



## Data Acquisition Systems for Quasi-Digital Temperature Sensors Based on Universal Frequency-to-Digital Converter

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**Abstract:** The application specific paper describes a design approach for data acquisition systems for quasi-digital temperature sensors. It is based on the Universal Frequency-to-Digital Converter (UFDC-1) working well with any frequency output sensors. Such design approach lets significantly simplify the design process, reduce time-to-market and production price and produce data acquisition systems with high metrological performances. Practical examples of direct interfacing of temperature quasi-digital sensors to the UFDC-1 are given.

**Keywords:** universal frequency-to-digital converter, quasi-digital temperature sensor, data acquisition system, frequency output sensors, sensor interfacing, UFDC-1

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### 1. Introduction

Due to many advantages of frequency as an informative parameter of sensors (high noise immunity, high output signal power, wide dynamic range, high accuracy of frequency standards, simplicity of signal switching, interfacing, integration and coding, etc.), more and more manufactures produce different sensors and transducers with frequency, period, time interval or duty-cycle output. Sometimes such sensors are called “digital sensors” but really it should be called “quasi-digital sensors” because of frequency signal has features of analog and digital signals at the same time. The definition of quasi-digital sensor was given in [1]. We will consider a digital sensor as a sensor with parallel (data bus, LPT, etc.), serial (COM port, RS-232, RS-422, RS-485, USB interfaces, etc.) or bus

(I<sup>2</sup>C, SPI, IS<sup>2</sup>, SMBus, CAN, etc.) output.

Temperature is one of the most widely measured variables in industrial, consumer, and computer applications. It is an analog quantity, but digital systems often use temperature to implement measurement, control, and protection functions. In most applications in which temperature is measured, the measured value must be converted from analog to digital form. By providing a digital output, digital sensors do not require external circuitry for linearization and data conversion.

Many modern manufactures produce frequency (period, duty-cycle) output temperature sensors. It is *Analog Devices* with its popular TMP03/04/05/06 sensors; *Maxim* with pulse-width modulation (PWM), period and frequency output sensors MAX6576/6577, MAX6666/67, MAX6672/73 and MAX6676/77 (PWM temperature sensors provide a square wave output whose duty cycle is proportional to the temperature); *Smartec* with its duty-cycle temperature sensor SMT160-30; *Sea-Bird Electronics* with its high precision frequency output sensors SBE3plus, SBE 3F and SBE8; *Slope Indicator* with its VW precision frequency sensors and other manufacturers [1, 2].

Performances of quasi-digital temperature sensors from different manufacturers are shown in Table 1.

**Table.1.** *Quasi-digital temperature sensors performances.*

Sensor	Max. Temp. Error, °C	Temp. Range, °C	Resolution, Bits	Output	Output Range
<i>Analog Devices</i>					
TMP03	± 1.5	-40 to +100	16	PWM	-
TMP04	± 1.5	-40 to +100	16	PWM	-
TMP05	± 0.5	-40 to +150	12	PWM	-
TMP06	± 0.5	-40 to +150	12	PWM	-
<i>Maxim Integrated Products</i>					
MAX6576	± 3.0	-40 to +125	N/A	Period	0.0023 to 0.26 s
MAX6577	± 3.0	-40 to +125	N/A	Frequency	14.57to1592.6 Hz
MAX6666	± 1.0	-40 to +125	11	PWM	-
MAX6667	± 1.0	-40 to +125	11	PWM	-
MAX6672	± 3.0	-40 to +125	N/A	PWM	-
MAX6673	± 3.0	-40 to +125	N/A	PWM	-
MAX6676	± 1.5	-40 to +125	N/A	PWM	-
MAX6677	± 1.5	-40 to +125	N/A	PWM	-
<i>Sea-Bird Electronics</i>					
SBE 3F	± 0.001	-5 to +35	N/A	Frequency	2 to 6 kHz
SBE 3plus	± 0.001	-5 to +35	N/A	Frequency	2 to 6 kHz
SBE 8	± 0.01	-3 to +30	16	Frequency	0.1 to 200 Hz
<i>Slope Indicator</i>					
VW	± 0.3	-20 to +80	N/A	Frequency	N/A
<i>Smartec</i>					
SMT160-30	± 0.7	-45 to +130	N/A	Duty-cycle	1 to 4 kHz

N/A – information is not available

As it is visible from this table modern quasi-digital temperature sensors have high accuracy and wide frequency range. So, SBE3plus temperature has 0.003 % relative FS error. The frequency-to-digital converter should have 0.0003 % or at least 0.0006 % error in order to be neglected. Quasi-digital temperature sensors can simply interfacing to microcontroller. But it means the use of program-oriented conversion methods. These introduce additional error components due to so-called program-dependent or software-related effects [1, 3, 4, 5], for example, the error due to delay of reaction to interruption and error of shift in time of the response for interruption. Both components take place at any

waveform of signals, including rectangular. Very often these components exceed the quantization error and it is necessary to use non-trivial methods and optimization counter techniques for its minimization. The Universal Frequency-to-Digital Converter (UFDC) lets eliminate these design problems, because of it uses the advanced conversion method to convert different frequency-time parameters to digital [6]. Such design approach lets significantly simplify the design process, reduce time to market and production price and produce data acquisition (DAQ) systems for quasi-digital temperature sensors with high metrological performances. Let consider quasi-digital sensors interfacing to the UFDC-1 in order to produce such DAQ systems.

## 2. Quasi-Digital Sensors Interfacing

### 2.1 Analog Devices' Quasi-Digital Temperature Sensors

The **TMP03/TMP04** are monolithic temperature detectors that generate a modulated serial digital output that varies in direct proportion to the temperature of the device [7]. The digital output of the TMP04 is CMOS/TTL compatible, and is easily interfaced to the input of UFDC-1. The open-collector output of the TMP03 is capable of sinking 5 mA. The TMP03 is best suited for systems requiring isolated circuits utilizing optocouplers or isolation transformers. The output of the TMP03 is a square wave with a nominal frequency of 35 Hz ( $\pm 20\%$ ) at 25°C. The output format is shown in Figure 1.

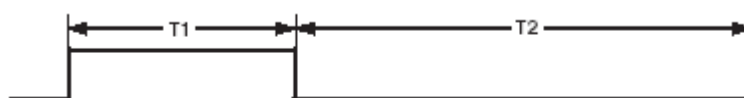


Fig. 1. TMP03 output format.

The temperature should be calculated according to the following equations:

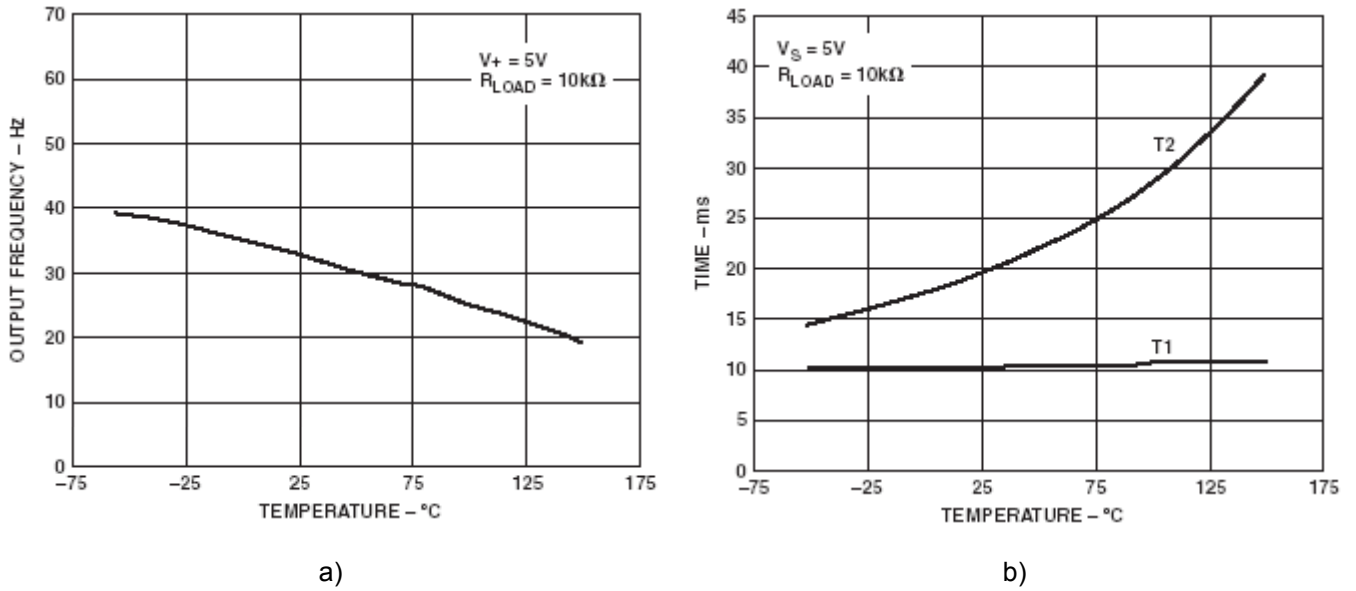
$$T(^{\circ}C) = 235 - \left( \frac{400 \times T1}{T2} \right) \quad (1)$$

$$T(^{\circ}F) = 455 - \left( \frac{720 \times T1}{T2} \right) \quad (2)$$

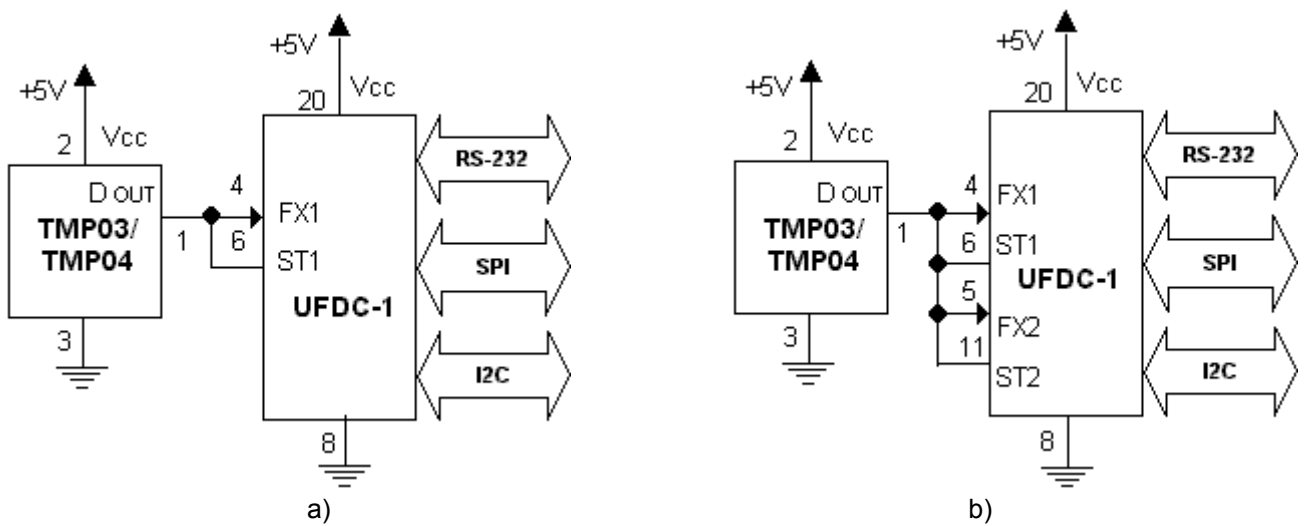
The time interval T1 (pulse width) and T2 (space interval) can be easily read by the UFDC-1, with the above calculations performed in software by PC connected through COM-port or master microcontroller in case of I<sup>2</sup>C or SPI buses. T1 is nominally 10 ms, and compared to T2 is relatively insensitive to temperature changes. A useful worst-case assumption is that T1 will never exceed 12 ms over the specified temperature range. The output frequency vs. temperature is shown in Figure 2a and T1 and T2 time intervals vs. temperature - in Figure 2b.

The UFDC-1s simply measures the T1 and T2 time intervals or period  $T_x = T1 + T2$  with beforehand setup accuracy, space interval  $T2$  and  $T1 = T_x - T2$  then calculates the temperature using the equations (1), (2). Taking into account that the UFDC-1 has two inputs, the period and space interval can be measured at the same time. Both interfacing cases are shown in Figure 3 a) and b) accordingly. Appropriate commands (RS-232 interface) for the UFDC-1 operation in two interfacing modes are shown in Figure 4.

Taking into account the sensors' relative error 1.5 % FS the UFDC-1 conversion error should be chosen 0.1 % in order to be neglected.



**Fig. 2.** Output frequency vs. temperature (a) and T1 and T2 time intervals vs. temperature. (Reproduced from [7]).



**Fig. 3.** TMP03/TMP04 interfacing: T1 and T2 time intervals measurement (a), and period (T1+T2) and space interval (T2) measurement (b).

Example 1:

- >MB; Pulse interval T1 measurement initialization
- >S; Start a measurement
- >R; Read a result for T1
- >MC; Space interval T2 measurement initialization
- >S; Start a measurement
- >R; Read a result for T2

a)

Example 2:

- >MF; Period  $T_x = T1 + T2$  measurement initialization
- >A3; 0.1 % period conversion error set up
- >S; Start a measurement
- >R; Read a result for T1
- >MC; Space interval T2 measurement initialization
- >S; Start a measurement
- >R; Read a result for T2

b)

**Fig. 4.** Appropriate UFDC-1 commands (RS-232) for T1 and T2 time intervals measurement (a) and period (T1+T2) and space interval (T2) measurement (b).

The **TMP05/TMP06** are monolithic temperature sensors that generate a modulated serial digital output (PWM), which varies in direct proportion to the temperature of the devices [8]. The pulse width (T1) of the PWM remains static over all temperatures, while the space interval (T2) varies (Figure 1).

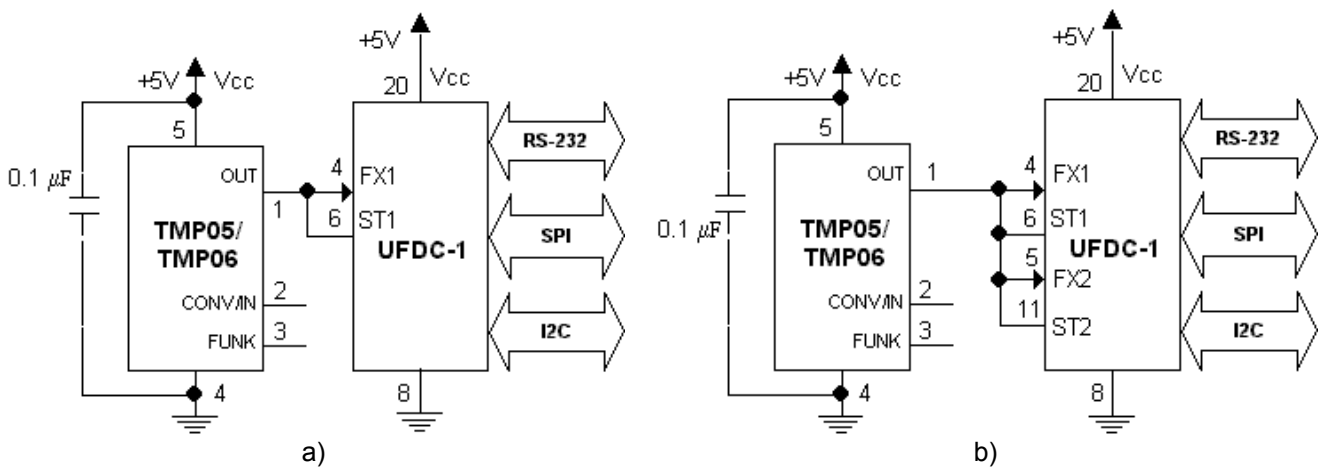
The output of the TMP05/TMP06 is CMOS/TTL compatible, and is easily interfaced to the input of UFDC-1. Pulse-width modulated (PWM) output gives a square wave whose ratio of pulse width to space interval is proportional to temperature. The typical period is 116 ms at 25°C. This format is easily decoded by a PC (RS-232 interfacing) or master microcontroller (I<sup>2</sup>C or SPI bus communication modes) into either °C or °F values.

The temperature should be calculated according to the following equation:

$$T(^{\circ}C) = 421 - \left( 751 \cdot \frac{T1}{T2} \right) \tag{3}$$

The pulse width T1 and space interval T2 are values easily read by the UFDC-1. In standard interfacing mode to the UFDC-1, the TMP05/TMP06 should be used in continuously converting mode with appropriate conversion rate [8]. In order to use the shot or daisy-chain mode the custom UFDC design should be ordered.

Figure 5 a) and b) show how TMP05/TMP06 quasi-digital sensors can be interfaced to the UFDC-1. This corresponds to the continuously converting mode (floating FUNC pin) and the nominal conversion rate T1/T2=40/76 (floating CONV/IN pin). The appropriate UFDC-1 commands are the same as in Example 1 and Example 2 (Figure 4).



**Fig. 5.** TMP05/TMP06 interfacing: T1 and T2 time intervals measurement (a), and period (T1+T2) and space interval (T2) measurement (b).

## 2.2 Maxim’s Quasi-Digital Temperature Sensors

The **MAX6576/MAX6577** are low-cost, low-current temperature sensors with a quasi-digital output [9]. The MAX6576 converts ambient temperature into a 50 % duty-cycle square wave with a period proportional to absolute temperature (°K):

$$T(^{\circ}C) = \frac{T_x(\mu s)}{K_s} - 273.15, \tag{4}$$

where *K<sub>s</sub>* is the scalar multiplier.

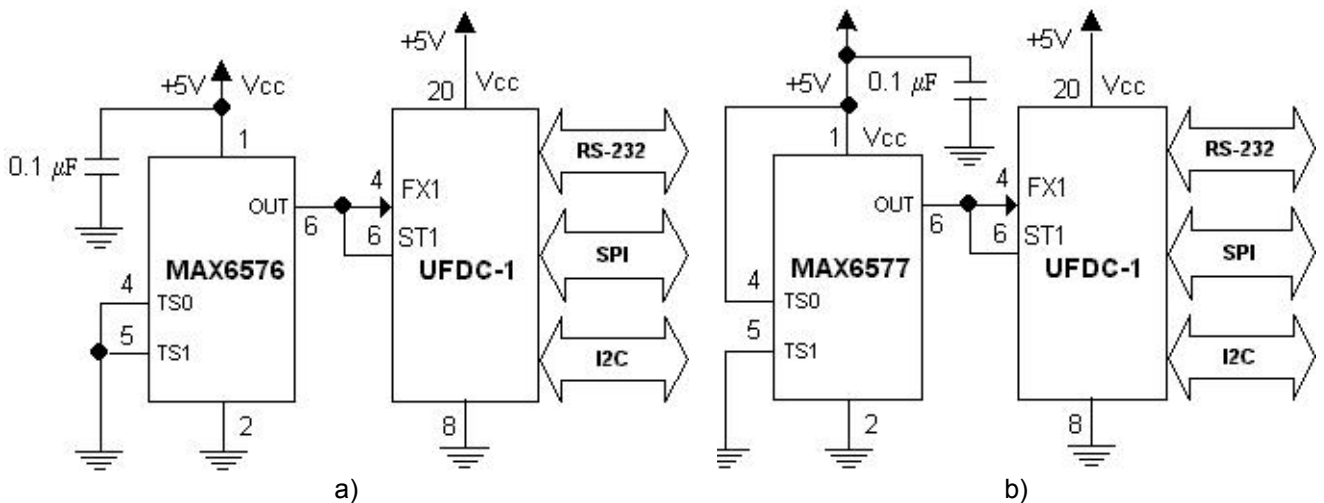
The MAX6577 converts the ambient temperature into a 50% duty-cycle square wave with a frequency a square wave with a frequency proportional to absolute temperature:

$$T(^{\circ}\text{C}) = \frac{fx(\text{Hz})}{Ks} - 273.15 \quad (5)$$

The period/frequency range (the scalar multiplier  $Ks$ ) of the output square wave can be selected by hard-wiring the two time-select pins (TS0, TS1) to either  $V_{DD}$  or  $GND$ .

Figure 6 a) shows the MAX6576 interfacing to the UFDC-1. In this example, TS1 and TS0 are tied to ground to select a scalar multiplier of  $10 \mu\text{s}/^{\circ}\text{K}$ . The MAX6576 converts the ambient temperature into a square wave with a period that is equal to the absolute temperature. The UFDC-1 reads the period of the square-wave sensor's output. The PC (RS-232 communication mode) or master microcontroller ( $I^2\text{C}$  or SPI buses communication modes) calculate the temperature in  $^{\circ}\text{C}$  according to equation (4).

Figure 6 b) shows the MAX6577 interfaced with the UFDC-1. In this example, TS1 is tied to ground and TS0 is tied to  $V_{DD}$  to select a scalar multiplier of  $1\text{Hz}/^{\circ}\text{K}$ . The MAX6577 converts the ambient temperature into a square wave with a frequency that is equal to the absolute temperature. The UFDC-1 reads the period of the square-wave sensor's output. The PC (RS-232 communication mode) or master microcontroller ( $I^2\text{C}$  or SPI buses communication modes) calculate the temperature in  $^{\circ}\text{C}$  according to equation (5). The result of frequency measurement equals to temperature in  $^{\circ}\text{K}$ . So, this mode is also very useful for digital temperature sensor design with  $^{\circ}\text{K}$  unit. No any calculation for temperature is necessary in this case.



**Fig. 6.** MAX6576 period output sensor interfacing (a) and MAX6577 frequency output sensor interfacing (b).

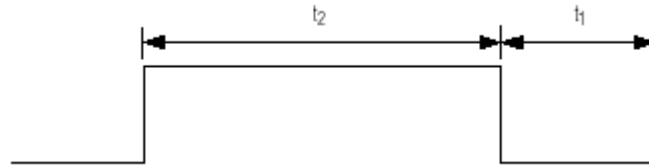
Taking into account the wide conversion frequency range of UFDC-1 it is not matter of fact which of scalar multiplier  $Ks$  is used.

The **MAX6666/MAX6667** are high-accuracy, low-cost, low-power temperature sensors with a single-wire output. The MAX6666/MAX6667 convert the ambient temperature into a ratiometric PWM output with temperature information contained in the duty cycle of the output square wave. The MAX6666 has a push-pull output and the MAX6667 has an open-drain output [10]. The output is a square wave with a nominal frequency of  $35\text{Hz} (\pm 20\%)$  at  $+25^{\circ}\text{C}$ . The output format is decoded as in equation (1), where  $T1$  is fixed with a typical value of  $10\text{ms}$  and  $T2$  is modulated by the temperature.

These temperature sensors can be interfacing to the UFDC-1 by the same manner as the TMP03/TMP04 sensors from *Analog Devices*.

Another models of PWM output sensors are **MAX6672/MAX6673** low-current temperature sensors with a single-wire output. These temperature sensors convert the ambient temperature into a 1.4 kHz PWM output, which contains the temperature information in its duty cycle. The MAX6672 has an open-drain output and the MAX6673 has a push-pull output [11].

The square wave output waveform time ratio contains the temperature information. The output is a square wave with a nominal frequency of 1.4 kHz at +25°C. The output format is shown in Figure 7.



**Fig. 7.** MAX6672/MAX6673 output format.

The temperature is obtained with the following formula:

$$T(^{\circ}C) = -200 \cdot \left( 0.85 - \frac{t_1}{t_2} \right)^3 + \left( 425 \cdot \frac{t_1}{t_2} \right) - 273, \tag{6}$$

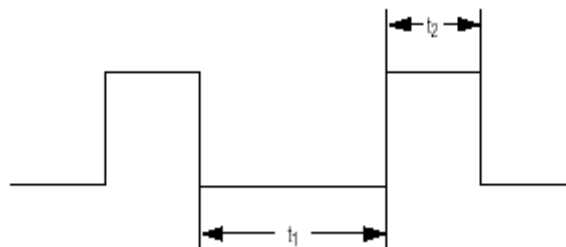
where  $t_1$  is a fixed value and  $t_2$  is modulated with the temperature.

For temperatures greater than +50°C, the temperature error is primarily first order and the following equation can be used:

$$T(^{\circ}C) = \left( 425 \cdot \frac{t_1}{t_2} \right) - 273 \tag{7}$$

These temperature sensors also can be interfacing to the UFDC-1 by the same manner as the TMP03/TMP04 sensors from *Analog Devices*.

The **MAX6676/MAX6677** are high-accuracy, low-power temperature sensors with a single-wire output. The MAX6676/MAX6677 convert the ambient temperature into a ratiometric PWM output with temperature information contained in the duty cycle of the output square wave. The MAX6676 has an open-drain output and the MAX6677 has a push-pull output [12]. The output is a square wave with a nominal frequency of 1.8 kHz ( $\pm 20\%$ ) at +25°C. Its format is shown in Figure 8.



**Fig. 8.** MAX6676/MAX6677 output format.

The output format is decoded as follows:

$$T(^{\circ}C) = 398.15 \cdot \left( \frac{t_1}{t_2} \right) - 273.15, \quad (8)$$

where  $t_1$  is fixed with a typical value of 0.24ms and  $t_2$  is modulated by the temperature.

The MAX6676/MAX6677 sensors interfacing to the UFDC-1 is shown in Figure 9. The resistor is required only for MAX6676 sensor.

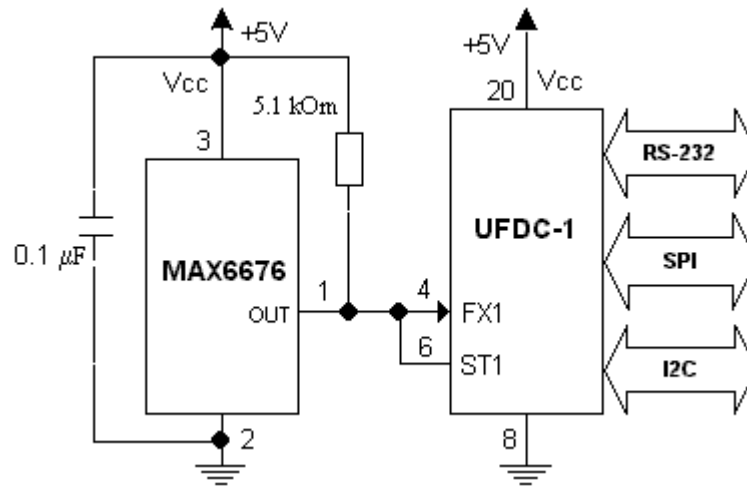


Fig. 9. MAX6676 interfacing to UFDC-1.

The MAX6676/MAX6677 can be interfacing to the UFDC-1 by two ways: as it was shown in Figure 9 and similar to Figures 3b and 5b, when instead of pulse width and space interval, period and space interval are measured using two channels of UFDC-1.

### 2.3 High Accuracy Temperature Sensors from *Sea-Bird Electronics*

The main distinction of frequency output sensors from *Sea-Bird Electronics* is its very high accuracy. The frequency-to-digital converter should have one order less or at least in five times less conversion error than the sensor's error in order to be neglected. Taking into account the high accuracy and working frequency range let see what we have if are using the standard counting method or indirect counting method (both methods are classical and using widely till now) for frequency-to-digital conversion. In order to maintain the accuracy for SBE 3F and SBE 3plus sensors, the standard counting technique for frequency-to-digital conversion needs 166.7 s conversion time. The UFDC-1 is based on the advanced conversion method with non-redundant conversion time and can supply the requested accuracy during 0.66 s conversion time.

The standard version of UFDC-1 is working well with SBE8 temperature sensor. In this case the programmable error for frequency-to-digital conversion of UFDC-1 should be chosen 0.0025 %. In case of SBE 3F and SBE 3plus sensors the custom design of UFDC should be ordered [6].

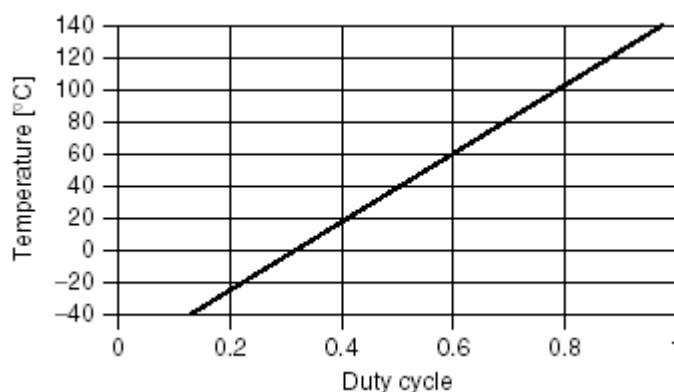
## 2.4 Smartec's Temperature Sensor SMT160-30 with Duty-cycle Output

The temperature sensor **SMT160-30** is a sophisticated full silicon temperature sensor with a quasi-digital (duty-cycle) output [13]. The output of the sensor can handle cable length up to 20 meters. This makes the SMT160-30 very useful in remote sensing and control applications and its output can be easily interpretable by the UFDC-1.

The duty-cycle of the output signal is linearly related to the temperature (Figure 10) and the temperature can be calculated according to the following equation:

$$T(^{\circ}\text{C}) = \frac{D.C. - 0.320}{0.0047}, \quad (9)$$

where *D.C.* is the duty-cycle.



**Fig. 10.** SMT160-30 sensor characteristic (temperature vs. duty-cycle).

Appropriate commands (RS-232 interface) for the UFDC-1 operation mode for duty-cycle – to digital conversion are shown in Figure 11.

*Example 3:*

```
>M4; Duty-cycle measurement initialization
>S; Start a measurement
>R; Read a result for T1
>MC; Space interval T2 measurement initialization
>S; Start a measurement
>R; Read a result for T2
```

**Fig. 11.** Appropriate UFDC-1 commands (RS-232) for duty-cycle measurement.

## 3. Software and Applications

There are many ways to display the measurement results. Any terminal software for Windows can be used with the UFDC-1 using the serial port of a PC [6, 14]. One of the possible choices is Terminal

V1.9b (<http://bray.velenje.cx/avr/terminal>) free software. Other possibilities are Component Works 2.0 (ActiveX control) or LabView. Both software products are from *National Instruments*.

The virtual thermometer based on SMT160-30 quasi-digital temperature sensor is shown in Figure 12.

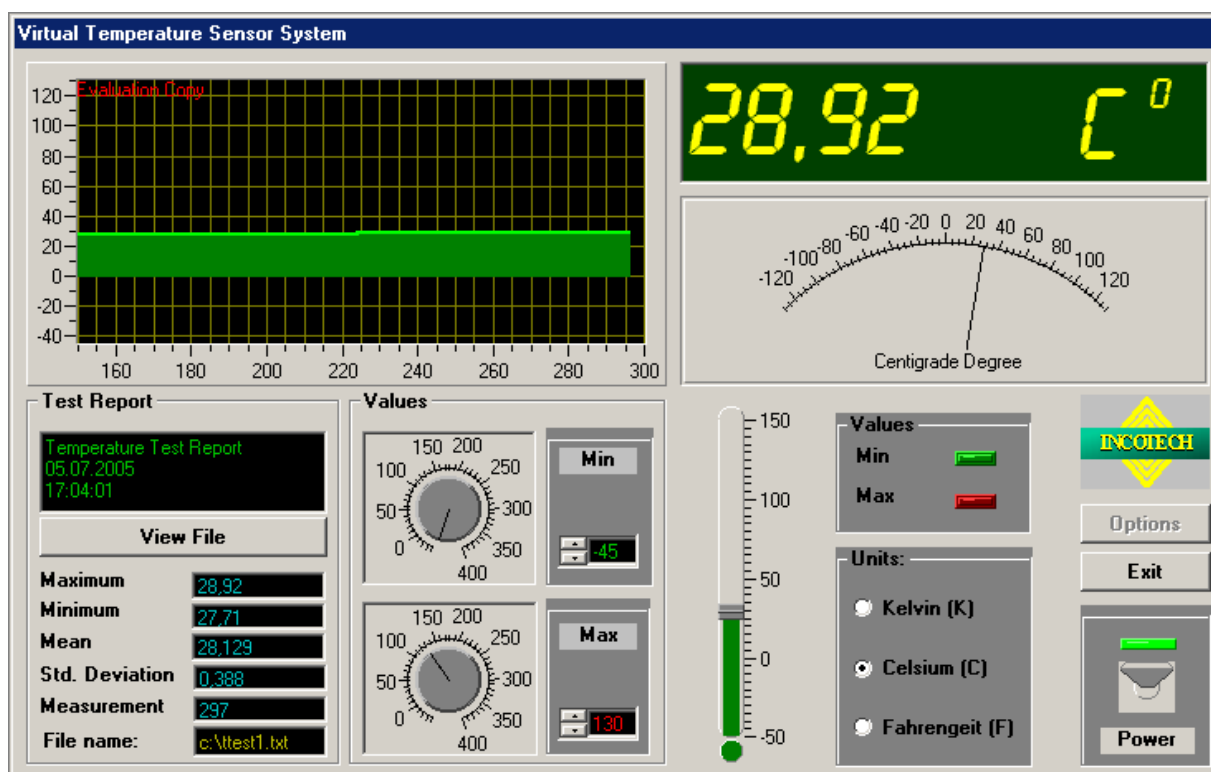


Fig. 12. Virtual thermometer based on SMT160-30 quasi-digital temperature sensor.

Designed DAQ systems for quasi-digital temperature sensors based on the UFDC-1 can be used for different applications: temperature monitoring, remote temperature measurements, environmental control systems, industrial process control, thermal protection, etc.

## 4. Conclusions

The described design approach based on the UFDC-1 lets significantly simplify the design process, reduce time to market and production of digital temperature sensors and DAQ systems for quasi-digital temperature sensors with high metrological performances.

In comparison with the direct microcontroller interfacing the proposed approach also lets to eliminate many design problems connected with the use of advanced measurement methods for frequency-time measurements, microcontroller choice, its programming and additional error components due to so-called program-dependent or software-related effects.

Designed DAQ systems for quasi-digital temperature sensors based on the UFDC-1 can be used for different applications: temperature monitoring, remote temperature measurement, environmental control systems, industrial process control, thermal protection, etc.

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