***Measuring accurately small – capacitive (and other)- sensor signals via long wires with a microcontroller.***

## 1. Introduction

The migration from analog to digital circuitry in the industry has been going on for quite a few years now, but is far from complete ….

More than ten years ago, at the beginning of this changeover, a Dutch company called Smartec b.v. in Breda, foresaw the need for smart sensors and developed a highly accurate temperature sensor with a combined analogue / digital output, to be sampled directly by a microcontroller input. Because of the clever way the output signal is created, the resolution (0.005 K) is only limited by fundamental physics (signal to noise ratio) and the sampling speed of the controller.

This information is important, because it was the basis for the next - even more important – development. Smartec realised that over the years, experienced designers of electronic circuitry had become very familiar with 'their' well-known analogue sensors, like Pt100, Pt1000, capacitive elements, resistive bridges etc. Therefore, Smartec started the development of an interface, which could directly connect such analogue sensors to microcontroller inputs. An interface like this would combine the long-term experience from the designer, with the ultimate advantage of processing the data digitally.

The design constraints were amongst others:

1. Single chip interface for measuring both R, C and resistive bridges
2. High overall accuracy and resolution (13 to 14 bits).
3. Long distance measurement (3 and 4 wire measurement).
4. Accuracy independent from processor clock accuracy and no external quartz.
5. Continuous auto-calibration of offset and gain.
6. No temperature drift.
7. No long term drift.
8. Suppression of 50/60 Hz.
9. Easy multiplexing for multiple sensors.
10. Single power sully and low power consumption.

The interface was developed in cooperation with the Delft University of Technology, and resulted in the UTI (Universal Transducer Interface).

The article below explains in detail how the UTI functions. We will show you how you can measure the value of an unknown capacitor in the range of 2 pf, at a distance of several meters, with an accuracy of 13 bits and a resolution of 14 bits, meaning that the resolution is better than 0,0002 pF!. Once the designer has fully understood how to do this, he can use the UTI just as easily in any of the other 15 modes of operation, like measuring three unknown capacitors simultaneously, Pt elements, resistors, resistive bridges etc. At the end of this article you find a list with the 16 available modes.

The UTI was designed to combine two principles:

1. Four wire measurement (to overcome impedance problems, like parasitic capacitances)
2. Three signal technique, in order to
   A. overcome Offset and gain inaccuracies temp drift etc. (auto-calibration),
   B. become independent from processor clock stability

If you use the UTI, while applying both principles, you can get very good results, with very few components. Because principle 2 is implemented in the microcontroller program, hardware is replaced by software, which helps cutting down your production costs.

## 1. A little theory

Measuring the value of a capacitor accurately, without dedicated electronics, is not very easy.

Suppose you want to measure the value of a capacitor $C_x$ using a digital multimeter, with a dedicated input for this task. If you insert the capacitor directly into the multimeter with its leads as short as possible, you might get a reasonably accurate reading, depending on the quality of the multimeter. This is called the one-port method and works fine if you don't need real accuracy, there is no distance involved, you just need a single reading and there's no need to process the data.

If you would try to measure the value of a capacitor accurately over a certain distance using connecting wires and the same multimeter, the situation is shown in *fig. 1*.

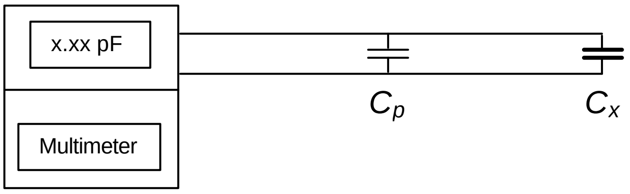


***Fig. 1 Failing One-port multimeter measurement (measuring $C_x + C_p$)***

The multimeter would simply give you the value of $C_x + C_p$, where $C_p$ is the parasite capacitance of the connecting wires. The antenna function of the unshielded wires would make things even worse. As you can see, in this situation, the one-port method fails, and there is no simple workaround. A quick solution to this problem is to use the UTI, with its two-port measurement.

## 3. Two-port measurement

If we move from one-port measurement to two-port measurement, the situation completely changes. *Fig.2* shows how the two-port principle works. For clarity, we have drawn the UTI in two parts, with the UTI output on one side and the UTI input on the other.

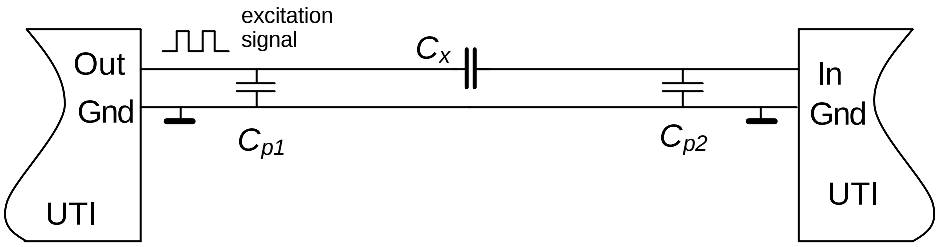


***Fig.2 Two-port UTI approach***
***(measuring $C_x$ only)***

The left-hand plate of $C_x$ is excited with a signal from a voltage source with a very low output impedance. The result is that $C_{p1}$ has no influence. By collecting the charge which is induced on the right hand plate, with the aid of a current input, which also has a very low impedance, we avoid $C_{p2}$ collecting any of the induced charge. In fact, both $C_{p1}$ and $C_{p2}$ are short-circuited by the UTI. The result is that $C_{p2}$ has lost its parasite property as well and does not influence the measurement of $C_x$ either.
Because there's only one signal ground, the actual measurement can be performed with three connecting UTI pins, as shown in *fig.3*.

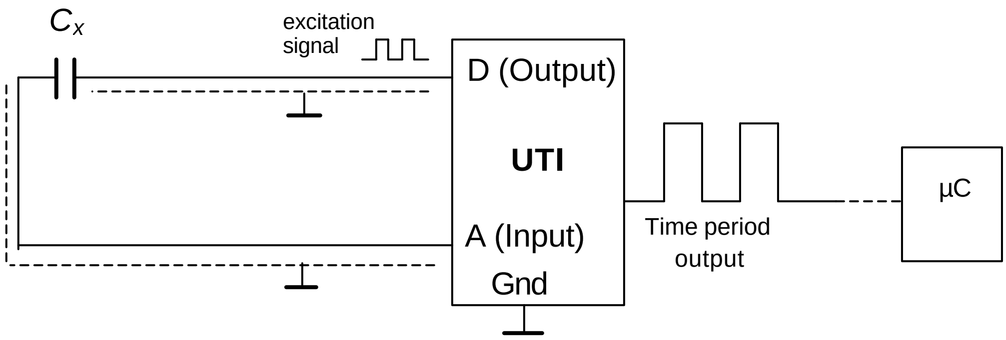


***Fig. 3 Practical UTI connection***
***(measuring $C_x$ only)***

Because UTI input A is a very sensitive input, the connecting wires should be of the shielded type, with the shields connected to the UTI signal ground.

The induced charge, which is collected by input A, controls the excitation frequency. The period of the internal oscillator is proportional to the value of the capacitor. This frequency then is divided by 128 (fast mode) or by 1024 (slow mode). One full period of the resulting (divided) signal becomes an output phase (sampled by the microcontroller). In fast mode you get more measured values per second ( 8 times more), but at the cost of a reduced accuracy. In slow mode you have maximum accuracy. The values for $a_0$ and $a_1$ are different for slow and fast mode.

Using the set-up from *fig.3*, the UTI would give you a good –relative - indication of the value for $C_x$, with the parasite capacitance from the connecting wires eliminated. The digital output timer period related to $C_x$ is proportional to the value of $C_x$. ($T = a_0 + a_1 * C$).

If we would replace the UTI with another one, it would probably give you a slightly different value (just as another multimeter would!) This results from the internal amplifier offset and gain differences between different UTI's. For this problem, the UTI also has a beautiful solution and its called Three-Signal Technique.

## 4. Three Signal Technique

We will use a second capacitor – with a well-known value, the so-called Reference capacitor -, connected by a second wire to output C. *Fig. 4* shows how this would look. Because the capacity of the connecting wires is handled by the UTI, the wires do not have to be identical. The reference capacitor could be mounted close to the UTI, without loosing accuracy.

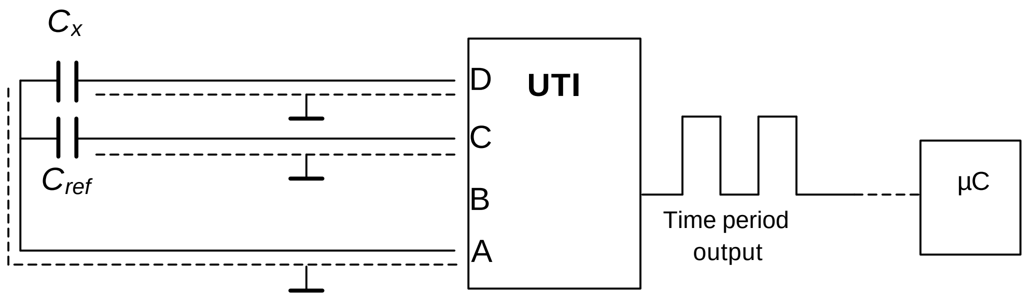


***Fig. 4 Three Signal Technique***

When we switch on the UTI, the digital output gives us three time intervals *Toff*, *Tref* and *Tx* (see *fig. 5*). These intervals are proportional to the values of $C_{off}$ (normally zero), $C_x$ and $C_{ref}$. respectively.

We could have connected a third capacitor between B and A, an external offset capacitor $C_{off,\ ext}$, but at this moment it is preferable, to give this one a value of zero, i.e. the capacitor is non-existent, but there is still the internal pin to pin capacitance ($C_{off,\ int}$).

In the next paragraph we will show you that we can eliminate the offset and gain errors, as well as other sources of inaccuracy, like temperature drift, by processing the timer information together with the known value of $C_{ref}$. (See below).

## 5. Practice and a little math

If you connect a UTI to two capacitors, as shown in *fig. 4* and make the UTI operate in mode 1 (which is the 1 unknown capacitor mode), you will get an output signal like in *fig. 5*.

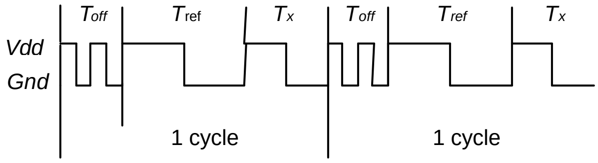


***Fig. 5 Digital output from UTI***

The signal consists of three phases, with duration of *Toff*, *Tref* and *Tx* respectively. The duration of the first phase, *Toff*, is always the shortest and corresponds to the value of open output B. It gives you information about the offset error and is always recognizable from the double period (two high's and two low's).

Let's be more specific. All capacitor values are represented by the UTI through their corresponding period duration. The general formula is:

$T = a_0 + a_1 * C_{ext}$, where $a_0$ represents the internal UTI offset and $a_1$ represents the UTI gain.

With two capacitors, we have the following two equations:

$T_x = a_0 + a_1 * C_x$ (I)
$T_{ref} = a_0 + a_1 * C_{ref}$ (II)
$T_{off} = a_0 + a_1 * C_{off}$ (III)

By measuring the duration of each of the three phase periods $T_{off}$, $T_{ref}$ and $T_x$, we are able to find values for $C_x$, $a_0$ and $a_1$ as we will show. These periods can be measured with only one input pin on any microcontroller.
The obtained accuracy - see below - depends on the sampling rate and on which mode the UTI is in. Increased accuracy can always be obtained by sampling over multiple periods and / or sampling at a higher rate.

Because we have not connected any external capacitor to output B, the value of $C_{off}$ is zero. This gives us:

$T_{off} = a_0$ (IV)

Now we have three equations *(I),(II) and (III)* and three unknowns ($C_x$, $a_0$ and $a_1$), so we can solve the equations. Lets compute

$M = (T_x - Toff) \div (T_{ref} - T_{off})$ (V)

$T_x - T_{off} = (a_0 + a_1 * C_x) - (a_0) = a1 * C_x$
$T_{ref} - T_{off} = (a_0 + a_1 * C_{ref}) - (a_0) = a1 * C_{ref}$

Thus $M = C_x / C_{ref}$, and

$C_x = M * C_{ref}$ *(VI)*

This means that the value of $C_x$ can be found by computing the value of *M* according to *(V)* and multiplying the result with the value of our reference capacitor.

When the UTI is used in mode1, typical values for $a_0$ and $a_1$ are

$a_0 = 2$ [ms] (offset)
$a_1 = 1$ [ms/pF] (gain)

In slow mode these values are 8 times larger.

Normally the user is only interested in an estimation of the value of $C_x$, as accurate as possible, which we obtained by solving *(I),(II) and (III)*. If one is interested in the offset and the gain, they may be computed as follows:

$a_0 = T_{off}$ and
$a1 = (T_x - T_{off}) / C_x$ or
$a1 = (T_{ref} - T_{off}) / C_{ref}$

## 6. Resolution considerations

The maximum resolution that can be obtained with the UTI is different for the different operating modes (C, R, bridge, etc) and the speed mode (fast or slow). In fast mode the UTI performs one complete measurement cycle about every 10 ms, in slow mode it takes about 100 ms. In slow mode the maximum obtained resolution is better (about 3 bits), then in fast mode. As you can see, in order to highly accurate results, while measuring C, R or resistive bridges, only a little procesing power is needed.

Generally speaking, the resolution depends on mainly two different sources of noise. One is the internal UTI thermal noise and the other is the quantization noise, which depends on the sampling rate. The UTI thermal noise is 1/f noise and behaves always like shown in *fig 6*.

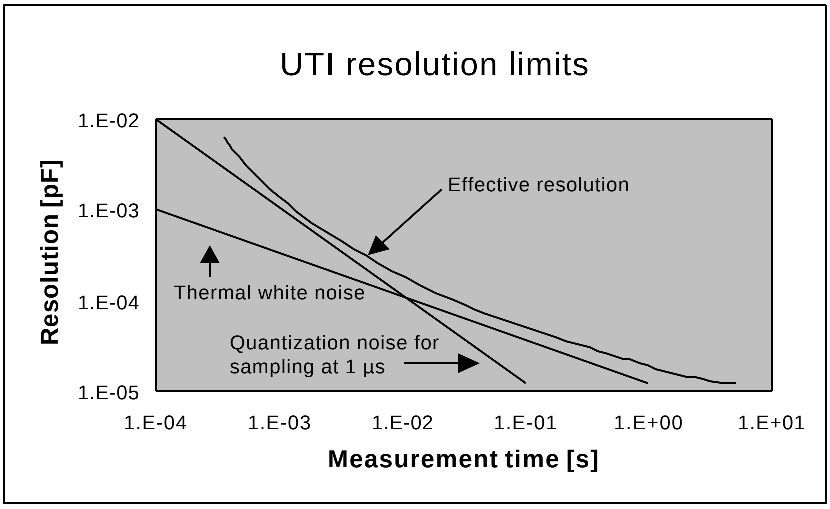

***Fig.6 UTI resolution***

The relative standard deviation of the quantization noise of a measurement phase amounts to:

$$s_q = \frac{t_s}{T_{off} \cdot \sqrt{6}} \quad (I)$$

Here $t_s$ is the sampling time and is $T_{off}$ the duration of the offset phase. We take $T_{off}$ , because it is the shortest phase and therefore results in a conservative estimation of the resolution.

The quantization noise shown in *fig. 6* corresponds to a sampling rate of 1 MHz, the full measuring scale is 2 pF and the UTI is in slow mode. In this mode 1024 cycles of the excitation frequency (50 kHz when free running) are used, to create one output phase. Then $T_{off}$ amounts to 1024 * 20 µs which equals about 20 ms. Formula (I) then yields $s_q$ = 0.02E-3. Therefore, in this case the best relative standard deviation corresponds to a maximum resolution of 15.5 bits.

As you can see in *fig.6*. there is no point in increasing the sampling rate (which would actually lower the quantization noise line graph in *fig. 6*), because the thermal noise is already becoming the biggest noise factor. Because of this, in reality, the maximum resolution for measuring small capacitances is 14 bit (and not 15.5) bit.

Another factor that has to be taken into account, is the effect of the parasitic capacitance $C_p$. Above it was stated that the effect of this capacitance is fully encountered by the impedance of the exciting output and the charge collecting input. This, however, is only true, if the value of *Cp* is ‘reasonable’ with respect to the scale chosen. On a scale of 2pF, this would mean $C_p$ must not be more than 50 to 100 pF. As the value of $C_p$ increases, the all-over resolution decreases. This property of the UTI is well documented, but lies beyond the scope of this article.

## 7. Additional information

*List of operational modes*

| Mode type | Phases | Mode Name | Mode No. |
|---|---|---|---|
| 5 Capacitors, 0-2pF | 5 | C25 | 0 |
| 3 Capacitors, 0-2pF | 3 | C23 | 1 |
| 5 Capacitors, 0-12pF | 5 | C12 | 2 |
| Capacitors, 0-2pF, external MUX CML=0 | - | CMUX | 3 |
| Capacitors, 0-12pF, external MUX CML=1 | - | CMUX | 3 |
| 3 Capacitors, variable range to 300pF | 3 | C300 | 4 |
| Platinum resistor Pt100-Pt1000, 4-wire | 4 | Pt | 5 |
| Thermistor 1κW-25κW, 4-wire | 4 | Ther | 6 |
| 2 or 3 platinum resistors Pt100-Pt1000 | 5 | Pt2 | 7 |
| 2 or 3 thermistors, 1κW-25κW, | 5 | Ther2 | 8 |
| Resistive bridge, ref. is Vbridge, +/- 200mV | 3 | Ub2 | 9 |
| Resistive bridge, ref. is Vbridge, +/- 12.5mV | 3 | Ub1 | 10 |
| Resistive bridge, ref. is Ibridge, +/- 200mV | 3 | Ib2 | 11 |
| Resistive bridge, ref. is Ibridge, +/- 12.5mV | 3 | Ib1 | 12 |
| Res. bridge and two resistors, +/- 200mV | 5 | Brg2 | 13 |
| Res. bridge and two resistors, +/- 12.5mV | 5 | Brg1 | 14 |
| 3 Potentiometers 1κW-50κΩ | 5 | Potm | 15 |

*Application notes*

On the website smartec.www.fr (**supportshop**) application notes can be found for the UTI, including circuitry diagrams, software listings and flowcharts.

## 8. Summary

The UTI is a **self calibrating universal interface** for connecting a complete range of analogue sensors like small capacitors, PT100(0) elements, resistive bridges etc. directly to a microcontroller. The UTI takes care of the measuring of the values of the sensors and presents these values in digitized form on one output. The microcontroller samples this output and does a few simple calculations, which is called the *Three Variable Technique*. With this technique one eliminates errors like gain and offset errors and temperature drift. Applications that used to be implemented with advanced analogue circuitry and AD convertors, can now be created with one UTI chip and a microcontroller program. “HARDWARE is replaced by SOFTWARE!”

The microcontroller can be a simple PIC processor, as long as the sampling rate is high enough. To obtain maximum accuracy, about 100.000 samples are needed per phase. (5 Mhz during 20 ms).

With the UTI and it’s *Three Variable Technique* the job of a designer becomes a little bit easier.