Signal Processing and Calibration

15

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Sensors convert the physical quantity to be measured into an electrical signal. There are three points to consider:

1. The sensor signal is usually *very small.* It must therefore be amplified to a *standard level* so that it can be processed by a controller.
2. The influence of *disturbance variables* must be taken into account (e.g. influence of temperature on the characteristic curve of a humidity sensor).
3. Characteristic curves must be *filtered* and *linearized* very often.

Temperature measurement has a special position here. There are measuring elements with *undisturbed* and *linear* character (e.g. PT100 and thermocouple). These elements can often be connected directly to special inputs of control systems. In this sense, they form their *own signal standard.*

15.1 Signal Processing

With a large number of sensor elements, the output signal is generated by relatively few physical effects, which can be summarized as follows

- Generation of a *charge* or a *voltage* (e.g. piezoelectric effect, thermocouple, photoelement).
- Change of *resistance* or a *conductance* (e.g. strain gauge, photoresistance, change of the channel resistance of FETs by ions).

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- Change in *capacitance* or *inductance* and resulting *AC resistance* (e.g. humidity, distance and distances).

There are many specific methods of signal acquisition for discrete sensor systems. These range from pure *binary information* to the formation of *pulses* and *pulse groups* and *complex data sets* for image evaluation. In this group, time or frequency as an information-carrying variable is very common.

The following sections cover the basic possibilities of signal processing. These considerations are carried out exemplarily on a resistive sensor element since in this case the methods can be clarified very well.

15.1.1 Analog (Discrete) Signal Conditioning

The classic, analog signal conditioning still has its importance when it comes to *low-noise sensor signals*. Due to the simple circuit technology there are hardly any additional noise sources. This method is also suitable when a signal of low quality is required, for example for switching purposes.

In the circuit, in Fig. 15.1 the sensitive element is formed by the resistors R1 to R4. The available output signal of the bridge is tapped symmetrically with the differential amplifier IC1A and amplified asymmetrically to the standard level with IC1B. Zero adjustment is carried out with resistor R5, full-scale adjustment with resistor R7.

15.1.2 Signal Conditioning with System Circuits

In connection with frequently occurring tasks, system circuits have been developed by the industry which allow the coupling of different sensor elements and convert them to a standard signal. In Fig. 15.2, an IC from Texas Instruments was selected as an example, which is used to convert a thermal resistance to a current loop signal.

As is typical for system circuits, it contains not only the amplifiers but also the necessary additional components such as current sources and multiplexers. In the example, the necessary settings are stored in an external EEPROM.

15.1.3 Signal Conditioning with ASICs

For standard measuring tasks such as temperature, pressure or displacement measurements, it is advisable to develop circuits that are adapted to the specific measuring tasks of the individual sensor elements. This results in highly complex components that, thanks to a large number of adjustable parameters, cover the complete range of tasks from signal acquisition, processing and correction to analog or digital data output.

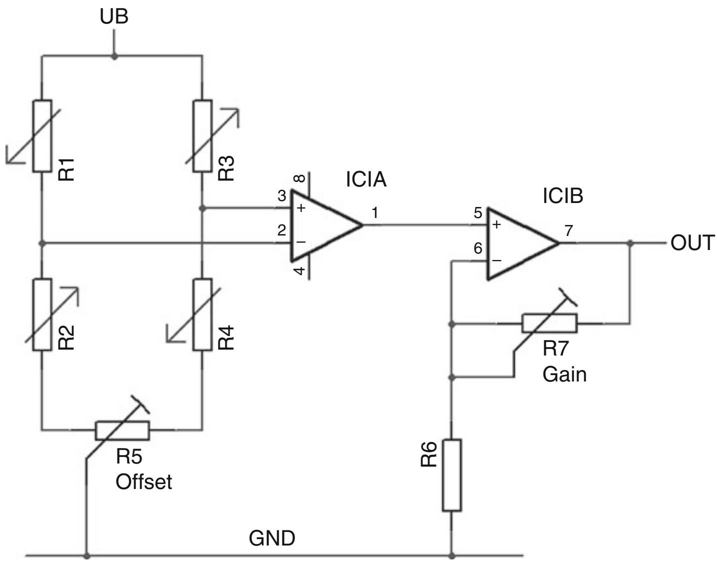

Fig. 15.1 Basic circuit for analog signal conditioning

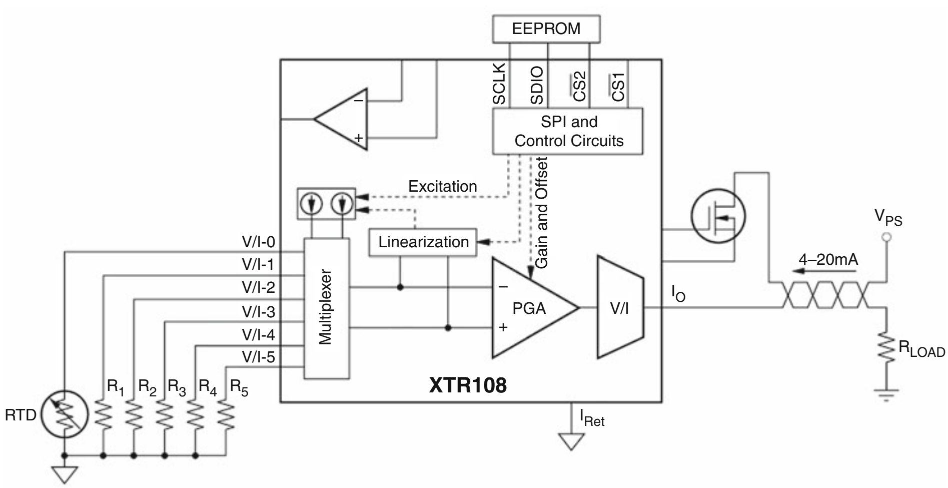

Fig. 15.2 System circuit XTR108 (Source: Texas Instruments)

As an example, the ZMD31050 was picked out, which is shown in Fig. 15.3 in the principle circuit for a ratiometric pressure transmitter. It has a 16-bit AD converter, an input filter and an 11-bit DA converter. Diode D1 is used to determine the temperature of the bridge which is required for compensation of the pressure characteristic curve. The output signal is calculated by solving a third-degree equation with both input variables.

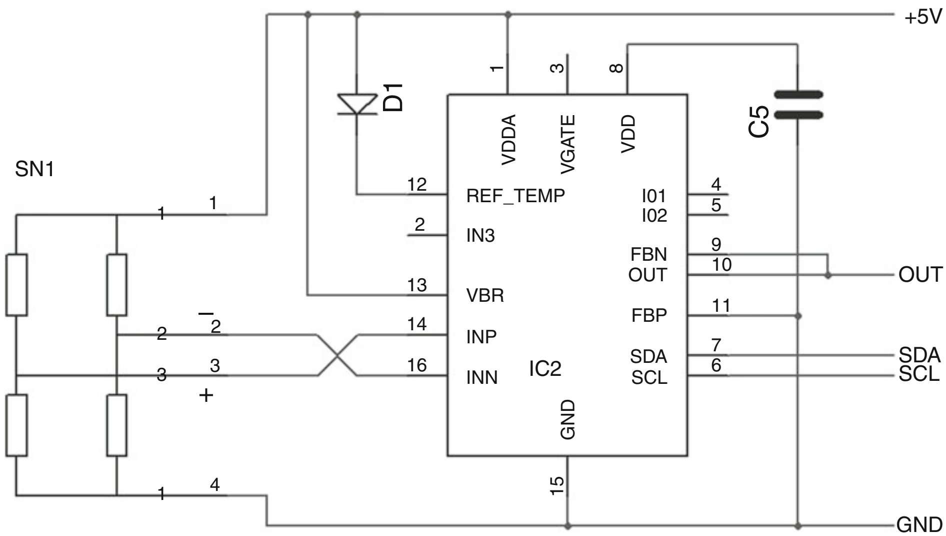

Fig. 15.3 ASIC for pressure transmitter

15.1.4 Signal Conditioning with Microcontrollers

The sensor signals can also be processed directly with a microcontroller. The most important requirement here is an analog-to-digital converter with a corresponding accuracy and the possibility of outputting an analog signal. This can be realized by a DA-converter or a PWM-unit. These units do not necessarily have to be integrated into the controller.

If the signal acquisition and processing is done with a processor, it is always in connection with an adjustment.

The advantage of this processing path is that characteristics on the input and output side that cannot be converted by analog means can also be realized. This is made possible by the use of the software. Figure 15.4 shows a circuit section for a sensor with a resistance bridge, which realizes a voltage output of, for example, 0–10 V.

However, this path has the disadvantage that signal processing with software is always slower than in an analog signal path. It becomes slower the more complex the correction algorithm and signal processing becomes (Sect. 15.2.3).

15.2 Sensor Calibration

Although the term sensor calibration has become established in linguistic usage, it is wrong in the technical sense. In *calibration,* the *deviation* of a measured variable from a *standard* is documented. If the *signal* of a sensor is adjusted to a *setpoint value,* this is called an *adjustment.* The sensor adjustment has the task of freeing the measurement signal from

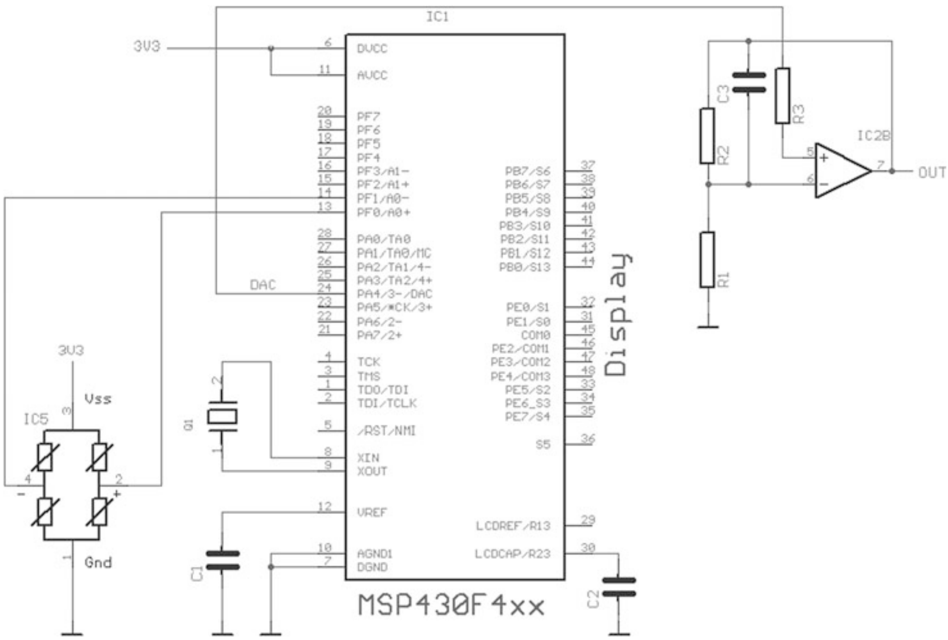

Fig. 15.4 Sensor circuit with a microcontroller

nonlinearities and disturbance variables by technical or mathematical methods. The main disturbance variable is usually the temperature.

15.2.1 Passive Compensation

For simple applications, for example in connection with the circuit in Fig. 15.5, a passively compensated measuring bridge can be used. This compensated sensor element then generates a defined output signal and can thus be conditioned with a permanently set simple amplifier. The adjustment of the resistors R1 to R4 is carried out within the scope of sensor manufacture. Figure 15.5 shows the schematic.

The resistors R3 and R4 are used to zero the bridge. Depending on the sign of the offset, one or the other resistor must be detuned.

The total resistance of the bridge and the change in resistance due to the measured variable results in a *slope,* which is specified in mV/V(Ub). This ratio can be changed by the resistors R1 and R2 so that the slope takes on a defined value. This target value is always smaller than the possible slope. The resistor value determined for this purpose is applied to R1 and R2 half each so that the output voltage of the bridge remains at Ub/2.

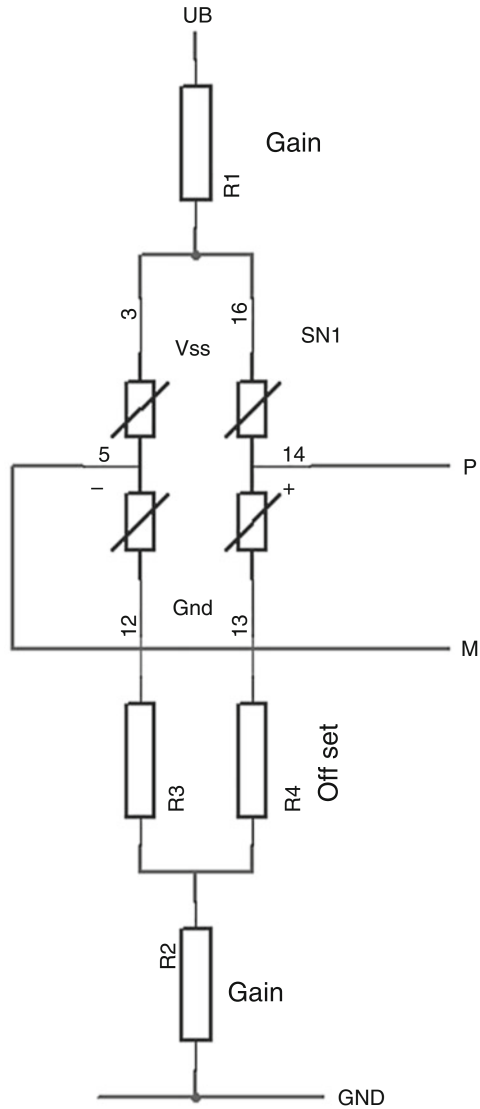

Fig. 15.5 Passive compensated measuring bridge

15.2.2 Adjustment with Analog Signal Processing

If the required corrective measures and properties are known for a sensing element, the required equation can be simulated as a sequence of linear and non-linear amplifier elements. In Fig. 15.6 an older analog ASIC is used as an example. The whole circuit is composed of amplifiers and multiplying DA-converters. As a result, a linear characteristic

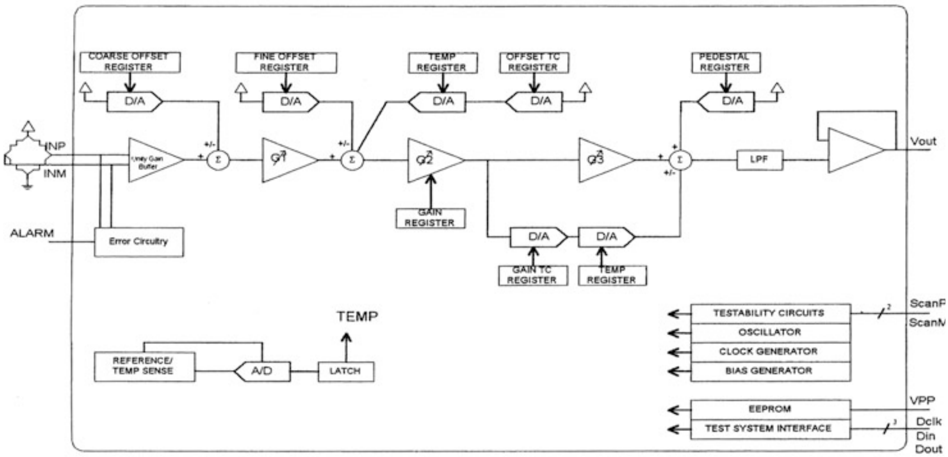

Fig. 15.6 ASIC with analog signal processing (SCA2096)

with offset and gain correction is realized for the useful signal, which is influenced in a second path by the measured temperature with a second-degree characteristic.

The adjustment procedure is carried out in three steps:

1. At room temperature, the offset (left two steps) and gain (middle step) are set as a direct relationship between input and output signal.
2. Then the adjustment is carried out at a higher temperature when the input conditions are repeated by changing the offset and gain of the temperature branch.
3. This process is repeated at a lower temperature.

If higher accuracies are required, these adjustments have to be run through several times, since the settings of the individual registers are not without effect on the other settings. The found settings are permanently stored in a memory in the ASIC. The ASIC itself generally works ratiometrically, that is, the output signal also behaves proportionally to the supply voltage.

15.2.3 Adjustment with Digital Signal Processing

A wide range of solutions exists for digital signal processing. Between the ASIC with a pure analog signal path and the pure computer solution, there is a wide range of ICs, which are equipped with an analog front end and have a special, fixed programmed computer structure internally. One of these is the circuit shown in Fig. 15.3, which is used to realize an arithmetic adjustment.

The basic structure in digital signal processing always consists of an input stage with offset correction and a high-resolution AD converter and an output stage as a DA converter.

It is irrelevant whether this is formed by separate components or integrated into an ASIC or processor module. The starting value for the processing is always the value of the input converter, which is supplemented by any interference signals measured on other channels. The result of the operation must be a value for the output DA converter, for the determination of which there are several methods.

Arithmetic method

To use this method, the *correction function* must be available as an *equation* through a closed mathematical representation. During operation, the processor calculates this instruction cyclically, using the input variables and the coefficients determined during calibration.

To determine the coefficients, a system of equations with n unknowns must be solved according to the degree of the functions. In the example of the ZMD31050, these are 7–9 equations for which a corresponding number of measured values is necessary. These measured values are obtained by setting the complete transmitter, for example, to different temperature/pressure combinations, and reading out the corresponding AD values for pressure and temperature. The equation system is then solved in an external computer and the results are stored in the ASIC. Figure 15.7 shows the equations of the ZMD31050. The computational effort can easily be estimated here.

In the example case, this method allows a high measuring rate (up to 4000 measurements/s), since the computer structure is adapted to the equation. If this path is taken by means of general processors, very long computing times can result, which drastically reduce the measuring rate. Some time can be gained by dispensing with floating-point arithmetic, but this requires exact knowledge of the measuring elements and their scattering.

Characteristic curve interpolation

If the arithmetic path cannot be traversed, for example, because no closed equation can be created, the path of characteristic curve interpolation is possible. Here, several interpolation points are determined from the input characteristic curve. The positions of the interpolation points (X-axis) are stored in the computer and the rise and offset of the characteristic curve range between them is determined from the measured values of neighbouring values. By using several interpolation points, the characteristic curve section can also be represented by a function of a higher degree. During the execution of the program, it is determined between which interpolation points the input signal is located and the corresponding set of coefficients is selected for processing. The calculation is then relatively simple.

If disturbance variables are still included in the processing, the characteristic curve expands to the surface or the room. A set of coefficients is then stored for each direction and each pair of interpolation points and the dimensions are processed sequentially.

If the interpolation points are closely spaced, linear interpolation is generally sufficient to determine the output value.

⇒ Range definition of inputs

$$Z_P \in \left[-2^R; 2^R\right) \qquad Z_{T1} \in \left[-2^{R-1}; 2^{R-1}\right)$$

$$c_i \in \left[-2^{15}; 2^{15}\right)$$

⇒ Conditioning Equations

$$Y = \frac{Z_P + \text{Offset}(Z_{T1})}{\text{Gain}(Z_{T1})} \qquad Y \in [0;1)$$

$$Y = \frac{Z_P + c_0 + 2^{-(R-1)} \cdot c_4 \cdot Z_{T1} + 2^{-2(R-1)} \cdot c_5 \cdot Z_{T1}^2}{c_1 + 2^{-(R-1)} \cdot c_6 \cdot Z_{T1} + 2^{-2(R-1)} \cdot c_7 \cdot Z_{T1}^2}$$

$$P = Y \cdot \left(1 - 2^{-15} \cdot c_2 - 2^{-15} \cdot c_3\right) + 2^{-15} \cdot c_2 \cdot Y^2 + 2^{-15} \cdot c_3 \cdot Y^3$$

$$P \in [0;1)$$

R	...	Resolution of A/D-Conversion
Z_P	...	Raw A/D-result for pressure (auto-zero compensated)
Z_{T1}	...	Raw A/D-result for temperature 1 (auto-zero compensated)
		Conditioning coefficients stored in EEPROM Register 0 to 7; $c_i \in [-2^{15}; 2^{15})$ complement on two:
c_0	···	Bridge Offset
c_1	···	Gain
c_2	···	Nonlinearity 2nd order
c_3	···	Nonlinearity 3rd order
c_4	···	Temperature coefficient Bridge Offset 1st order
c_5	···	Temperature coefficient Bridge Offset 2nd order
c_6	···	Temperature coefficient Gain 1st order
c_7	···	Temperature coefficient Gain 2nd order

Fig. 15.7 Equations for adjusting the ZMD31050

The characteristic curve interpolation is faster in execution than the arithmetic method because it is based on simpler operations. A disadvantage is the large number of necessary measuring points and the relatively large coefficient memory.

Look-up table

The fastest and most memory-consuming way is to correct the data using a look-up table (LUT). For the simple characteristic curve, a corresponding output value is stored in a table for each possible input value. This assignment can also be multidimensional. In this way, very high accuracies can be achieved. However, since this requires many tables, a *reduced table* is often created in which intermediate positions are obtained by interpolation. This can also be regarded as a *characteristic curve interpolation* with a *high number of interpolation points.*

The clear advantage, however, is the *processing speed,* since only memory accesses are involved. If the interpolated LUT is set to binary values, for example, to every fourth input value, the interpolation can be limited to addition, subtraction and shift operations, so that high processing speeds are achieved here as well.

15.3 Energy Management for Sensors

Energy management is a current topic not only because of the increased environmental awareness but also because of a multitude of new applications. Today, sensor applications are increasingly used in mobile and self-sufficient systems that need to be supplied with energy. To keep energy consumption as low as possible, the power consumption in the sensor must be as low as possible.

There are two basic ways to manage energy: Either you build an *extremely energy-saving* sensor (e.g. measuring consumption on the radiator) or you *reduce* the *active time* of the sensor. Especially the latter variant requires a processor to realize this control process.

To produce a low energy sensor, several factors and influences must be taken into account. In the considerations, it is assumed that a processor core is present in the signal processing.

Circuitry measures and quiescent current

The processor used must itself have internal power management, that is, the peripheral units must be *switchable*. This means that only the required parts can be activated. In addition, the power consumption should be as low as possible in a sleep mode, although basic functions must still be active in this state, such as the clock and possibly a display. These design requirements also apply to the same extent to the external circuitry. For example, the sensor element, any external amplifiers and the areas of data communication must also be switchable.

The values for the quiescent current achievable with current processors are in the range of less μA. As an example, the circuit shown in Fig. 15.4 is used to achieve 13 μA in the quiescent state with the display is running.

Measuring time and active current

The two variables are related because they influence each other directly. In CMOS circuits, the *current consumption* is always related to the *clock speed*. The faster a processor works, the higher its power consumption. On the other hand, the measurement process is completed faster with a faster processor. The energy consumption is calculated as the product of time and current. Therefore, other criteria must be found that enable fast execution at a lower clock frequency. These include, for example:

- The influence of the selected *software* or *programming language*.

  The programming of the functions should be done in a minimalist form. The use of common high-level languages is rarely optimal because too many unnecessary functions are dragged along. Since the signal processing tasks are compact, one should also consider assembler programming.
- The influence of the *correction algorithms*.

  As already mentioned in Sect. 15.2, the choice of the correction path has a strong influence on the computational effort and the execution speed.
- The choice of *number format*.

  Calculating a signal correction in floating-point format is the easiest way, but also the slowest. Therefore, it should be considered to perform the calculations without a floating-point in an integer format. However, this requires more effort, since the

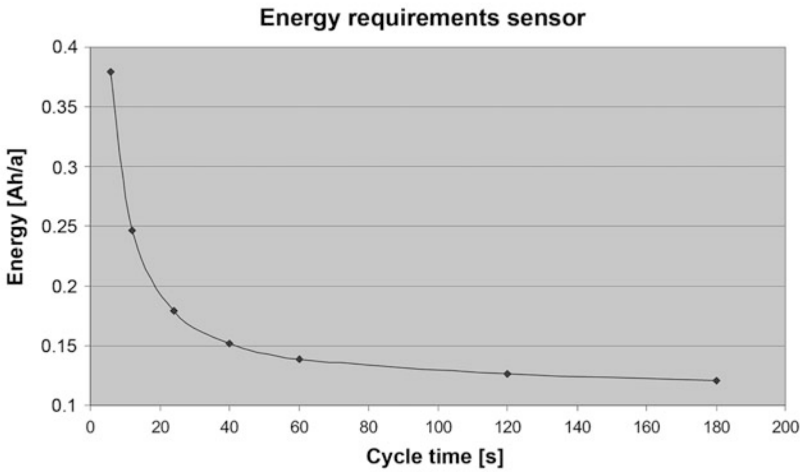

Fig. 15.8 Energy requirement as a function of the active time

estimation of the number range in connection with the sequence of arithmetic operations must be made in advance.

- *Place* of processing.

  A part of the correction tasks can also be shifted to the superordinate computer system in favour of active time. This allows time-consuming functions to be delegated to a location without energy problems.

Measuring cycle

The frequency of measurement also influences the *energy balance*, as it determines the ratio of active time to resting time. For this reason, it is necessary to define exactly how often measurements must be taken in a specific case. The interval between measurements can range from seconds for technical applications to hours for climatic sensors.

Figure 15.8 shows the energy requirement of a digital manometer for 1 year as a function of the measuring cycle. The quiescent current is 13 μA, the active current 3.7 mA and the active time 50 ms.

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