a major advantage as the noise coupled into the interconnecting cables does not have to be considered unless the digital communication is disrupted. What must not be overlooked is the possible noise introduced into the system by the A/D conversion. This includes noise coupled into the analogue section of the integrated system from the microprocessor and A/D converter, quantification errors, aliasing errors and dynamic response errors caused by variation in data transmission to the host.

Referring to the instruction manual for an eight channel thermocouple input module [8] the input bandwidth is specified at 3 Hz and the sample rate for each channel 0,8 s or 1,25 Hz. This would cause serious aliasing noise from all signals with a frequencies above 0,625 Hz. If the bandwidth was specified at the -3dB points the frequencies that will cause an aliased signals will be lower than 0,625 Hz.

One of the concerns in using network based systems for communicating between integrated sensors and the supervisory computer is the unknown variation in the transmission rate [11]. This will introduce noise, referred to as jitter [12, 13], as the sample rate could vary at an unknown rate. This must be considered when designing or analysing a measurement system.

3 Conclusion

There are many advantages in using "integrated" components when designing or using a measurement system. However, the basic characteristics of all the components must be considered as well as errors that may be inherent in an integrated system using microprocessors and digital communications. Using digital communications may eliminate noise coupled into the cable connecting the remote transducer to a central processor but the problems of communication delays, often variable, will introduce noise which will have to be included in the data analysis. The statement by Miklovic [9], in section 2.3, should always be born in mind, and all components of a measurement system should be analysed so that the data does not end up being meaningless.

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