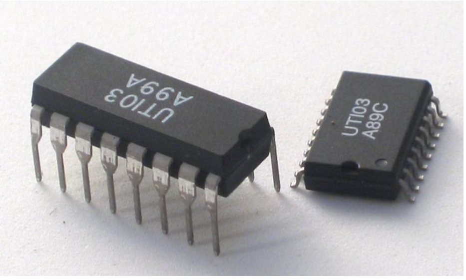
Universal Transducer Interface (UTI)

Features

- Provides interfacing for many types of sensor elements:
  Capacitors, platinum resistors, **thermistors**,
  Resistive bridges and **potentiometers**
- Measurement of multiple sensor elements
- Single 2.9 V - 5.5 V power supply, current consumption below 2.5 mA
- Resolution and linearity up to 14 bits and 13 bits
- Continuous auto-calibration of offset and gain
- Microcontroller-compatible output signal
- Tri-state output
- Typical measurement time 10 ms or 100 ms
- 2/3/4-wire measurement available for almost all measurements
- AC excitation voltage signal for all sensor elements
- Suppression of 50/60 Hz interference
- Power down mode
- Operating temperature range for DIL and SO -40ºC to 85ºC
- Operating temperature range for naked die -40°C to 180ºC



Applications

Automotive, industrial and medical applications for

- Capacitive level sensing
- Position sensing
- Angle sensing
- Accurate temperature measurement (Platinum, NTC)
- Bridge sensors for pressure, force etc.

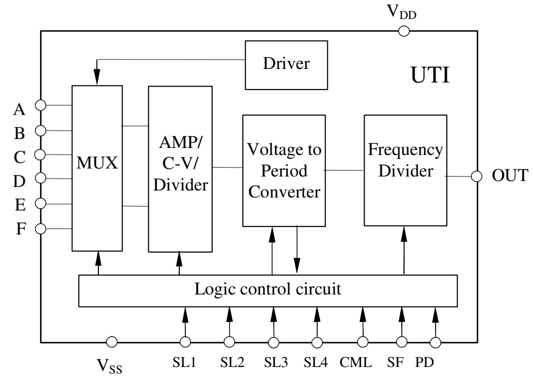
1. General Description

The Universal Transducer Interface (UTI) is a complete analog front end for low frequency measurement applications, based on a period-modulated oscillator. Sensing elements can be directly connected to the UTI without the need for extra electronics. Only a single reference element, of the same kind as the sensor, is required. The UTI outputs a microcontroller-compatible period-modulated signal. The UTI can provide interfacing for:

- Capacitive sensors 0 - 2 pF, 0 -12 pF, variable range up to 300 pF
- Platinum resistors Pt100, Pt1000
- Thermistors 1 kΩ - 25 kΩ
- Resistive bridges 250 Ω - 10 kΩ with maximum imbalance +/- 4% or +/- 0.25%
- Potentiometers 1 kΩ - 50 kΩ
- Combinations of the items mentioned above

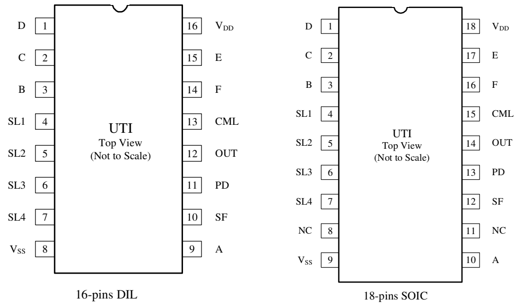
The UTI is ideal for use in smart microcontroller-based systems. All data is present on a single microcontroller compatible output, which reduces the number of connecting wires and reduces the number of couplers required in insulated systems. For information about insulated UTI applications, please see the relevant **application notes** in the support shop of our website. Continuous auto-calibration of offset and gain of the complete system is performed by using the three-signal technique. The low-frequency interference is removed by an advanced chopping technique. Selection of any of the sixteen operating modes takes place by setting four mode-bits.

Functional block diagram



2. Pin-out and Ratings

The UTI is available in a 16-pin plastic dual-in-line package (DIP) as well as a 18-lead small outline package (SOIC). Figure 1 shows the pin configurations of DIP and SOIC. The function of the pins is listed in *Table 1*.



(a) (b)

Figure 1. Pin configuration

Name	Function of the pin
V_{DD}, V_{ss}	Power supply
A, B, C, D, E, F	Sensor connections
SEL1..SEL4	Mode selection (see Table 2)
OUT	Output
SF	Slow/fast mode selection
CML	CMUX02/CMUX12 mode selection
PD	Power Down (tri-state)

Table 1. Function of the pins

3. Absolute Maximum Ratings

T_A=25°

Power supply voltage	-0.3 V to +7 V
Power supply current (excluding connection to the sensor)	3 mA @ 5 V
Power dissipation	21 mW
Power dissipation at power down	7 µW
Output voltage	-0.3 V to V_{DD}+0.3 V
Output driving current (A,F)	8 mA
Output impedance	60 Ω
Input voltage ref. to V_{SS}	-0.3 V to V_{DD}+0.3 V
Input current on each pin	±20 mA
ESD rating	> 4000 V
Storage temperature range	-65°C to +150°C
Operating temperature range	-40°C to +85°C
Lead temperature (soldering, 10 sec)	+300°C

4 General specifications

4.0 Functionality

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

Table 2. Modes of the UTI , including the name of the modes and the number of phases within 1 cycle

4.1 Output

The UTI outputs a microcontroller-compatible period-modulated signal and excitation signals to drive the sensing elements. *Table 3* shows some output specifications of the UTI. Because all UTI data is present on one single digital output, only four wires are needed to make a versatile insulated front end. For information about insulated use of UTI please go to the relevant **application notes** in the support shop of our website.

V_{DD} = 5 V, T_A = +25°C

Parameter	Value	Unit	Conditions/Comments
V_{OL}, Output low voltage	0.4	**V max**	
V_{OH}, Output high voltage	V_{DD}-0.6	**V min**	
Output resistance at OUT	60	**Ω**	
Maximum load at OUT	8	**mA**	V_{DD} = 5 V
Output resistance at pins B, C, D, E and F	800	**Ω**	The pins B – F are used as output in the capacitive modes, 0 – 4.
Maximum output current from E and F	20	**mA**	For resistive and resistive-bridge modes
Rise time Fast mode Slow mode	14 14	**ns** **ns**	
Fall time Fast mode Slow mode	13 13	**ns** **ns**	
Intrinsic propagation delay time t_{PLH} (PD-OUT) t_{PHL}	30 30	**ms** **ms**	For the fast mode, these values are 8 times smaller.
Intrinsic propagation delay time t_{PLH} (SELi-OUT) t_{PHL}	30 30	**ms** **ms**	For the fast mode, these values are 8 times smaller.

Table 3. Output specifications of the UTI

4.2 Analog inputs

Various sensing elements can be directly connected to the inputs of the UTI. The connections of the sensing elements with the UTI for various modes are described in section 8. *Table 4* shows some input specifications of the UTI.

V_{DD} = 5 V, T_A = +25°C

Parameter	Value	Unit	Conditions/Comments
Input capacitance	20	**pF**	
Capacitance leakage between A to B, C, D, E, F	30×10^{-3}	**pF**	DIP package
Suppression of 50/60 Hz	60	**dB**	

Table 4. Some input specifications of the UTI

4.3 Control lines

As described in section 4.1, the UTI has 16 operating modes. These modes are selected by using four selection pins, **SEL1**, **SEL2**, **SEL3** and **SEL4**. In *Table 2*, a ‘1’ corresponds to V_{DD} and ‘0’ to GND. Some special functions are available, such as, Slow/fast selection and power-down. These modes are set by **SF** and **PD**, respectively.

The pin **SF** is used to set the measurement speed. When SF = 1, the UTI is working in the fast mode. In this mode the duration of one complete cycle of the output signal is about 10 ms. When SF = 0, the UTI is working in the slow mode and the duration of one complete cycle of the output signal is about 100 ms.
The pin **PD** is used to set the power-down of the UTI. When PD = 0, the UTI is powered down and the output node is floating (high-impedance). This enables to connect several UTI outputs to a single output wire, provided that only a single UTI is selected (PD = 1).

The pin **CML** is always connected to GND except in mode CMUX.
In mode CMUX, the pin CML is used for the measurement-range selection. These ranges are 0 - 2 pF (CML = 0) and 0 - 12 pF (CML = 1), respectively.

Floating inputs are not allowed, unless stated.

In the next sections, the UTI is specified for all possible modes. The names of these modes are the same as used in *Table 2*. In this section, CML = 0 and SF = 0 unless otherwise stated. Important parameters to be specified are:
- accuracy
- resolution
- number of phases
- specified signals in the various phases

5. Some theory about measuring sensor elements

5.1 About the three-signal technique and calibration

The three-signal technique is a technique to eliminate the effects of unknown offset and unknown gain in a linear system. In order to apply this technique, in addition to the measurement of the sensor signal, two reference signals are required to be measured in an identical way. Suppose a system has a linear transfer function of:

$$M_i = kE_i + M_{off}$$

We feed the system three different input values:

$E_1=0$
$E_2=E_{ref}$
$E_3=E_x$

The three measured output signals (values) are

$M_1=M_{off}$
$M_2=M_{ref}=k*E_{ref}+M_{off}$
$M_3=M_x=k*E_x+M_{off}$

We then calculate:

$$M = \frac{M3 - M1}{M2 - M1} = \frac{Mx - Moff}{Mref - Moff} = \frac{Ex}{Eref}$$

When the system is linear, then in this ratio the influence of the unknown offset M_{off} and the unknown gain k of the measurement system is eliminated and the calculated value of M represents the ratio between the values of the (unknown) sensor element and the (known) reference element. This technique is called the three variable technique or three signal technique. The values of offset and gain may vary over time, but since they play no role in the final result, a UTI based measuring system is self calibrating.

The implementation of the three signal technique requires a microcontroller, which is used to digitize the period-modulated UTI output signals and perform the data storage and calculations. Such a system combining a sensing element (sensor), a signal-processing circuit, such as the UTI, and a microcontroller is called a microcontroller-based smart sensor system. The auto-calibration properties of the UTI render such a system insensitive to temperature effects.

5.2 The measurement of sensing elements

The output of the UTI is a period modulated signal. As an example, *Figure 2* shows two complete cycles of the output signal from the UTI, each consisting of three phases.

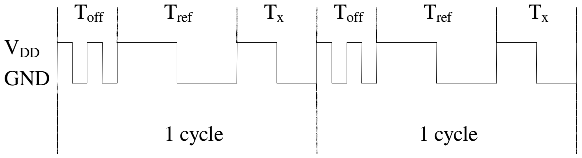


Figure 2. The output signal of the UTI for a 3-phase mode

As explained above in the theory of the three signal technique the internal input of the UTI has to be switched to three or more elements. During the first phase the internal offset of the linear system is measured (normally there are no external components connected to the corresponding pins). During the second phase the UTI measures the value of a reference element, by switching to the corresponding connecting pins.

During the following phase(s) the UTI is measuring the value(s) of one or more sensor elements. The output signal depicted in *figure 2* applies to a situation where only one unknown sensor element is being measured. The switching between these phases is completely controlled by the UTI, without microcontroller interference.

During the first phase T_{off}, the offset of the overall linear system is measured. During the second phase T_{ref}, the reference signal is measured and during the last phase T_x, the actual sensor signal is measured. The duration of each phase is proportional to the signal which is measured during that phase. The duration of the three phases is given by:

For capacitive measurement:	**For resistive measurement:**
$T_{off} = NK_1C_0$ $T_{ref} = NK_1(C_{ref} + C_0)$ $T_x = NK_1(C_x + C_0)$	$T_{off} = NK_2V_0$ $T_{ref} = NK_2(V_{ref} + V_0)$ $T_x = NK_2(V_x + V_0)$

where C_x or V_x is the sensor signal to be measured, C_{ref} or V_{ref} the reference signal, C_0 or V_0 a constant part (including offset voltages etc.) and K_1 or K_2 the gain. The factor N represents the number of internal oscillator periods in one phase. In slow mode, $N = 1024$ and in fast mode $N = 128$. The voltages V_x and V_{ref} are, for instance, the voltages across the sensor resistor and the reference resistor respectively or, in another mode, V_x and V_{ref} represent the bridge output voltage and the bridge supply voltage, respectively. The output signal of the UTI can be digitized by counting the number of microcontroller clock cycles fitting each phase. This results in the numbers N_{off}, N_{ref} and N_x. The ratio C_x/C_{ref} or V_x/V_{ref} can now be calculated by the microcontroller:

$$\begin{aligned} M &= \frac{N_x - N_{off}}{N_{ref} - N_{off}} = \frac{C_x}{C_{ref}} \quad or \\ M &= \frac{N_x - N_{off}}{N_{ref} - N_{off}} = \frac{V_x}{V_{ref}} \end{aligned} \qquad (1)$$

Because this ratio does not depend on the offset of the system, nor on the gain, the system is calibrated for offset and gain by definition and therefore called auto-calibrating. Even in the case of drift or other slow variations of offset and gain, maximum accuracy is maintained.

The three phases are time-multiplexed, as depicted in *Figure 2.* The offset phase is consists of two half periods (the output frequency is temporarily doubled). Because of this, the microcontroller can identify the respective phase and make the correct calculation, according to formula (1). Because the offset phase is always the shortest, this fact can also be used for identifying the phases. The number of phases in a complete cycle varies between 3 and 5, depending on the mode of the UTI. Each specific mode has a fixed number of periods. There is always one offset measurement, one reference measurement and one or more measurements of an unknown value.

5.3 Resolution

The output signal of the UTI is digitized by the microcontroller. This sampling introduces quantization noise, which also limits the resolution. The quantization noise of any phase measurement, as given by the relative standard deviation σ_q, amounts to:

$$\sigma_q = \frac{1}{\sqrt{6}} \frac{t_s}{T_{phase}} \qquad (2)$$

where t_s is the sampling time and T_{phase} the phase duration. When, for example, the sampling time is 1 µs and the offset phase duration is 20 ms (slow mode), the standard deviation of the offset phase is 1/45,000, which results in a resolution of maximum 15.5 bits. In fast mode this resolution would be 12.5 bits. Further improvement of the resolution can be obtained by averaging over several values of *M*. When *P* values $M_1 \ldots M_P$ is used to calculate $\overline{M}$, the value of σ_q decreases with a factor of $P^{1/2}$.

Besides quantization noise, another limitation of the resolution is the thermal noise of the oscillator itself and the possible effect of a parasitic (cable) capacitance C_p *(*see paragraph *5.5).* For the CMUX mode, the resolution as a function of the parasitic capacitance C_p (see Fig. 7) is shown in *figure 4.*

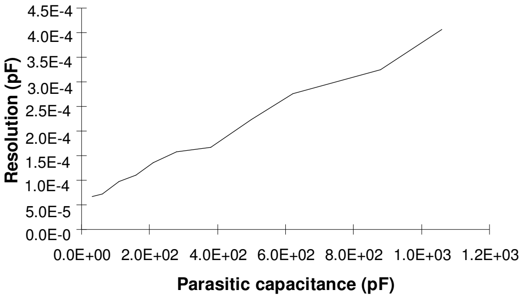


Figure 4. The resolution versus the parasitic capacitance C_p

5.4 Linearity

Typically, the linearity of the UTI has values between 11 bits and 14 bits, depending on the mode.
For the CMUX mode, the nonlinearity as a function of the parasitic capacitance C_p (see *Figure 7*) is shown in *Figure 5.*

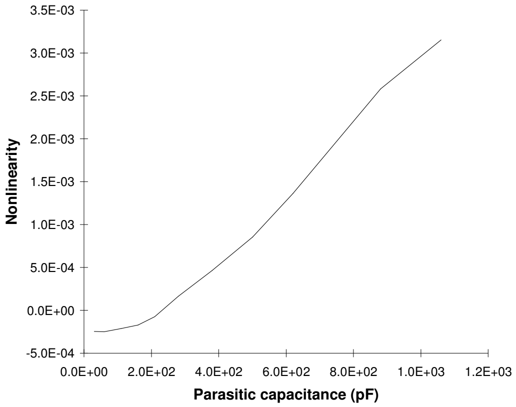


Figure 5. The nonlinearity versus the parasitic capacitance C_p
The measurement range equals 0 -2 pF

5.5 Capacitive measurements with the UTI

The way UTI measures capacitance values is special. In general when a capacitor has to be measured the capacitance of the cable is measured in parallel. See *figure a and b.*

Parasitic Cp parallel to Cx

Figure a) classical way of measuring capacitors, b) UTI way of measuring capacitors

In the classical way of measuring a capacitor, the cable capacitance is parallel to the capacitance to be measured. To avoid this effect is not so easy and measuring small capacitance values in combination with long cables is very hard. In the UTI this problem is solved by measuring the Cx in a four pole way, based on charge transfer over the capacitor which is to be measured. The excitation of the capacitor comes from a voltage source. This means Cp1 is connected parallel to this voltage source and therefore not a part of the measurement circuit. The transferred charge over Cx is absorbed by the virtual ground of a charge amplifier. This means that the parasitic capacitance Cp2 is also short circuited. With this four-pole measurement technique it is possible to measure capacitances as small as attoFarads (aF.) while the cable capacitances may have value of up to several hundred's of Pico Farads.

In *figure 5* the relation between accuracy and parasitic cable capacitance Cp is depicted. From the graph it can be seen that the linearity is still 1.0E-3 in case of a cable capacitance of about 500 pF.

When multiple capacitances are measured, each node (fi B, C,D,E,F) is activated for a certain time and after that the UTI switches on to the next node. The nodes that are not active are connected to ground and become parasitic and have therefore no influence on the measurement. Node selection is automatically controlled by the UTI. In the CMUX mode the number of capacitors is unlimited. All the capacitors are connected to a different voltage source and are all wired together to the receiver input of the charge amplifier (point A). Further CMUX applications are given in the CMUX specifications. For more information about measuring capacitors with the UTI please look into relevant **application notes** in the support shop of our website.

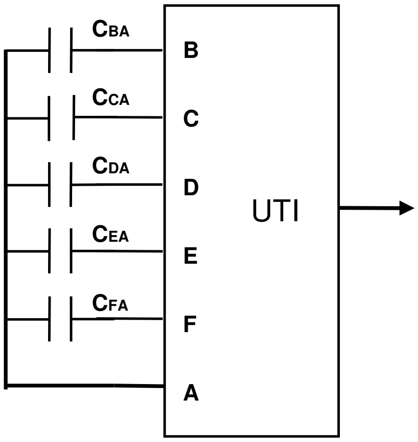
Note:
In most capacitive applications the input which is measured during the first phase (offset phase) is left unconnected. Under those circumstances only the internal capacitance of the device is measured (capacitance of the chip + capacitance of the bonding wires and leads). During the second phase the reference capacitor is measured. This is the most straight forward way to apply the three variable methods and to eliminate the offset and gain from the equations. Using this method, in **5-capacitor** mode (mode 0 or mode 2), **three unknown capacitors can be measured,** while in **3-capacitor** mode (mode 1 or mode 4) **one unknown capacitor can be measured**,

However, under certain circumstances, it may be desirable to connect an external offset component (C_0). When the value of this offset component is known with the same accuracy as the value of the reference component, the three signal method can still be applied.

6 CAPACITIVE MODES (MODE 0 – 4)

6.1 Mode 0. C25: 5 capacitors 0-2pF

In this mode, 5 capacitors in the range of 0 - 2 pF with one common electrode can be measured. In order to understand what this means in practical terms, **please refer to the note in paragraph 5.5**. The connection of capacitors is depicted in *Fig 6.* All measured capacitors should have a common receiver electrode, connected to node A. The signal at the transmitting electrodes (B to F) is a square wave with amplitude V_{DD}. When a capacitor is not measured, the node corresponding to this capacitor is internally grounded. In mode C25, one cycle takes 5 measurement phases as depicted in *Table 5*



Phase	Measured capacitors	Output periods
1	C_{BA}+ C_0	$T_{BA} = NK_1(C_{BA} + C_0)$
2	C_{CA}+ C_0	$T_{CA} = NK_1(C_{CA} + C_0)$
3	C_{DA}+ C_0	$T_{DA} = NK_1(C_{DA} + C_0)$
4	C_{EA}+ C_0	$T_{EA} = NK_1(C_{EA} + C_0)$
5	C_{FA}+ C_0	$T_{FA} = NK_1(C_{FA} + C_0)$

Table 5. Measured capacitors during each phase.

Parameter	Typical value
K_1	10 µs/pF
C_0	2 pF
Maximum capacitance C_{iA}	2 pF
Linearity	13 bits
Resolution (SF = 0, C_p=30 pF)	14 bits
Remaining offset	< 15×10^{-3} pF

Figure 6. Connection of capacitors to the UTI

Table 6. Specifications of the C25 and C23 modes

In phase 1 the input capacitor C_{BA}+ C_0 is measured. In this phase the output frequency is doubled, resulting in two short periods. This enables synchronization of the microcontroller. In straight forward applications, no capacitor is connected between B and A, as explained in the note in paragraph 5.5 the specifications for the mode C25 (mode 0) are listed in *Table 6.*
The remaining offset capacitance is caused by the parasitics between bonding wires, bonding pads and IC pins. When this offset is too large, one should use the mode CMUX. In this case, an external multiplexer is used and offset can be as low as 20×10^{-6} pF.

6.2 Mode 1. C23: 3 capacitors 0-2pF

In this mode, 3 capacitors in the range of 0 - 2 pF with one common electrode can be measured. In order to understand what this means in practical terms, **please refer to the note in paragraph 5.5.** The difference with mode C25 is that one cycle consists of only 3 phases. The connection of the capacitors is shown in *Fig 6* where C_{EA} and C_{FA} are omitted now. The measured capacitors during each phase are listed in *Table 7.* The specifications are listed in *Table 6.*

Phase	Measured capacitors	Output periods
1	C_{BA}+C_0	$T_{BA} = NK_1(C_{BA} + C_0)$
2	C_{CA}+C_0	$T_{CA} = NK_1(C_{CA} + C_0)$
3	C_{DA}+C_0	$T_{DA} = NK_1(C_{DA} + C_0)$

Table 7. Measured capacitors during each phase of the mode C23

6.3 Mode 2. C12: 5 capacitors 0-12pF

In this mode, 5 capacitors in the range of 0 - 12 pF with one common electrode can be measured. In order to understand what this means in practical terms, **please refer to the note in paragraph 5.5.** The connection of the capacitors to the UTI is shown in *Fig.6*. The maximum value of the capacitance C_{iA} (i is B, C, D or E) is 12 pF. The number of phases is 5. The specifications are listed in *Table* 8. The measured capacitors during each phase are indicated in *Table 5*. The main difference with mode 0 is that the maximum measurable capacitance is 12 pF.

Parameter	Typical value
K_1	1.7 µs/pF
C_0	12 pF
Maximum capacitance C_{iA}	12 pF
Linearity	13 bits
Resolution (SF = 0, C_p = 30 pF)	14 bits
Remaining offset	$< 15\times10^{-3}$ pF

Table 8. Specifications of the C12 mode

The remaining offset capacitance is caused by the parasitics between bonding wires, bonding pads and IC pins. When this offset is too large, one should use the mode CMUX. In this case, an external multiplexer is used and offset can be as low as 20×10^{-6} pF.

6.4 Mode 3. CMUX: X capacitors 0-2pF/0-12pF, external MUX

In this mode, an arbitrary number of capacitors in the range of 0 - 2 pF (CML = 0) or the range of 0 - 12 pF (CML = 1) with a common electrode can be measured. The UTI does not perform a phase selection, so an external multiplexer should be used. Just for this application, Smartec developed a novel multiplexer MUX with nine outputs and four inputs. The specifications of the CMUX mode are listed in *Table 9.*

Parameter	Typical value (CML = 0)	Typical value (CML = 1)
K_1	10 µs/pF	1.7 µs/pF
C_0	2 pF	12 pF
Maximum capacitance C_{iA}	2 pF	12 pF
Linearity (C_p< 300 pF)	13 bits	13 bits
Offset	2×10^{-5} pF	2×10^{-5} pF
Resolution (SF = 0, C_p < 30 pF)	14 bits	14 bits

Table 9. Specifications of the CMUX mode

A possible measurement setup is shown in *Figure 7*. An external multiplexer, which is controlled by the microcontroller (µC), multiplexes the signal at node B to one (or more) of the capacitors. The UTI output appears on the node "output". Nominal frequencies of the output signal during an offset measurement (none of the capacitors are selected) are 6 kHz (SF = 1) and 50 Hz (SF = 0). More information about this UTI mode can be found in the specifications of the Multiplexer.

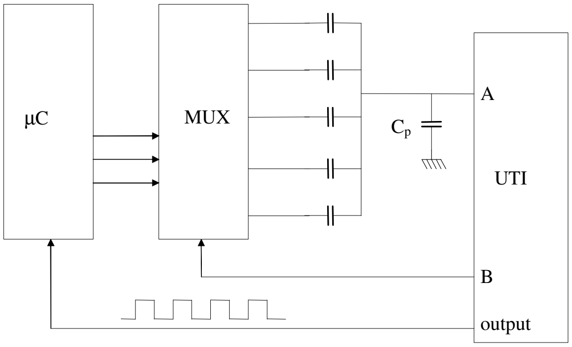


Figure 7. Possible measurement setup in the CMUX mode to measure multiple capacitors

6.5 Mode 4. C300: 3 capacitors, range up to 300pF

In this mode, 3 capacitors in a variable range up to 300 pF with a common electrode can be measured. **In order to understand what this means in practical terms,** please refer to the note in paragraph 5.5. The connection of sensors and external resistors is depicted in *Figure 8*. These resistors set the voltage swing at the transmitting electrode of C_{iA}.

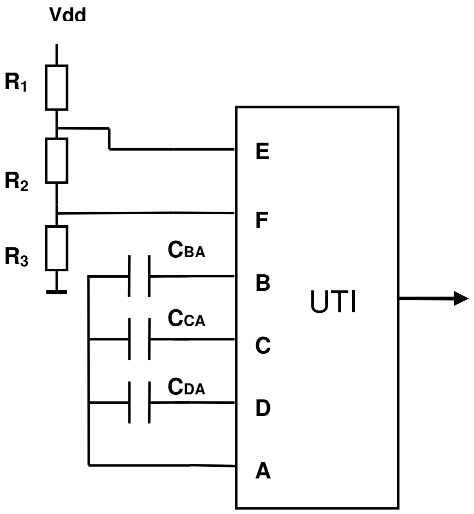


Figure 8. Connection of sensors to the UTI for the C300 mode

The total capacitance at node A must be limited to 500 pF in order to keep the nonlinearity below 10^{-3}. The voltage swing at the transmitting electrodes equals V_{EF} which is set externally by means of three inaccurate resistors R_1, R_2 and R_3, of which R_1 or R_3 may be zero. The DC voltage V_{EF} should satisfy the following condition: $V_{EF} < K_V/C_{max}$, where the constant $K_V = 60$ V·pF, and C_{max} is the maximum value of C_{BA}, C_{CA} and C_{DA} expressed in pF. The total time constant of all resistors and capacitors should be less than 500 ns. This sets the values of the resistors.

Example. When $C_{CA} = 300$ pF, $C_{DA} = 200$ pF, $C_{BA} = 0$ and $V_{DD} = 5$ V , practical values of the resistors are $R_1 = 25$ kΩ, $R_2 = 1$ kΩ and $R_3 = 0$. The voltage swing V_{EF} at the transmitting electrode amounts to 0.2 V.
The system contains two time constants $C_{tot}\cdot(R_3//(R_1+R_2))$ and $C_{tot}\cdot(R_1//(R_2+R_3))$, where $C_{tot} = C_{BA}+C_{CA}+C_{DA}+C_p$. Both time constants must be smaller than 500 ns. The nonlinearity and resolution in the

slow mode are depicted in *Table* 10. Here, the value of C_{DA} = 0 pF, C_p = 30 pF and V_{EF} has the maximum value K_V/C_{max}, as described before. The measured capacitors during each phase are listed in *Table 11*.

Capacitors	Nonlinearity	Resolution (pF)
$C_{BA}=C_{CA}$=33 pF	1.4×10^{-4}	1.2×10^{-3}
$C_{BA}=C_{CA}$=150 pF	1.9×10^{-4}	6.6×10^{-3}
$C_{BA}=C_{CA}$=270 pF	9.0×10^{-4}	17×10^{-3}
$C_{BA}=C_{CA}$=330 pF	2.6×10^{-3}	20×10^{-3}
$C_{BA}=C_{CA}$=560 pF	6.3×10^{-3}	46×10^{-3}

Table 10. Values of nonlinearity and resolution in C300 mode for different capacitor values

Phase	Capacitor	Output periods
1	$C_{BA} + C_0$	$T_{BA} = NK_1(C_{BA} + C_0)$
2	$C_{CA} + C_0$	$T_{CA} = NK_1(C_{CA} + C_0)$
3	$C_{DA} + C_0$	$T_{DA} = NK_1(C_{DA} + C_0)$

Table 11. The measured capacitors during each phase of the mode C300

7 RESISTIVE MODES (MODE 5 – 15)

7.1 Mode 5. Pt: 1 platinum resistor Pt100/ Pt1000, 4-wire

In this mode, one platinum resistor and one reference resistor can be measured. The connection of the resistors to the UTI is depicted in *Figure 9*. Because of the use of force/sense wires, both resistors R_x and R_{ref} are measured in a 4-wire setup, thereby completely eliminating the effect of lead resistances. The driving voltage V_{EF} is a square wave with amplitude V_{DD} at 1/4 of the internal oscillator frequency. The resistor R_{BIAS} is used to set the current through the chain. For a measurement of a Pt100, the measurement accuracy amounts to ±40 mΩ. This 40 mΩ can be considered as a systematic error caused by the internal design of the chip.

Excitation of the measurement chain is done with an AC voltage. The cable capacitance has influence on the measurement accuracy. For applications with any significant length of (shielded) cable a special interface is developed. Please refer to the relevant application notes in the support shop of our website and you will see how cable lengths up to 200 meter can be implemented without loss of precision. Smartec recommends this solution for all resistive applications, where the sensing element is not close to the UTI.

One measurement cycle consists of 4 phases. These phases contain the information for a 2-, 3- or 4-wire measurement.

Phase	Measured voltages	Output periods
1	V_0	$T_{off} = NK_2V_0$
2	$V_{AB} + V_0$	$T_{AB} = NK_2(V_{AB} + V_0)$
3	$V_{CD} + V_0$	$T_{CD} = NK_2(V_{CD} + V_0)$
4	$V_{BC} + V_0$	$T_{BC} = NK_2(V_{BC} + V_0)$

Table 12. Measured voltages during the measurement of platinum resistors

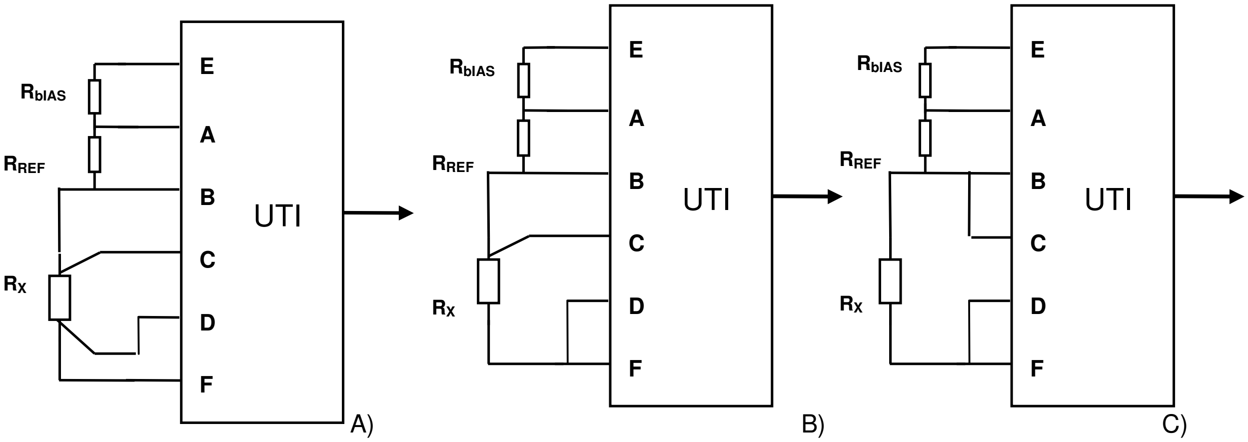


Figure 9. Connection of platinum resistors to the UTI in a 4-wire (a), 3-wire (b) and a 2-wire (c) connection

To calculate the ratio as in (1), we have to make different calculations for the 2-, 3- and 4 wire measurement:

$$M_{2-,4-wire}=\frac{T_{phase3}-T_{phase1}}{T_{phase2}-T_{phase1}}=\frac{R_x}{R_{ref}}$$
$$M_{3-wire}=\frac{T_{phase3}-T_{phase4}}{T_{phase2}-T_{phase1}}=\frac{R_x}{R_{ref}} \qquad (3)$$

The linearity is better than 13 bits provided that the amplitude of the voltages V_{AB} and V_{CD} is below 0.7 V for V_{DD} = 5V. For V_{DD} = 3.3 V, these voltages should be less than 0.4 V. This limits the current through the platinum resistor.

Current limitation is also required to limit the error due to self-heating. For instance, for a thermal resistance of 200 K/W (still air) at V_{CD} = 0.7 V and 0ºC, the self-heating effect of a Pt100 causes an error of 1 K. If this self-heating error is too large, R_{BIAS} must be increased to limit the current through the Pt100. For V_{CD} = 0.2 V, the temperature error due to self-heating would amount to 80 mK. This is two times less than the initial inaccuracy of a class A Pt100. In this case, the current through the Pt100 amounts to 2 mA which requires R_{BIAS} = 2.2 kΩ.

The relative sensitivity of a Pt100 is 3.9×10^{-3}/K. When the current through the Pt100 is 2 mA, this sensitivity corresponds to 780 µV/K. The UTI resolution in this mode is 7 µV, corresponding to 9 mK resolution for the measurement in slow mode. *Table* 13 lists the specifications of the UTI in the Pt mode.

Parameter (V_{DD} = 5 V)	**Typical value**
K_2	56 µs/V
V_0	0.36 V
R_{BIAS} (Pt100, self-heating for 200K/W = 80 mK)	2.2 kΩ (5%), I = 2 mA
R_{BIAS} (Pt1000, self-heating for 200K/W = 80 mK)	6.2 kΩ (5%), I = 600 µA
Excitation current from E and F	20 mA
Offset	10 µV
Linearity	13 bits
Resolution (SF = 0) (Pt100, 2 mA)	14 bits (9 mK)

Table 13. Specifications of the Pt mode

Amplitudes of V_{CD} and V_{AB} up to 2.5 V peak-to-peak are allowed (very good resolutions can be obtained), but self-heating effects and nonlinearity have to be taken into account. ***However, linearity can decrease to 8 bits for peak-to-peak amplitudes in the range of 0.7-2.5 V.***

Platinum resistors can also be measured using mode 11.

7.2 Mode 6. Ther: 1 thermistor, 4-wire

In this mode, one thermistor and one reference resistor can be measured. The connection of the thermistor and the reference resistor is shown in *Figure 10*.

The driving voltage V_{EF} is a chopped voltage with an amplitude of $V_{DD}/12.5$ (0.4 V at $V_{DD} = 5$ V) and a DC value $V_{DD}/2$.

The ratio of the thermistor and the reference resistor is also given by (3). The signals, which are measured during the various phases, are listed in *Table 12*. The voltage V_{AB} is not constant, but has the same temperature information as V_{CD}, which linearises the sensor characteristic.

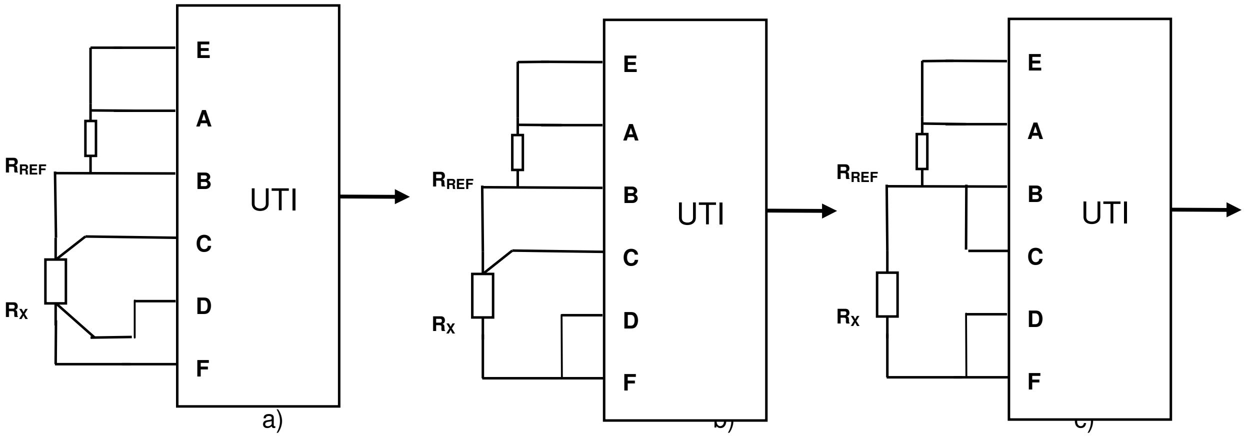


Figure 10. Connection of the thermistor to the UTI in a 4-wire (a), 3-wire (b) and 2-wire (c) connection

Parameter ($V_{DD} = 5$ V)	Typical value
K_2	56 µs/V
V_0	0.36 V
$R_{ref}//R_x$	<5 kΩ
$R_{ref}+R_x$	>1 kΩ
Offset	10 µV
Linearity	13 bits
Resolution (SF = 0)	7 µV (1 mK)

Table 14. Specifications of the Ther mode

The specification of the thermistor mode is shown in *Table* 14. For very large and very small values of R_x (10 times or 0.1 times R_{ref}), the resolution, in voltage, is still the same, but the resolution in temperature is decreased. This is due to the linearization method.

For a thermistor with a sensitivity of 4%/K, the resolution is 1 mK for $V_{DD} = 5$ V.

7.3 Mode 7. Pt2: 2 or 3 platinum resistors

In this mode, 2 or 3 platinum resistors can be measured. The connection of the resistors to the UTI is shown in Figure 11. The voltage V_{EF} is the same as in the mode Pt.

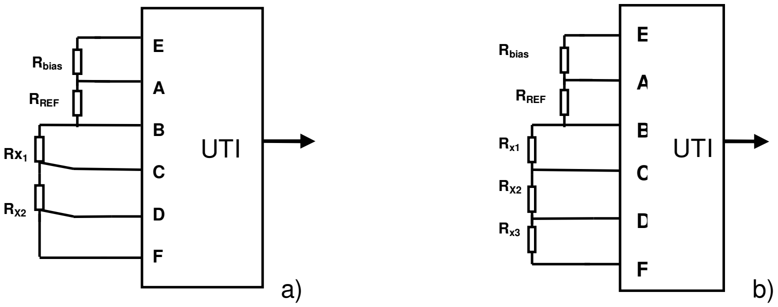


Figure 11. Connection of 2 (a) or 3 (b) platinum resistors for the Pt2 mode

The same restrictions for the current through the resistors as in the Pt mode apply here as well. The specifications are listed in *Table 13*. Note that R_{x2} can be measured with a 4-wire setup. Phase 5 can be used to measure just one lead resistance or to measure R_{x3}. The main difference with the Pt mode is that one measurement cycle takes 5 phases, as listed in *Table 15.*

Phase	Measured voltages	Output periods
1	V_0	$T_{off} = NK_2V_0$
2	$V_{AB}+V_0$	$T_{AB} = NK_2(V_{AB}+V_0)$
3	$V_{CD}+V_0$	$T_{CD} = NK_2(V_{CD}+V_0)$
4	$V_{BC}+V_0$	$T_{BC} = NK_2(V_{BC}+V_0)$
5	$V_{DF}+V_0$	$T_{DF} = NK_2(V_{DF}+V_0)$

Table 15 Measured voltages during the phases of the Pt2 mode

With the connection shown in *Figure 11(b),* the effect of lead resistances can not be eliminated. Especially, when R_{x3} is measured with the connection shown in *Figure 11(b),* the internal connection wires of the UTI will cause an error of 0.9 Ω for the Pt100 and 3 Ω for the Pt1000, respectively. This measured error depends on the supply current of the platinum resistors and temperature, but is stable and systematic.

7.4 Mode 8. Ther2: 2 or 3 thermistors

In this mode, 2 or 3 thermistors can be measured. The connection is depicted in *Figure 12*. The number of phases is also 5, as listed in *Table 15*. The specifications listed in *Table 14* also hold for this mode.
With the connection shown in *Figure* 12(a), the effect of lead resistances can not be eliminated. Especially, when R_{x3} is measured with the connection shown in *Figure* 12(b), the internal connection wires of the UTI will cause an error of 11.5 Ω for the resistor R_{x3} with a value of 2.5 kΩ. This measured error depends on the supply current of the thermistor and the temperature.

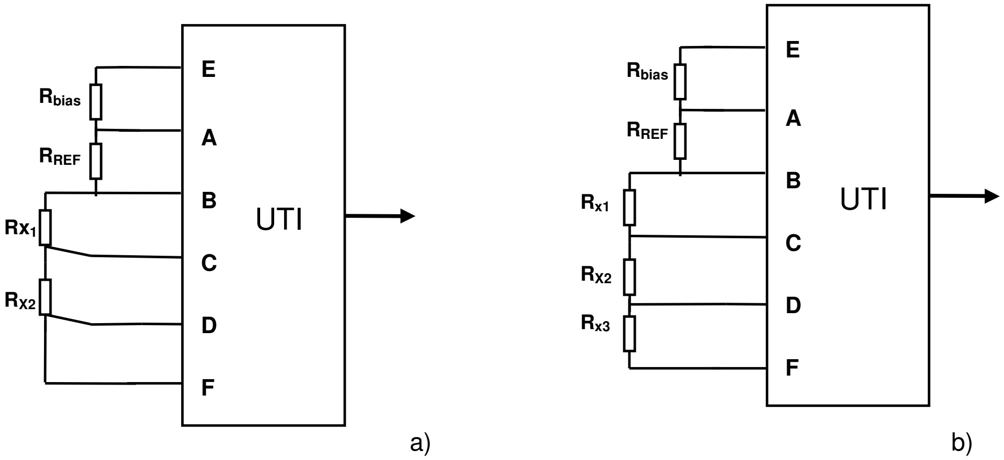


Figure 12. Connections of 2 (a) and 3 (b) thermistors to the UTI

8 RESITIVE BRIDGE MODES (MODE 9 – 14)

8.1 Mode 9. Ub2: resistive bridge, ref. is V_{bridge}, +/- 4% imbalance

In this mode, a resistive bridge can be measured where the ratio of the bridge output voltage V_{CD} and the bridge supply voltage V_{AB} represents the physical signal.
The measurement range of the bridge imbalance is +/-4% in this mode.
The connection of the bridge to the UTI is shown in *Figure* 13. The driving voltage across the bridge V_{EF} is a square wave with amplitude V_{DD}. The frequency of this signal is 1/4 of the internal oscillator frequency. Because force/sense wires are used, the bridge is measured in a 4-wire setup, as shown in

Figure *13* (a). The signals measured in the various phases are given in *Table 16*.

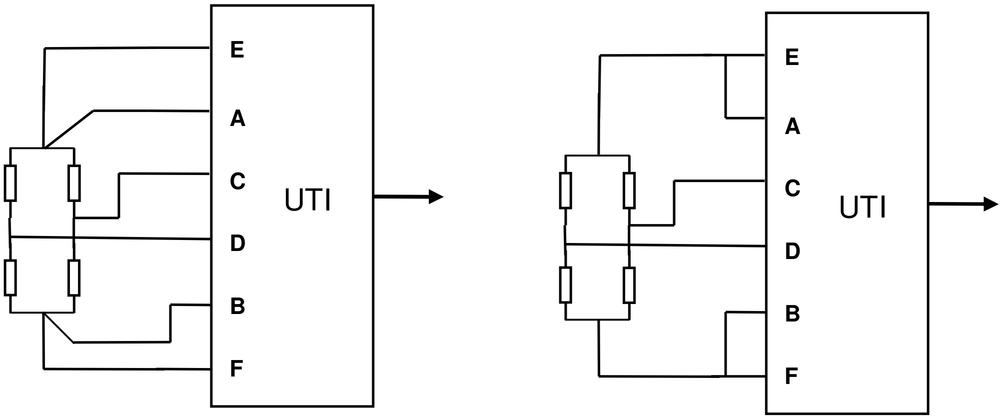


Figure 13. Connection of the resistive bridge to the UTI for the Ub2 mode in a 4-wire setup (a) and a 2-wire setup (b)

During phase 2, the voltage across the bridge V_{AB} is measured. A very accurate on-chip voltage divider divides this voltage by 32. This divider does not need calibration. After division, V_{AB} is processed in the same way as V_{CD}.

Phase	Measured voltages	Output periods
1	V_0	$T_{off} = NK_2V_0$
2	$V_{AB}/32 + V_0$	$T_{AB} = NK_2(V_{AB} / 32 + V$
3	$V_{CD} + V_0$	$T_{CD} = NK_2(V_{CD} + V_0)$

Table 16. Measurement phases of the Ub2 mode

To find the bridge imbalance, the microcontroller calculates:

$$M = \frac{1}{32}\frac{T_{phase3} - T_{phase1}}{T_{phase2} - T_{phase1}} = \frac{V_{CD}}{V_{AB}} \qquad (4)$$

The specifications are listed in *Table 17*

Parameter	Typical value
K_2	56 µs/V
V_0	0.54 V
Bridge excitation	AC V_{DD}
Excitation current from E and F	20 mA
Bridge resistance R_b	250 Ω < R_b < 10 kΩ
Bridge output voltage	max +/- 0.2V
Accuracy	11 bits
Offset	10 µV
Resolution (SF = 0)	7 µV

Table 17. Specifications of the Ub2 mode

8.2 Mode 10. Ub1: res. bridge, ref. is V_{bridge}, +/- 0.25% imbalance

In this mode, a resistive bridge can be measured where the ratio of the bridge output voltage and the bridge supply voltage represents the physical signal. ***The main difference with mode Ub2 is that the measurement range of the bridge imbalance is 0.25%. (V_{CD} = 12.5 mV for V_{DD} = 5V).***

The connection of the bridge to the UTI is the same as in the Ub2 mode. An on-chip 15-times voltage amplifier amplifies the small output voltage before it is processed in the same way as the divided voltage across the bridge. Both the amplifier and divider do not need calibration. To calculate the bridge imbalance, Equation (7) can be used, where 32 must be replaced by 480. Due to the use of the force/sense wires, the bridge is measured in a 4-wire setup. The various voltages measured during each phase are indicated in *Table 18*. The specifications are listed in *Table 19*

Phase	Measured voltages	Output periods
1	V_0	$T_{off} = NK_2V_0$
2	$V_{AB}/32 + V_0$	$T_{AB} = NK_2(V_{AB}/32 + V_0)$
3	$15V_{CD} + V_0$	$T_{CD} = NK_2(15 \cdot V_{CD} + V_0)$

Table 18. Measured voltages during each phase of the Ub1 mode

Parameter	Typical value
K_2	56 µs/V
V_0	0.54 V
Bridge excitation	AC V_{DD}
Excitation current from E and F	20 mA
Bridge resistance R_b	250 Ω < R_b < 10 kΩ
Bridge output voltage	max +/- 12.5 mV
Accuracy	10 bits
Offset	10 µV
Resolution (SF = 0)	700 nV

Table 19. Specifications of the Ub1 mode

8.3 Mode 11. Ib2: resistive bridge, ref. is I_{bridge}, +/- 4% imbalance

In this mode, a resistive bridge can be measured where the physical signal is represented by the output voltage of the bridge and the current through the bridge. This current I is converted into a reference voltage. The connection of the bridge and the reference element is shown in *Figure 14(a).* ***The value of R_{ref} should be chosen such that V_{AB} is between 0.1 V and 0.2 V.*** This mode can also be used to measure platinum resistors in a 4-wire setup. This is shown in *Figure 14(b).* The advantage in comparison with mode Pt is that now only three phases have to be measured.

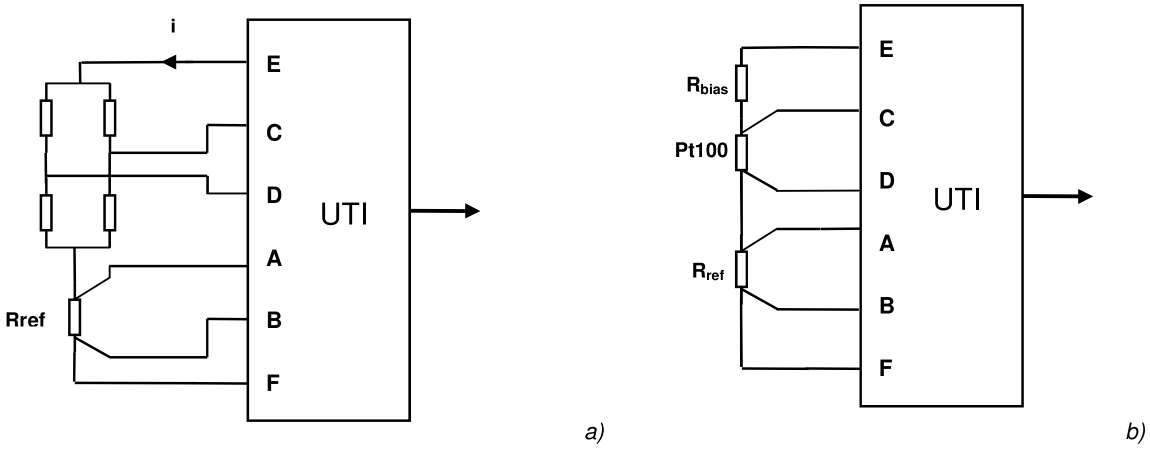


Figure 14. Connection of the resistive bridge and a reference resistor to the UTI (a) and connection of a platinum resistor in 4-wire setup (b)

Phase	Measured voltages	Output periods
1	V_0	$T_{off} = NK_2V_0$
2	$V_{AB}+V_0$	$T_{AB} = NK_2(V_{AB}+V_0)$
3	$V_{CD}+V_0$	$T_{CD} = NK_2(V_{CD}+V_0)$

Table 20. Measured voltages for each phase of the Ib2 mode

Parameter	Typical value
K_2	56 µs/V
V_0	0.54 V
Bridge excitation	AC V_{DD}
Excitation current from E and F	20 mA
Bridge resistance R_b	250 Ω < R_b < 10 kΩ
Bridge output voltage	max +/- 0.2 V
Accuracy	12 bits
Offset	10 µV
Resolution (SF=0)	7 µV

Table 21. Specifications of the Ib2 mode

8.4 Mode 12. Ib1: resistive bridge, ref. is I_{bridge}, +/- 0.25% imbalance

This mode is similar to mode 11. The connection of the bridge and the resistor is shown in *Figure 14*.

The difference with mode 11 is that the bridge imbalance range is +/- 0.25%. The voltage across the reference resistor should be between 0.1 V and 0.2 V, as in mode 11.

The bridge output voltage is amplified 15 times before it is processed in the same way as the reference voltage. The voltages measured during each phase are indicated in *Table 22*. The specifications of the Ib1 mode are listed in *Table 23*.

Phase	Measured voltages	Output periods
1	V_0	$T_{off} = NK_2V_0$
2	$V_{AB} + V_0$	$T_{AB} = NK_2(V_{AB} + V_0)$
3	$15V_{CD} + V_0$	$T_{CD} = NK_2(15V_{CD} + V_0)$

Table 22. Measured voltages during each phase of the Ib1 mode

To find the bridge imbalance, the microcontroller calculates

$$M = \frac{1}{15}\frac{T_{phase3} - T_{phase1}}{T_{phase2} - T_{phase1}} = \frac{V_{CD}}{IR_{ref}} \qquad (5)$$

Parameter	Typical value
K_2	56 µs/V
V_0	0.54 V
Bridge excitation	AC V_{DD}
Excitation current from E and F	20 mA
Bridge resistance R_b	250 Ω < R_b < 10 kΩ
Bridge output voltage	max +/- 12.5 mV
Accuracy	10 bits
Offset	10 µV
Resolution (SF = 0)	700 nV

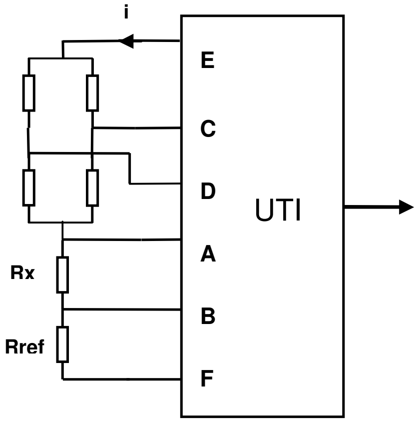
Table 23. Specifications of the Ib1 mode

8.5 Mode 13. Brg2: resistive bridge +/- 4% and 2 resistors

In this mode, a resistive bridge with a maximum imbalance of +/-4% and two resistors can be measured. One of the resistors can be temperature dependent, so the bridge output can be digitally corrected for temperature effects. Both the voltage across the bridge and the current through the bridge are measured. The connection of the elements to the UTI is shown in *Figure 15.*

The voltage V_{EF} is a square wave with amplitude V_{DD} at 1/4 of the oscillator frequency. The voltage across R_{ref} should be between 0.1 V and 0.2V.

The voltages to be measured are indicated in *Table 24.*



Phase	Measured voltages	Output periods
1	V_0	$T_{off} = NK_2V_0$
2	$V_{AB} + V_0$	$T_{AB} = NK_2(V_{AB} + V_0)$
3	$V_{CD} + V_0$	$T_{CD} = NK_2(V_{CD} + V_0)$
4	$V_{BF} + V_0$	$T_{BF} = NK_2(V_{BF} + V_0)$
5	$V_{EA}/32 + V_0$	$T_{EA} = NK_2(V_{EA} / 32 + V_0$

Figure 15. Connections of the sensors to the UTI

Table 24. Signals during the various phases of mode Brg2

The voltage across the bridge V_{EA} is divided by 32 before it is processed in the same way as the other measured voltages. The bridge imbalance V_{CD}/V_{EA} is obtained from:

$$M = \frac{1}{32}\frac{T_{phase3} - T_{phase1}}{T_{phase5} - T_{phase1}} = \frac{V_{CD}}{V_{EA}} \qquad (6)$$

The specifications of this mode are listed in *Table 25*

Parameter	Typical value
K_2	56 µs/V
V_0	0.54 V
Excitation V_{EF}	AC V_{DD}
Excitation current from E and F	20 mA
Bridge resistance R_b	250 Ω < R_b < 10 kΩ
Bridge output voltage	max +/- 0.2 V
Accuracy V_{CD}/V_{EA}	11 bits
Linearity V_{AB}/V_{BF}	12 bits
Offset V_{CD} or V_{AB}	10 µV
Resolution (SF = 0)	7 µV

Table 25. Specifications of the Brg2 mode

For the measurement of the signal V_{BF}, due to the effect of the internal connection wires of the UTI, an error of 1.2% will be caused on the result of V_{AB}/V_{BF}. This measured error depends on the supply current of the resistive bridge and the temperature.

8.6 Mode 14. Brg1: resistive bridge +/- 0.25% and 2 resistors

This mode is similar to mode 13. The connection is shown in *Figure 15*. The difference with mode 13 is that the measurement range of the bridge imbalance is 0.25%. The bridge output voltage V_{CD} is amplified 15 times before it is processed further. The voltages measured during each phase are indicated in *Table 26*. The specifications are listed in *Table 27*. For the measurement of the signal V_{BF}, due to the effect of the internal connection wires of the UTI, an error of 1.2% will be caused on the result of V_{AB}/V_{BF}. This measured error depends on the supply current of the resistive bridge and temperature.

Phase	Measured voltages	Output periods
1	V_0	$T_{off} = NK_2V_0$
2	$V_{AB} + V_0$	$T_{AB} = NK_2(V_{AB} + V_0)$
3	$15V_{CD} + V_0$	$T_{CD} = NK_2(15V_{CD} + V_0)$
4	$V_{BF} + V_0$	$T_{BF} = NK_2(V_{BF} + V_0)$
5	$V_{EA}/32 + V_0$	$T_{EA} = NK_2(V_{EA}/32 + V_0)$

Table 26. ***Measured voltages during each phase of the Brg1 mode***

Parameter	Typical value
K_2	56 µs/V
V_0	0.54 V
Excitation V_{EF}	AC V_{DD}
Excitation current from E and F	20 mA
Bridge resistance R_b	250 Ω < R_b < 10 kΩ
Bridge output voltage	max +/- 12.5 mV
Accuracy V_{CD}/V_{EA}	10 bits
Linearity V_{AB}/V_{BF}	12 bits
Offset V_{CD}	10 µV
Offset V_{AB}	10 µV
Resolution V_{CD} (SF = 0)	700 nV
Resolution V_{AB} (SF = 0)	7 µV

Table 27. Specifications of the mode Brg1

8.7 Mode 15. Potm: 3 potentiometers, 1kΩ-25kΩ

In this mode, 3 potentiometers in the range of 1 kΩ to 50 kΩ can be measured. The connection of potentiometers is depicted in *Figure 16*. When only a single potentiometer is measured with its slide connected to, for instance, node B, nodes C and D should be connected to F. The voltage across the potentiometers is a square wave with amplitude V_{DD} and frequency 1/4 of the internal oscillator frequency.

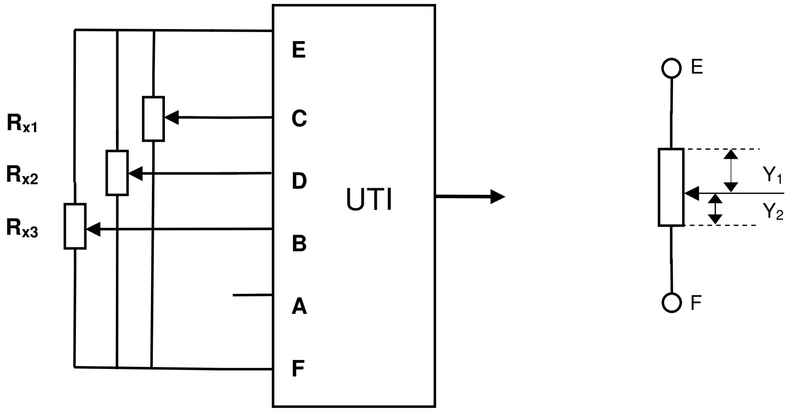


Figure 16. Connection of potentiometers to the UTI

It is not possible to compensate for the effect of lead wires in this mode. Therefore, the use of low-ohmic potentiometers should be avoided. The measured voltages during each phase are indicated in *Table 28* and the specifications in *Table 29.* The relative position *M* for each potentiometer is given by:

$$M = \frac{T_{phase3,4,5} - T_{phase1}}{T_{phase2} - T_{phase1}} = \frac{y_2}{y_1 + y_2} \qquad (7)$$

Parameter	Typical value
K_2	4 µs/V
V_0	5 V
Potentiometer value R_{xi}	1 kΩ < R_{xi} < 25 kΩ
Accuracy	10^{-3}
Resolution (SF = 0)	14 bits

Table 29. Specifications of the Potm mode

	Measured Voltages	**Output periods**
1	V_0	$T_{off} = NK_2V_0$
2	$V_{EF}+V_0$	$T_{EF} = NK_2(V_{EF}+V_0)$
3	$V_{CF}+V_0$	$T_{CF} = NK_2(V_{CF}+V_0)$
4	$V_{BF}+V_0$	$T_{BF} = NK_2(V_{BF}+V_0)$
5	$V_{DF}+V_0$	$T_{DF} = NK_2(V_{DF}+V_0)$

Table 28. Measured voltages for each phase during measurement of potentiometers

11. Encapsulations

Figure 17 shows the pad configuration of the UTI die and the SOIC encapsulation. The size of the die amounts to 3.1 mm × 2.1 mm.

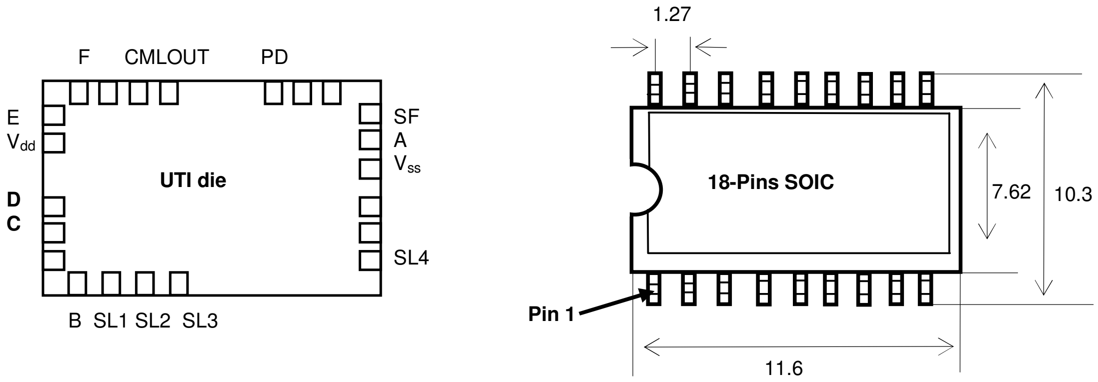


Figure 17 The pad configuration of UTI SOIC/die

All sizes in mm

12. Development Kit

For actual development purposes, a development kit is available. This kit can be connected directly to a personal computer. Additional practical information can be found in the UTI **application notes** in the supports shop of our website.