A Method for Temperature Measurement on Reconfigurable Systems

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Abstract- *Thermal verification on reconfigurable systems allow several failures to be detected. Typical problems like configuration errors or bus contention are manifested producing an anomalous chip dissipation. In this work, a fully digital FPGA-oriented temperature monitoring scheme is presented. A control circuit enables a ring-oscillator during a short period and measures their output frequency, a value that is function of the die temperature. Several experiments have been performed using Xilinx 4000 series chips, obtaining sensibilities between 14 kHz per °C and 77 kHz per °C. The main advantage of the proposed method is that neither external transducers nor analog parts are necessary: all the circuits can be constructed using the standard resources of an FPGA. In addition, the complete meter can be dynamically inserted or eliminated of the system.*

1. Introduction

Nowadays, thermal verification on FPGA-based systems like custom computers (FCCMs) result mandatory. Their exhaustive utilization of dynamic reconfiguration increases the risk of configuration errors and signal contention, two situations that can produce a permanent chip damage. Moreover, the consumption associated to a given configuration is a priori unknown; thus, the particular features of an implementation (fine-grain pipelined datapaths, heavily loaded buses, etc.) can produce an unforeseen power overhead. Consequently, the inclusion of a thermal monitoring unit allows several failures to be detected. For example, a thermal protection has been adopted in the XMOD commercial FCCM board [1]: an 8-bit CPU examines both the temperature and current at each FPGA.

Considering that the processing tasks on multiple- FPGA board are performed in several chips, the detection of hot-spots requires to sense the temperature in each integrated circuit that composes the system. However, if the number of chips is relatively high, it is difficult to use classic thermal transducers, as is common on current PC boards. Thermocouples, thermistors, or integrated sensors require both extra wiring and hardware that must be immune to the influence of the high-frequency signals usually present on the board. Moreover, the designer must also pay attention to topics beyond the scope of fast-prototyping, like sensor positioning, thermal coupling, or analog instrumentation.

The implementation of on-chip thermal transducers allows the designer to avoid the inconveniences described above. Main techniques to construct temperature sensors on CMOS technology make use of analog effects like the temperature dependence of the junction forward voltage, or the Seebeck effect [2]. Although these ideas can be useful to VLSI circuit designers, they appear inadequate to the end-users of commercial chips. In this paper, this limitation is overcome by using ring oscillators as temperature transducers. This type of circuits can be easily implemented using few FPGA elements. The advantages of this approach are multiple: a) Like other on-chip sensors, the junction temperature instead of the package one is measured; b) All signals are digital; thus, they can be routed using the general interconnection network of the board; c) The sensor itself is small: practical circuits make use of one or two logic blocks, and a minimum-size sensor can be fitted in just an I/O block; d) A sensor or even an array of them can be placed in virtually in any

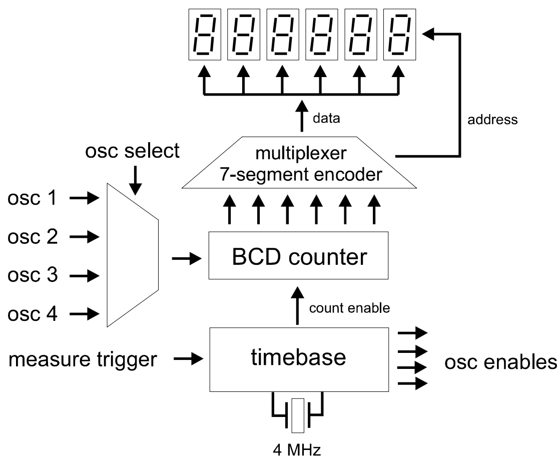

Fig. 1: FPGA-based control unit and frequency meter

position of the chip, making possible to construct a thermal map of the die; and f) The sensor can be dynamically inserted or eliminated.

Several researchers have proposed the use of on-chip thermal transducers. In [3], ring oscillators are used to measure both the temperature and power supply fluctuations. The oscillator is activated during a fixed period, and a counter with an scan path is used to read back the resulting frequency. In [4], an approach based on a "thermal-feedback oscillator" have been developed, whose main advantage is the small dependence between frequency and power supply fluctuations. At PCB level, a thermal monitoring method based on the measurement of a copper trace resistance has been proposed in [5].

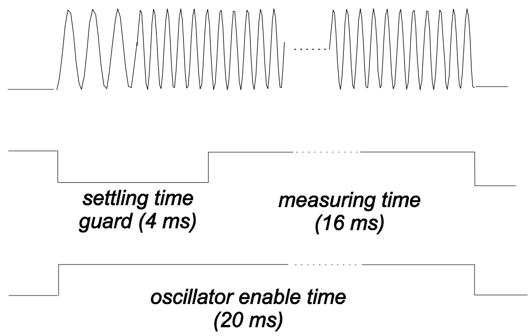

Fig. 2: Frequency measurement timing

2. A complete on-chip temperature meter scheme

The use of oscillators as thermal transducer requires to sense a frequency signal. This task can be done in an FCCM by using the host computer, by including a low-cost microcontroller in the board, or simply by implementing an ad-hoc frequency counter using resources of an FPGA. In Fig.1, the block diagram of the control unit and frequency counter proposed in this paper is shown. The circuit have been built using an Xilinx 3130PC84, and makes use of 79 CLBs. For demonstration purposes, the unit includes a multiplexer to monitor the status of up to four sensors, and a 7-segment display.

The main characteristic of the circuit is the measurement procedure, designed to reduce the error caused by the self-heating of the oscillator. Each measurement is performed in a cycle of 20 milliseconds: first, the oscillator to be read is enabled and it is left running during 4 ms in order to stabilize it. After that, the counting is done during the last 16 ms (Fig.2). Previous experiments have shown that the oscillators actually stabilize much faster, usually in two periods, but these numbers provided a good compromise between design simplicity and short period of measurement. Although this strategy allows the authors to improve the oscillator characterization, in a practical application it is possibly to avoid it, considering that the error caused by self-heating was found to be less than 3 ºC in the worst case (faster oscillator continuously enabled). Besides, continuously enabling the four oscillators may produce a sensible self-heating, as much as 8 ºC.

The frequency meter block is mainly composed by two counters, one providing the time base for the intervals described above, and another one which actually measures the input frequency. This unit is composed of a BCD counter with a prescaler in order to obtain a bandwidth of more than 50 MHz. The last stage (optional) includes the logic for driving six multiplexed 7-segment displays. The measured frequency is presented in MHz with three decimals precision.

3. Sensor Calibration

Ring-oscillators can be mapped on FPGAs using the look-up tables or the programmable inverters included on the I/O blocks. Just it is necessary to create a feedback loop including an odd number of invertions. Thus, the necessary phase shifting to start the oscillation is produced; the resulting period is twice the sum of the delays of all elements that compose the loop. In addition, it is useful to insert an external control signal *ANDed* with the loop, in order to allow the oscillator to be stopped. This paper have been focused on XC4000, CLB-based oscillators, but preliminary studies including IOB-based rings or XC3000 circuit characterization can be found in [6].

Taking into account that different interconnection elements can be inserted in the loop, the number of possible implementations is extremely large. In order to restrict the experiments, just four different circuits, called osc1, osc2 and osc3 have been characterized. In addition, the thermal response of the 8-MHz output of the built-in clock signal generator osc4 [7] was measured. Main circuit features are summarized in Tables 1 and 2.

The frequency-to-temperature response of each sensor was measured for two different Xilinx parts: the 4005PC84-6 and the 4005EPC84-3. The same configuration bitstream was used for both chips. Then, the chip temperature was increased by introducing them in a temperature-controlled oven.

Circuit	Features
osc1	high net delay four F/G LUTs plus two H LUTs
osc2	similar net and LUT delay four F/G LUTs plus two H LUTs
osc3	high LUT delay eight F/G LUTs plus four H LUTs
osc4	8 MHz built-in oscillator cell.

Table 1: XC4000 based ring-oscillators main characteristics.

Circuit	4005-6 delays		4005E-3 delays	
	LUT	net	LUT	net
osc1	28.0	47.8	12.6	26.0
osc2	28.0	20.1	12.6	11.6
osc3	56.0	18.2	25.2	11.9

Table 2: Ring-oscillator loop delay (timing data in ns obtained via Xdelay)

In order to more precisely measure the temperature, an Iron-Constantan (Fe-CuNi) thermocouple probe was placed in the center of the package, and was fixed to it with a heat conductive silver epoxy. An study about mechanical details of thermal sensors can be found in [8]. The thermal equilibrium in the system after each temperature step was verified by means of an x-t curve tracer. The error in the temperature measurement was maintained near 1 °C. A set of long ribbon cables (near 0.8 meters) were utilized to carry both output and control signals outside the oven. In order to prevent an excessive sensor power consumption due to these high off-chip loads, a driver 74HC125 was inserted to isolate the FPGA from the cables

In Fig. 3 the main experimental results are shown. All sensors exhibit a quite linear dependence with the temperature in the normal range of operation. The temperature sensitivity (in percentage per °C) also is very similar for all circuits. Surprisingly, the best behavior corresponded to the built-in osc4 cell. This oscillator, not only runs at lower speed and do not make use of extra FPGA resources, but also exhibits a small sensitivity to power supply fluctuations. Low frequency oscillators are interesting because they are less prone to self-heating, and the signals they produce can be more

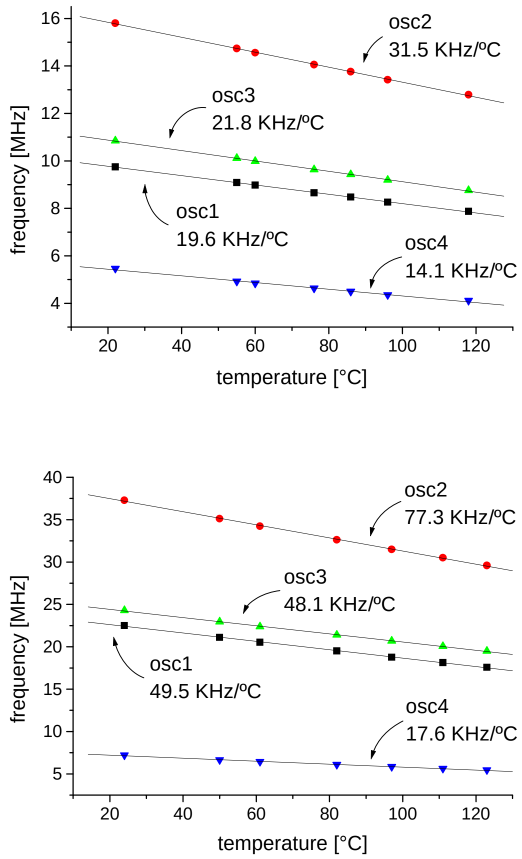

Fig. 3: Output frequency vs. Temperature, 4005E-3 (above), 4005-6 (bottom)

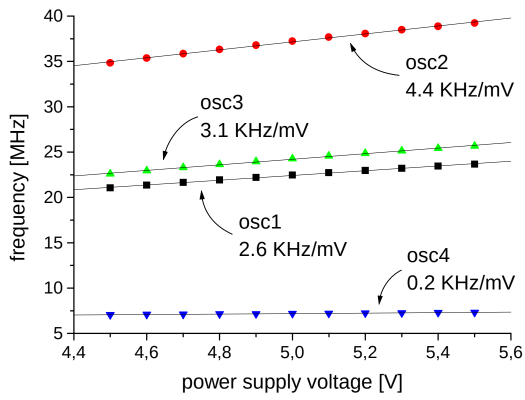

Fig. 4: Output frequency vs. Vcc, 4005E-3

easily managed. To the best of our knowledge, the use of this cell as thermal transducer have not been reported in the manufacturer literature.

The power supply dependence of all sensors results linear in the operation range, as is depicted in Fig. 4. Thus, errors caused by power supply

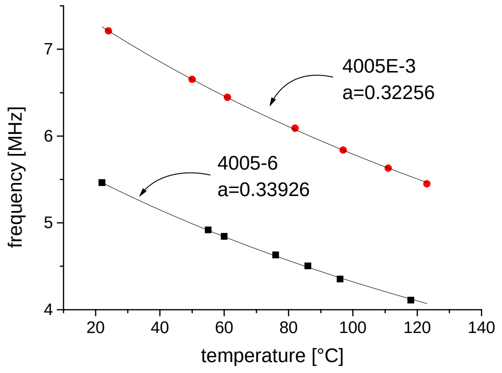

Fig. 5: CMOS delay coefficients (obtained by interpolation) for the osc4 cell.

fluctuations can be corrected if the voltage of the board also is monitored. However, the percentage sensibility is smaller for osc4. In addition, it should be noted that sensors whose loop delay is mainly caused by wiring are slightly less sensitive to power supply fluctuations.

An alternative method for the temperature calibration of a given sensor can be carried out if the approximate CMOS delay coefficient given by the manufacturers is utilized. This value is situated between 0.3 % per °C [9], and 0.35 % per °C [10]. In this way, the designer first constructs a particular oscillator, and then measures its output frequency at a known room temperature. After that, the remaining pairs (t,f) can be calculated by applying the delay coefficient to the measured point, using:

$$f(t) = \frac{f(t_a)}{1 + \frac{a(t - t_a)}{100}} \qquad [1]$$

Where 'a' is the delay coefficient. Two examples of this method are shown in Fig.5, where the Eq.1 have been interpolated from the measured point for the built-in osc4 cell. It can be observed that the obtained 'a' values fall inside the interval specified by the manufacturer. In addition, they are not very dependent on the part type. Using this calibration method, the maximum error committed at 120 °C when taking a=0.35 is 8 °C for the 4005E-3 built-in oscillator, and 3 °C for the 4005-6 one.

4. CONCLUSIONS

A group of experiments to demonstrate the feasibility of a FPGA-based fully-digital on-chip temperature monitoring system have been presented. The circuits proposed allow the junction temperature of an FPGA to be easily measured.

All prototypes show a linear response in relation to temperature, but the best results in frequency range, resource occupation, and power supply sensitivity corresponded to the built-in XC4000 oscillator. However, the main disadvantage of this circuit is their fixed position in a corner of the chip. On the contrary, CLB-based ring oscillators can be situated in virtually any position.

The combination of temperature transducers and FPGAs could be also a powerful tool for researchers interested in thermal aspects of integrated circuits. Just the possibility of "moving" a sensor (or an array of them) from one point of the die to other, in a simple and fast way, and without cost is almost unthinkable in any other VLSI technology.

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