# Digital correction of capacitive signals with the aid of *Frame ASIC* CAV414

**Measurements and readings are never completely accurate and must always be corrected using suitable methods in order to keep within the required error margins. One modern approach is to calibrate and compensate the measured sensor signal with the aid of correction algorithms implemented by a processor. There are integrated solutions currently on the market which in principle allow electronic correction such as the above to be performed. However, these ICs have usually been designed for a specific application or are not suitable for general use for a number of other reasons. This article illustrates how a simple and inexpensive sensor systems can be assembled – clearly distinguishing between analog and digital components – which permit electronic correction of capacitive signals and at the same time remedy the weaknesses of existing monolithic solutions.**

### Electronic correction of capacitive signals

The application outlined here illustrates how with the aid of a CAV414 (a ***Frame ASIC*** from Analog Microelectronics GmbH which converts capacitive signals into analog output voltages; see Figure 1), a simple, inexpensive RISC processor and some considered circuitry a sensor system can be compiled which enables a capacitive measurement signal to be corrected electronically. Figure 2 shows the configuration of the application. The term ***Frame ASIC*** describes a new class of integrated analog signal evaluation circuits for sensor technology. ***Frame ASIC*** is the name given to an IC whose input, output and analog peripheral functions surround the digital correction facilities of a sensor system (a processor or a controller) like a frame [1].

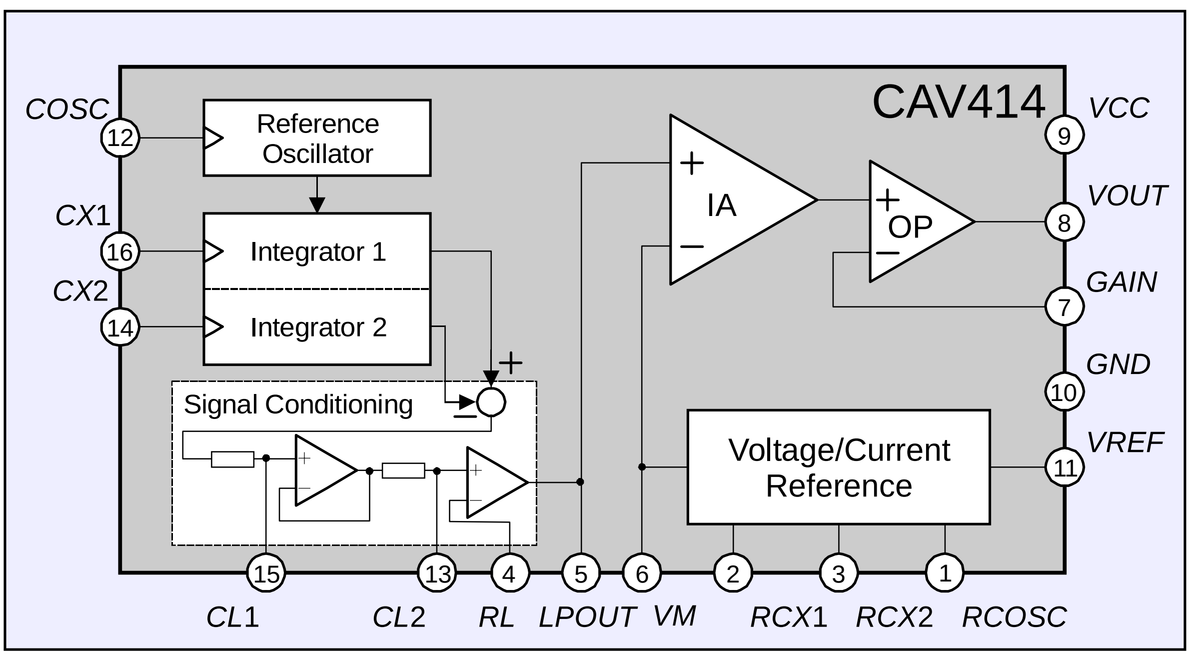


***Figure 1:*** block diagram of CAV414



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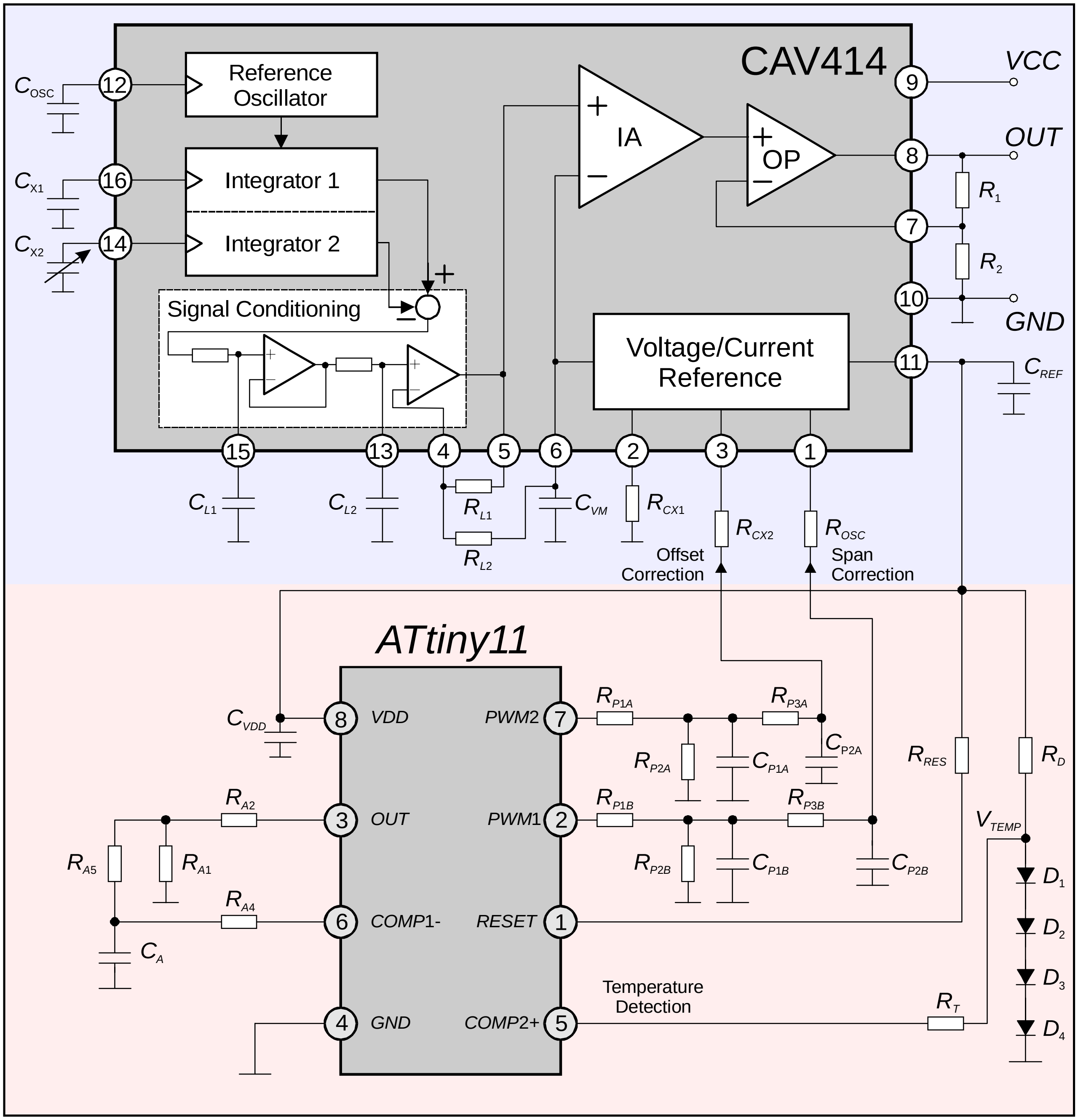


***Figure 2:*** theoretical assembly of the application

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## Signal conditioning IC CAV414 for capacitive signals

CAV414 is an industrial interface circuit for capacitive sensors which includes full analog signal acquisition and evaluation electronics and various protective functions (against reverse polarity, for example). In addition, the integrated reference voltage source allows further components, such as the processor, for example, to be supplied with power. When measuring a capacitance the IC detects the relative difference in capacitance between this and a given reference capacitance. The IC has been optimised for capacitances ranging from 10pF to 2nF; differences in full-scale (FS) capacitance can lie between 5 to 100% of the reference capacitance. CAV414 provides a signal proportional to the relatives difference capacitance which can act as a monitor, before it is converted into an industrial output voltage. This signal is internally temperature-compensated. Details are given in the data sheet [2]. A number of different applications can be assembled using the CAV414 industrial voltage output in combination with other ICs from Analog Microelectronics GmbH. Adding AM402 or AM422 to the setup, for example, permits simple current loop signals to be realised (see [4]).

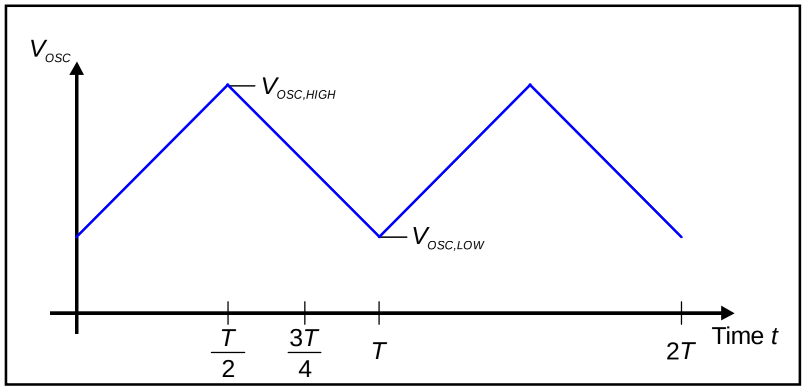


***Figure 3:*** voltage of oscillator

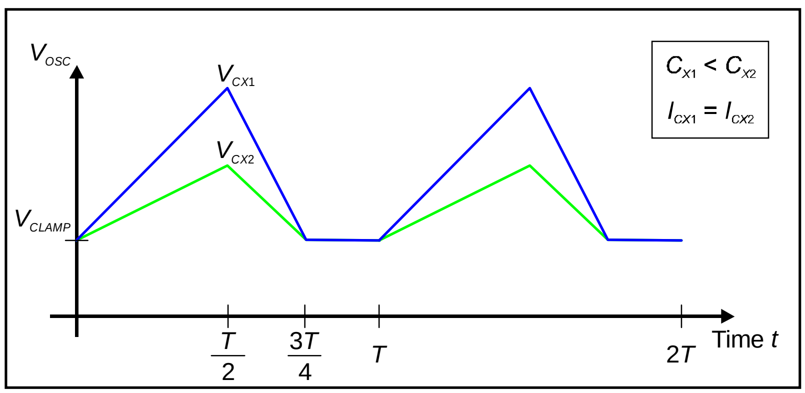


***Figure 4:*** voltage of integrators

Reference Oscillator:

CAV414 works according to the following principle. A reference oscillator, whose frequency is set using capacitance $C_{OSC}$, drives two symmetrical integrators in CAV414 which are phase-locked and clock-synchronised. The output signal amplitudes of the two driven integrators are determined by capacitances $C_{X1}$ (fixed reference capacitance) and $C_{X2}$ (capacitance to be measured).

With high common-mode rejection and a high resolution, comparison of the two integrator amplitudes produces the relative difference in capacitance between capacitances $C_{X1}$ and $C_{X2}$. This integrator amplitude differential signal is converted into direct voltage by a low pass whose cutoff frequency and amplification can be set using external components. The excitation current for capacitances $C_{X2}$ and $C_{OSC}$ is set with the aid of resistors $R_{CX2}$ and $R_{OSC}$. As described in the following section, this is used in electronic correction which entails calibrating the offset and span and compensating for the relevant temperature coefficients.

The functional description gives the necessary formulas to calculate the CAV414 with the sensing element (capacitor of a capacitive sensor). The formulas are a good approximation of the reality.

The reference oscillator works by charging and discharging the external oscillator capacitor $C_{OSC}$, the internal parasitic capacitor $C_{OSC,PAR,INT}$ of the IC and the external parasitic capacitor $C_{OSC,PAR,EXT}$ (e.g. of the circuit board). The external oscillator capacitor $C_{OSC}$ has to be

$$C_{OSC} = 1.6 \cdot C_{X1}$$

where $C_{X1}$ is the fixed capacitor of a capacitive sensor.

The reference oscillator current $I_{OSC}$ is determined by the external resistor $R_{OSC}$ and the reference voltage $V_M$ (see data sheet [2]):

$$I_{OSC} = \frac{V_M}{R_{OSC}}$$

The frequency of the reference oscillator $f_{OSC}$ is given by

$$f_{OSC} = \frac{I_{OSC}}{2 \cdot \Delta V_{OSC} \cdot \left(C_{OSC} + C_{OSC,PAR,INT} + C_{OSC,PAR,EXT}\right)}$$

whereby $\Delta V_{OSC}$ is the difference of the internal threshold voltages ($V_{OSC,HIGH}$ and $V_{OSC,LOW}$) of the reference oscillator. $\Delta V_{OSC}$ is defined by internal resistors and has $2.1\text{V} \pm 5\%$. The oscillator voltage is shown in Figure 3.

Capacitive Integrators:

The principle of operation is basically the same as the behaviour of the reference oscillator. The difference is the time of discharging the capacitors which is twice the time of charging and is clamped at an internal fixed voltage $V_{CLAMP}$. In Figure 4, the signal voltage over the capacitors $C_{X1}$ and $C_{X2}$ is shown.

The capacitive integrator current $I_{CX}$ is determined by the external resistor $R_{CX}$ and the reference voltage $V_M$ (see data sheet [2]):

$$I_{CX} = \frac{V_M}{R_{CX}}$$

The capacitor $C_X$ is charged up to the maximum voltage $V_{CX}$ (see Figure 4) and can be calculated as follows

$$V_{CX} = \frac{I_{CX}}{2 \cdot f_{OSC} \cdot \left(C_X + C_{X,PAR,INT} + C_{X,PAR,EXT}\right)} + V_{CLAMP}$$

The two voltages over the capacitors $C_{X1}$ and $C_{X2}$ are subtracted and the resulting differential voltage referred to the reference voltage $V_M$ is given by

$$V_{CX,DIFF} = \left(V_{CX1} - V_{CX2}\right) + V_M$$

The differential voltage $V_{CX,DIFF}$ goes directly into the 2nd-order lowpass. The 3dB-corner frequencies $f_{C1}$ and $f_{C2}$ of the two stages are adjusted with the external capacitors ($C_{L1}$, $C_{L2}$) and the internal resistors ($R_{01}$, $R_{02}$; typ. 20kΩ). The 3dB-corner frequencies have to be chosen depending on the reference oscillator frequency $f_{OSC}$ and the desired detection frequency $f_{DET}$ of the entire sensor system. The following relation for the different types of frequencies has to be fulfilled in all cases:

$$f_{DET} < f_C << f_{OSC}$$

The external capacitors for a desired corner frequency are calculated as follows

$$C_L = \frac{1}{2\pi \cdot R_0 \cdot f_C}$$

The output signal of the lowpass with the ideal waveform becomes

$$V_{LPOUT} = V_{DIFF,0} + V_M$$

with

$$V_{DIFF,0} = \frac{3}{8} \cdot \left(V_{CX1} - V_{CX2}\right)$$

If the differential output voltage $V_{DIFF,0}$ is too small, it can be amplified with the external resistors $R_{L1}$ and $R_{L2}$ while using the internal non-inverting amplifier of the lowpass.

The maximum amplification of the differential output voltage $V_{DIFF,0}$ is limited to the maximum allowed input voltage range of the following instrumentation amplifier ($V_{IA,IN,max}$ = 400mV).

The gain of the stage is

$$G_{LP} = 1 + \frac{R_{L1}}{R_{L2}}$$

Hence follows the output signal of the lowpass stage

$$V_{LPOUT} = V_{DIFF} + V_M$$

with

$$V_{DIFF} = G_{LP} \cdot V_{DIFF,0} = G_{LP} \cdot \frac{3}{8} \cdot \left(V_{CX1} - V_{CX2}\right)$$

With the instrumentation amplifier and the output stage, the output signal becomes

$$V_{OUT} = G_{IA} \cdot G_{OP} \cdot V_{DIFF}$$

with the fixed gain $G_{IA}$ = 5 and the adjustable gain

$$G_{OP} = 1 + \frac{R_1}{R_2}$$

# Digital correction of capacitive signals with the aid of *Frame ASIC* CAV414

**Information on the processor used and on the correction circuitry**

A processor (ATtiny series from Atmel) not necessarily designed for sensor applications is used as a digital corrective device. The tiny size and low cost of the processor, however, make it ideal for sensor applications. Yet before it is applied to the whole, a number of considerations as to the circuitry must be made.

The processor used here is a fully-static CMOS-RISC processor as an 8-pin SO package with a 1kByte re-writable flash ROM, a 32-byte RAM-similar register and a 1MHz clock frequency. The processor does not require an external clock or quartz as it has an internal RC oscillator. The supply voltage range is 2.7V...5.5V maximum (depending on the model of processor used) with ca. 4mA power consumption. All types of processor can cope with an operating temperature of between -55°C and +125°C. The flash memory can be programmed using either the extension port of the Atmel evaluation board, using special programming units from other suppliers or using individual setups with digital signals. As the processor has neither its own A/D or D/A converter nor pulse width modulation outputs included in the hardware, inevitably these missing functions must be realised using software.

<u>A low-cost ADC</u>

When measuring the temperature necessary for the compensation of the offset and span temperature coefficients, here the temperature-dependent flow voltage of semiconductor diodes is used (approx. –2.4mV/K). Alternatively, other temperature sensors which supply a suitable analog voltage signal can be applied. The analog temperature information now has to be converted into a digital signal so that it can be handled by the processor. ATtiny11 only has an integrated analog comparator which has to be turned into an A/D converter using suitable firmware (ramp principle). To this end the analog voltage to be measured (temperature signal) is applied to the positive comparator input (pin 5; see Figure 5). The negative input (pin 6) has a capacitor connected to it which is discharged through one of the processor's I/O pins via a resistor from a given point in time. As soon as the capacitor voltage discharges to the temperature signal value, a status

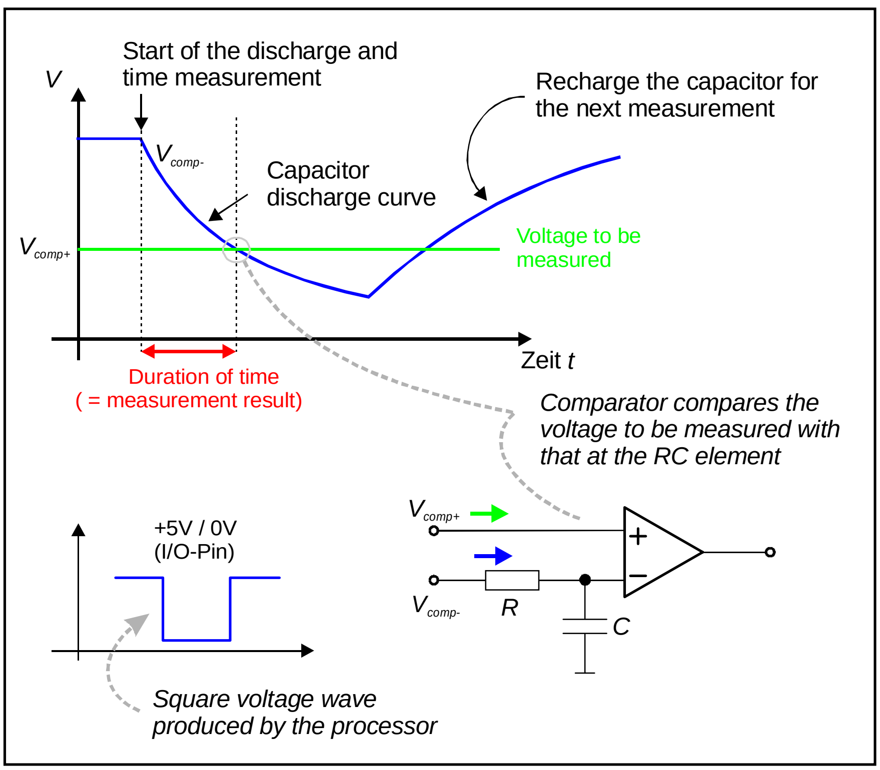


***Figure 5:*** the low-cost ADC principle

bit is set in the processor and the relevant temperature calculated from the discharge time elapsed. A/D conversion of the temperature signal thus involves transforming the input voltage into a time proportional to it and evaluating this.

PWM outputs as an alternative DAC

As already mentioned, the measurement signal is actually corrected by varying the excitation currents of capacitances $C_{X2}$ and $C_{OSC}$. In order to impact the current sources analog signals are required; these must be supplied by the processor for correction. As the processor itself does not contain a D/A converter which can emit signals such as these and as no pulse width modulation (PWM) outputs are included in the hardware the processor's two I/O pins 2 and 7 are programmed as PWM outputs. A dimensions guide of the external components is available from Analog Microelectronics GmbH as a Mathematica notebook.

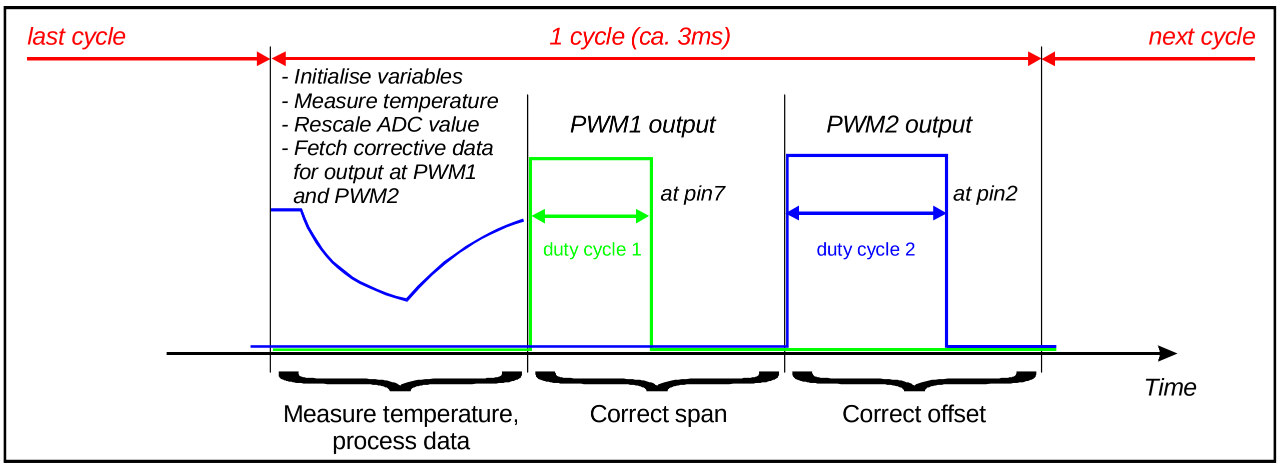


***Figure 6:*** temporal diagram of the main programme switching the PWM outputs.

The processor's outputs supply two discrete voltages (0 and 5V) and are switched on and off in cycles within a set period by software. An average voltage is produced by a back-end low pass; this serves as a correction voltage and is proportional to the duty cycle (ratio of the switch-on period to the total pulse-repetition period). The quantisation of the correction voltage and the level of accuracy which can be achieved with this correspond to the quantisation of the switch-on/switch-off time. The PWM signals produced in this manner thus supply correction voltages which can be used to set the excitation currents for offset and span compensation in CAV414. Figure 6 gives the programme cycle which is split into three areas:

- Initialisation of variables
- Temperature measurement using the ADC; calculation of the relevant temperature value address from the entries in the look-up table (correction values written into the flash during calibration)
- Output of the span correction signal at PWM output 1 and of the offset correction signal at PWM output 2.

Storing calibration data in the flash ROM

In place of an additional data EEPROM the processor flash ROM is used here to store correction data. The correction data is filed together with the operating software in the programme memory. The ATtiny11 used here supports the readout of data stored in the programme memory proper.

**Compensation of the sensor system**

The compensation process for the sensor system has two main stages: one entails setting the gain at room temperature and the other involves measuring the calibration data of the offset and span at various temperature approximation points.

Setting the gain at room temperature

Initially, resistors $R_{L1}$ and $R_{L2}$ are not connected to the circuitry and pin 4 (*RL*) is connected to pin 5 (*LPOUT*) so that the input gain is $G_{LP} = 1$.

1. Where variable capacitance $C_{X2}$ is at its lowest value and is thus approximately identical to set reference capacitance $C_{X1}$ (e.g. with a proximity sensor which does not have an object in front of its sensor area), the output differential voltage is calculated:

$$V_{DIFF,0,\min} = V_{LPOUT,0,\min} - V_M$$

2. Where variable capacitance $C_{X2}$ is at its highest value (e.g. with a proximity sensor which has an object directly in front of its sensor area), the maximum output differential voltage is calculated:

$$V_{DIFF,0,\max} = V_{LPOUT,0,\max} - V_M$$

3. Gain $G_{LP}$ with

$$G_{LP} = 1 + \frac{R_{L1}}{R_{L2}}$$

is set using resistors $R_{L1}$ and $R_{L2}$ so that for the maximum output differential voltage

$$V_{DIFF,\max} = G_{LP} \cdot (V_{DIFF,0,\max} - V_{DIFF,0,\min})$$

the value

$$V_{DIFF,\max} = 400\text{mV}$$

is produced. The sum of the two resistors $R_{L1}$ and $R_{L2}$ must lie within the permissible range of 100kΩ to 200kΩ when setting the gain.

Calibration of the entire system

Once the sensor system has been set to the relevant output values at room temperature the next stage in the process is to ascertain the correction data for temperature compensation for the processor and store this in the flash ROM. Measurements can be made at either two or three different temperatures, depending on how accurate the application is required to be. The offset and span values are determined at these temperature approximation points, with the digital temperature value relevant to the approximation point also being recorded. To compensate for the overall temperature error of the entire system the system output voltage values $V_{OUT}$ are recorded – not the voltage values of differential voltage $V_{DIFF}$. With the aid of a suitable programme on a PC these values can be used to generate correction values for the look-up table. Once the calibration process is finished the data has to be stored in the flash ROM.

**Results using the suggested setup**

Building a purely analog circuit without digital correction as described in the data sheet [2] or application instructions [3] for CAV414, without any additional temperature compensation a total error of ±1.5% in the industrial temperature range (-25°C to 85°C) can be achieved (with set input capacitances for offset and span). In such a setup each system must be corrected individually by setting external resistors, depending on the reference capacitances used. As this adjustment has to be carried out on an open board, faults can occur during packaging. If reference capacitances $C_{X1}$ and $C_{X2}$ demonstrate dissimilar temperature behaviour, the error becomes greater. For applications where accuracy is of the essence, compensation becomes extremely elaborate and time-consuming.

Figure 7 demonstrates what can be easily achieved by combining CAV414 with the ATtiny11 RISC

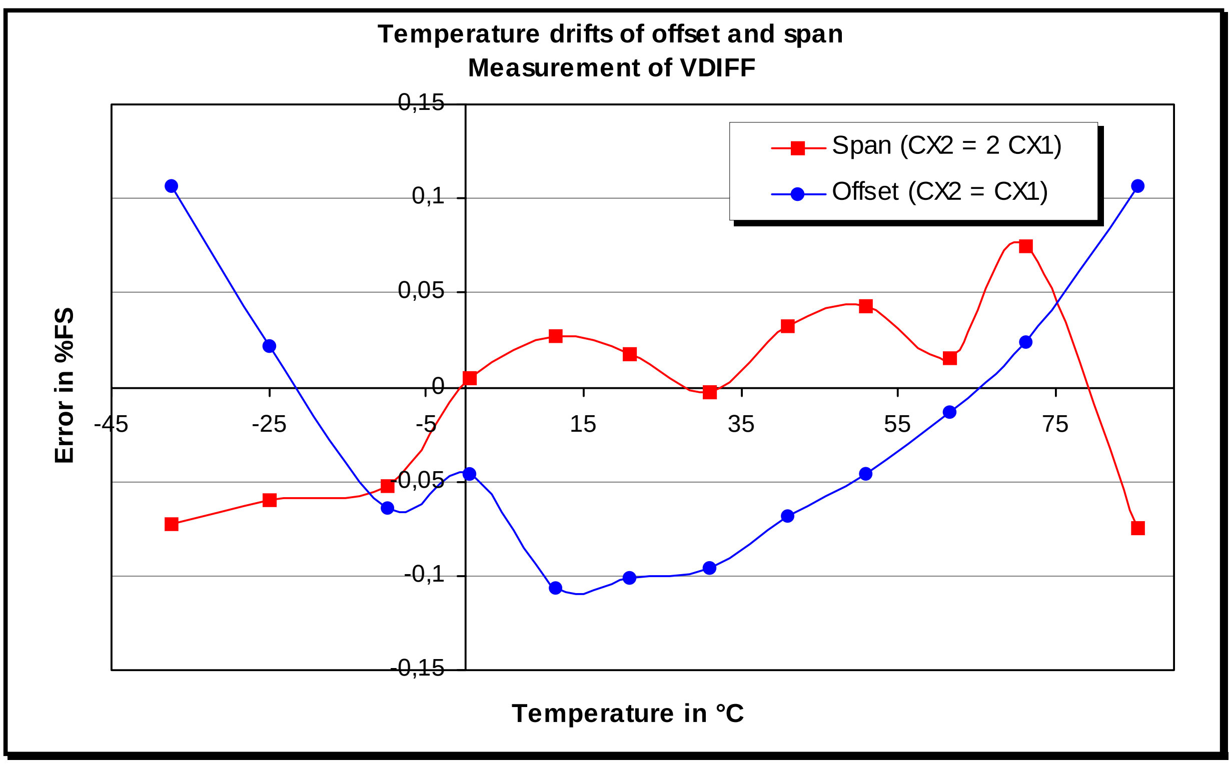


***Figure 7:*** measurements with discrete capacitors as input capacitances

processor. Readings were taken from the circuit illustrated in Figure 2. In order to simulate the offset and span a measuring capacitance of $C_{X2} = C_{X1}$ was used for the offset and $C_{X2} = 2\ C_{X1}$ was used for the span. The differential output of CAV414 pins 5 and 6 (voltage $V_{DIFF} = V_M – V_{LPOUT}$) was calibrated to zero for the offset value; for the span a value of 400mV was set at the same outputs. The external components in this particular application have been dimensioned so that using an ATtiny11 a change in offset of ca. ±30mV and a change in the output differential voltage span of ±50mV can be corrected. The device was calibrated at three different temperature approximation points (0°C, 30°C and 60°C), requiring relatively little effort with regard to measurement and correction. The temperature error was corrected using linear approximation.

The measurements indicate that the temperature drift of the system can be considerably improved. Compared to a setup which does not have a processor, using three-temperature correction accuracies of ±0.3%FS can be obtained.

A further advantage of this combination of CAV4141 and RISC processor is that the circuit can be corrected to the minimum error at the end of the production run in its packaged state. Possible faults arising during the packaging of the device are thus avoided.

The results show that using the Analog Microelectronics GmbH concept of ***modular signal evaluation*** outlined here (where analog and digital functions are kept separate), simple, inexpensive applications can be produced which through digital correction allow a high degree of accuracy to be achieved for the entire system.

**Future possibilities**

Development in the field of processor technology is steaming ahead. Atmel, for example, has announced that it will soon be launching successors to ATtiny11, one feature of which will be two integrated A/D converters. The application described in this article will thus not only then be able to be considerably simplified (less external components will be required); the second A/D converter also enables the sensor signal to be linearised. Bearing this in mind, it is evident that the ***Frame ASIC*** concept, coupled with the ongoing development of low-cost processors, will provide users with a number of ways of conditioning sensor signals.

All this naturally also encompasses the various possibilities mentioned in the information on CAV414 (the data sheet [2], application instructions [3] and article [5]). For example, the evaluation of a differential capacitor or the combination of CAV414 with AM402 to generate an industrial current loop signal (0/4...20mA) can also be applied in full to the example in [4]. The capacitive sensor system is used in moisture sensors, in inclinometers, in measurement of levels and in pressure sensor technology.

# Digital correction of capacitive signals with the aid of *Frame ASIC* CAV414

**Further information on CAV414**

Comprehensive information is available for ***Frame ASIC*** CAV414. The following lists the various documents with their relevant homepage link:

[1] **The *Frame ASIC* concept:**

http://www.analogmicro.de/products/info/german/pr1007.pdf

[2] **Data sheet for CAV414:**

http://www.analogmicro.de/products/sheets/english/cav414.pdf

[3] **Application instructions and dimensions guide for CAV414:**

http://www.analogmicro.de/products/sheets/german/appli414.pdf

[4] **Application instructions for CAV414 with AM402 for a 4...20mA application:**

http://www.analogmicro.de/products/sheets/english/appli414_402.pdf

[5] **Basic article on CAN404 and CAV414:**

http://www.analogmicro.de/products/info/german/pr1006.pdfs