A Low-Cost Validation Setup for the Thermal Modelling of Electronic Devices

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Abstract—**Modern integrated circuits generate very high heat fluxes that can lead to a high temperature, degrading the performance and reducing the life time of the device. Thermal simulation is used to prevent this kind of issues, and many models were introduced in recent years. However, their validation is challenging: it is either based on established simulators (with reduced accuracy), or requires to produce a specific test chip with several thermal sensors. In this paper we propose a methodology and measurement setup that uses existing commercial processors to validate thermal models. We use infrared thermography and low-cost thermoelectric cooling, avoiding the issues of mineral oil setups used in previous works. We show how our approach was used to validate two thermal simulators.**

I. INTRODUCTION

The thermal design of modern electronic devices has become increasingly complex. High power densities in compact devices can lead to high temperatures and uneven temperature distributions. This can ultimately reduce the performance and expected lifetime of these devices [1]. Rapid simulation is particularly important to allow the designer to evaluate multiple alternatives while the layout and power output of the device are still subject to change.

A large number of thermal models were recently presented in literature, with more being introduced every year. One major issue with the acceptance and use of these models is that their validation against real hardware (to ensure reliable results) is particularly challenging. Existing processors and other electronic components have few, if any, temperature sensors, and their position and accuracy is not necessarily well known.

Traditionally, models like Hotspot [2] are validated against devices built explicitly for this purpose. Manufacturing a device which is sufficiently representative, and placing a sufficient number of thermal sensors to obtain good validation accuracy is a costly, and time consuming endeavour.

Infrared thermography is an alternative solution that allows one to collect fine-grained temperature information from existing devices even if no temperature sensors are present. One of the main issues of infrared thermography is that it requires a clear line-of-sight between the thermal camera and the surface on which the temperature is going to be measured. Modern processors are usually covered by large heat spreaders and heat sinks, which block infrared radiation and diffuse the temperature in such a way to render accurate validation impossible. Removing the heat sinks leads to abnormal thermal behaviour, and could possibly damage the design under test.

Designers have tried to overcome this issue by using alternative cooling methods, liquid cooling using an infrared-transparent fluid in particular [3]. Liquid cooling introduces several problems: it is mechanically complex, it introduces additional refractive material between the camera and the design under test, and the fact that the fluid gets warmer while flowing over the surface of the chip can lead to non-uniform temperatures and reduce the accuracy of the measurement.

In this paper, we propose a low-cost platform and algorithm for the validation of thermal models on existing processors without liquid cooling. The setup is based on infrared thermography, coupled with a combination of thermoelectric cooling of the design under test that extracts heat from the processors' secondary thermal path. This setup can be used to measure the temperature at the surface of a chip or in the metal layer (below the silicon substrate) and match it with a thermal model using an arbitrary spatial discretization. We use our setup to validate two thermal models using a simple processor model and a low-resolution thermal camera.

The rest of the paper is organized as follows: Section II presents the state-of-the-art of the domain; Section III describes our measurements setup; Section V shows how we used our setup to validate two very different thermal models of the Intel Atom D2700 processor; and Section VI draws some concluding remarks.

II. RELATED WORK

The current interest on thermal simulation has led to a large body of research literature, among which, several works focus on the modelling of integrated circuits. Models such as Hotspot [4] are very popular, and are used in many academic and industrial projects. Hotspot was validated with a special test chip using infrared thermography.

The main issue with infrared thermography is that it requires special cooling solutions that allow to make temperature measurements for nominal thermal conditions [3].

[5] proposes a measurement method based on liquid cooling: IR-transparent mineral oil is pumped over the design under test to simulate a heat sink. The setup is rather complex, and causes some non-uniform temperature distributions along the flow of the oil that are difficult to compensate [6].

978-1-4799-8893-8/15/$31.00

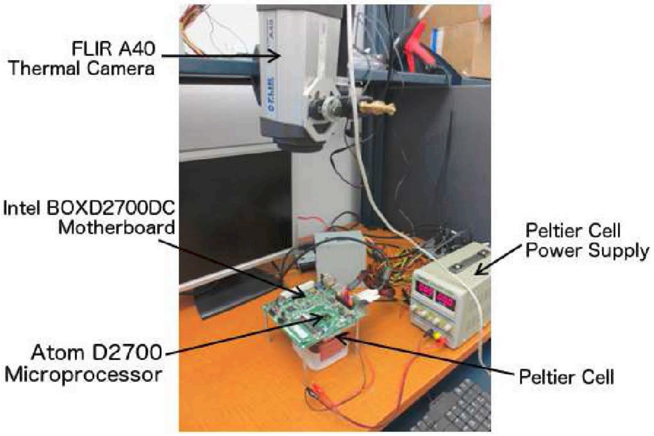


Figure 1: The validation system.

An alternative solution to oil cooling was proposed by [7], using a Peltier cell. A more complex system, using embedded thermoelectric coolers is presented in [8].

Palomino *et al.* proposed a low-cost thermoelectric solution for cooling low power processors which is not affected by the same issues of oil cooling [9]. This setup was not exploited for the validation of thermal models, but rather for assessing the quality of temperature-aware scheduling algorithms.

In this paper we propose a low-cost setup and methodology for the validation of thermal models. This is, to the best of the authors' knowledge, the first time such system is presented.

III. MEASUREMENT SETUP

Our system is composed of several elements. Figure 1 shows the assembled validation system.

a) Motherboard: An Intel BOXD2700DC motherboard houses the processor under study, as well as the components required for its proper functioning (e.g., memory). This motherboard is small but feature-rich.

b) Microprocessor: For the purposes of our study we utilized the Intel Atom D2700. This processor is composed of two 2.13 GHz cores, and integrated devices for graphics, video encoding, and cryptography.

c) Processor cooling: Despite the low power of the Intel Atom D2700 (about 10 W), a cooling device is necessary if the processor is to be used without a heat sink. Thus, we placed a copper plate under the motherboard, to act as a heat spreader. To prevent electrical contact between the motherboard and the copper plate, we used silicon-infused plastic thermal pad. A Peltier cell [7] was placed beneath the copper plate to remove the heat generated by the processor. The choice of a Peltier cell is justified by its small size, its adequate efficiency, and the ease of its installation into the motherboard. A self-contained liquid-cooling system is used to remove heat from the hot side of the Peltier cell, and dissipate it with a radiator and fan ensemble.

d) Thermal camera: We used a FLIR A40 thermal camera to collect the data. This camera can detect infrared radiation in the $7-14\,\mu\mathrm{m}$ range. Since the silicon substrate of the chip is not transparent to this wavelength, only the surface temperature can be measured, with a precision of $\pm 2\,^{\circ}\mathrm{C}$. The camera outputs $320 \times 240\,\mathrm{pixel}$ images at $60\,\mathrm{Hz}$. The top of the die was accessible as we removed the heat sink mounted on the Intel Atom. It is worth noting that any low-cost long-wave infrared camera can be used for this kind of measurements. A more expensive medium-wave camera (in the $3-5\,\mu\mathrm{m}$ range, where silicon is transparent) can provide the validation of junction temperature models using the same proposed methodology. Such camera was not available at the time of writing this paper.

e) Data storage and processing: To store and process data, we connected a dedicated workstation to the thermal camera. The workstation is equipped with FLIR's image analysis software to process the image data.

f) CPU activity generation: To generate different activity profiles and increase the CPU temperature, we utilized IMPACT Parboil [10], a common benchmark set for the study of the performance of computing throughput.

We would like to stress the low cost of our implementation: the total cost of the components was below 300 CAD at the time of writing, and an appropriate camera could be purchased for less than 1000 CAD. An oil-cooled setup would require additional materials (e.g. IR-transparent mineral oil) that would raise the complexity of the system and the cost to the thousands of CAD.

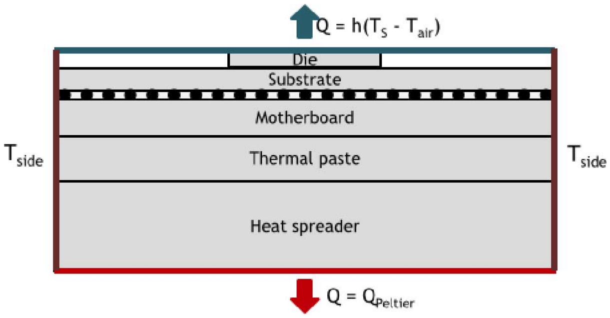
IV. THERMAL MODELS

The aim of a thermal model is to capture the behavior of the microprocessor. The other components in the motherboard are usually neglected. Thus, the thermal model focuses on the heat exchange between the microprocessor and its environment, i.e., the surrounding air and the Peltier cell.

We consider a model of the Atom processor composed of several layers, as depicted in Figure 2a. Each layer corresponds to a component of the system under study. Despite the fact that the layers are made of materials with different thermal properties, it is not necessary to model each layer individually. Rather, to keep the model simple, it is sufficient to model the entire system as a single entity characterized by a single thermal conductivity and a single thermal capacity. This is also justified by real data collected on the microprocessor. In fact, the data show that the temperature is highest on the die and lowest on the border (see Figure 4), and that the temperatures T_{side} of the four vertical sides are practically constant across the side areas.

Therefore, the model used in our tests focuses solely on the heat exchanged by the top and bottom faces of the processor. The top face is exposed to air (because the heat sink was removed), while the bottom face is in contact with the Peltier cell.

To show that our validation approach is independent from the model discretization (i.e., the point distribution and the resolution), we considered two implementations: *(i)* The first is realized with the ICTherm simulator, which discretizes the model as an orthogonal mesh (see Figure 3a); *(ii)* The second is realized with the COMSOL simulator, which discretizes the model as a tetrahedral mesh (see Figure 3b).

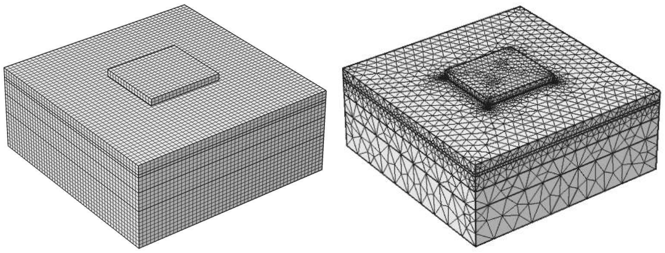


(a) Model layers.

Item	Material	Thickness (mm)
Die	Silicon	0.7
Active layer	Metal-dielectric mix	0.01
C4 Balls	Tin-Lead Compound	0.1
Substrate	FR4	1
BGA Balls	Tin-Lead Compound	0.3
Motherboard	FR4	1.5
Thermal paste	TIM	2
Heat spreader	Copper	4

(b) Model parameters.

Figure 2: The multi-layer model considered in this work and its parameters.



(a) ICTherm: Orthogonal mesh (b) COMSOL: Tetrahedral mesh

Figure 3: The discretized meshes of the model we validated.

V. EXPERIMENTAL EVALUATION

We validated the models through a comparison between the surface temperature detected through the system and the data obtained from simulations with ICTherm and COMSOL.

In particular, we focus on two scenarios that differ in the power consumption of the microprocessor. In the first scenario, the microprocessor is engaged in an activity that occupies 50% of its computing capacity, yielding a power consumption of 6 W. In the second scenario, the activity occupies 100% of the computing capacity, for a power consumption of 10 W. The level of activity is modulated using the cpulimit tool.

Figure 4 shows the typical output of the measuring system. The top figures are the heatmaps, in which the gray level corresponds to the temperature detected at a particular location of the motherboard. Two temperature profiles are shown for each scenario: one profile for a horizontal section, and one for a vertical section. As the data shows, the hottest areas are those where the die is located.

To compare the results obtained with the camera with those obtained with ICTherm and COMSOL, we devised a general algorithm. The algorithm associates the data points of a mesh with the corresponding pixels of the heatmap. It is important to remember that the heatmap corresponds to the surface temperature of the die; the meshes, however, include all the layers in the model. Thus, to compare the temperature profiles, the considered mesh data points are only those located at the top layer. Since the distribution of data points in ICTherm is a regular, square lattice, the top layer is composed of the points with the highest z coordinate for each (x, y). In COMSOL, however, points are distributed unevenly. In this case, the top layer is composed of those points whose z coordinate is within a user-defined depth d from the top ($d = .5\,\mathrm{mm}$ in this paper).

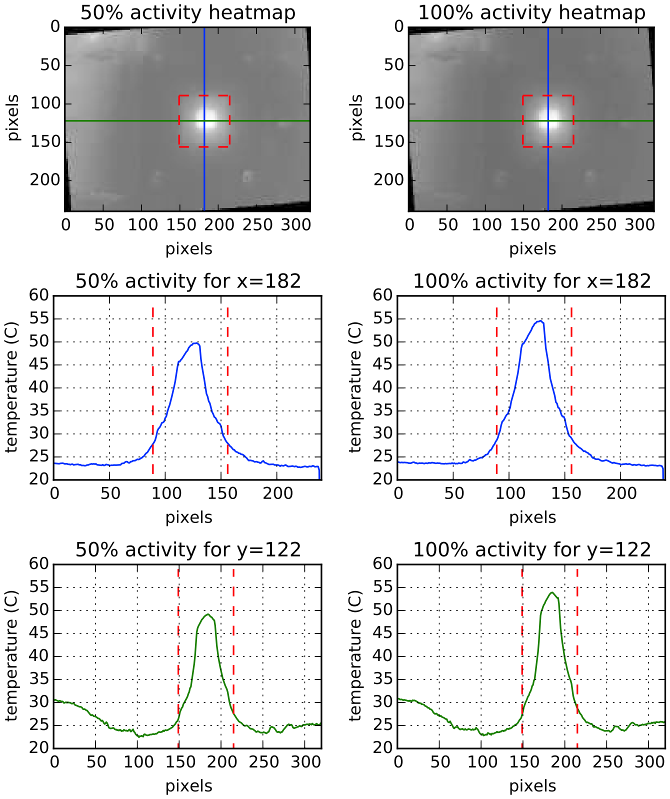
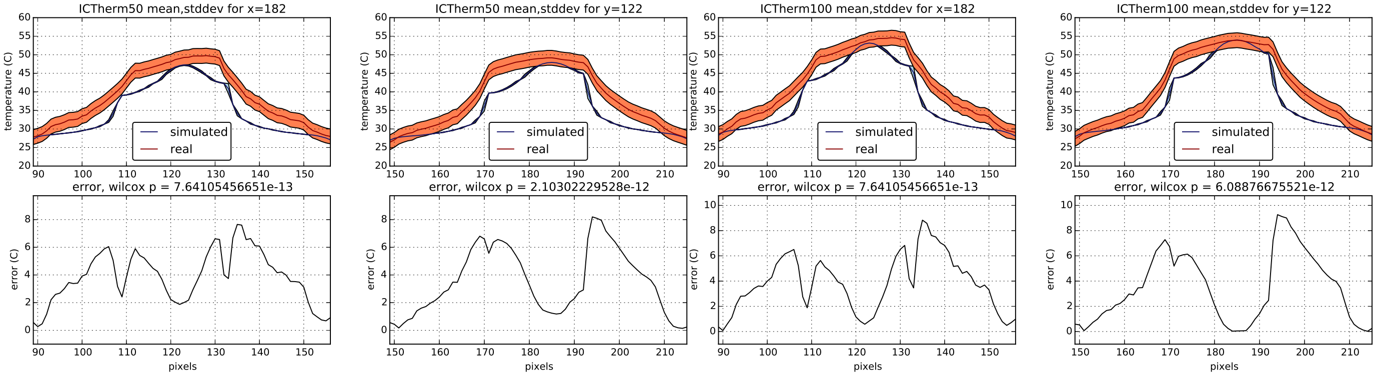


Figure 4: Heatmap and temperature profiles measured with the proposed measuring system. The microprocessor is located in the area delimited by the red dashed line.

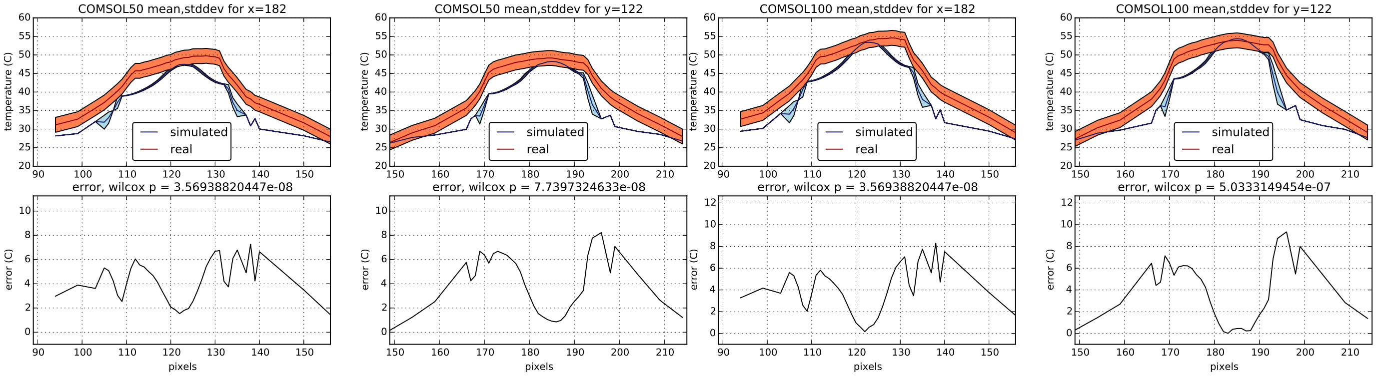
The algorithm stores each top-layer data point in a grid structure, in which each cell corresponds to a pixel of the heatmap. For each pixel, we calculate the mean and standard deviation of the associated temperatures. Figures 5 and 6 show the distribution of the temperatures obtained in simulation and the corresponding temperatures detected by the camera. The bottom plots report the difference between the mean of the simulated data and the detected temperatures.

The observed difference across the chip are as follows: *(i)* for ICTherm at 50% activity, the average difference is $2.61\,^{\circ}\mathrm{C}$ with a standard deviation of $2.11\,^{\circ}\mathrm{C}$; *(ii)* for ICTherm at 100% activity, the average difference is $2.73\,^{\circ}\mathrm{C}$ with a standard deviation of $2.28\,^{\circ}\mathrm{C}$; *(iii)* for COMSOL at 50% activity, the average difference is $3.79\,^{\circ}\mathrm{C}$ with a standard



(a) 50% activity. (b) 100% activity.

Figure 5: Difference between the temperature estimated by ICTherm and data measured by the camera.



(a) 50% activity. (b) 100% activity.

Figure 6: Difference between the temperature estimated by COMSOL and data measured by the camera.

deviation of $2.17\,^\circ\mathrm{C}$; *(iv)* for COMSOL at 100% activity, the average difference is $3.83\,^\circ\mathrm{C}$ with a standard deviation of $2.36\,^\circ\mathrm{C}$. When considering the position of the hotspot (a pixel with $T = 57\,^\circ\mathrm{C}$) on the chip, both models and the camera measurement differ by less than $1\,\mathrm{mm}$.

VI. CONCLUSIONS

In this paper we proposed a low-cost solution for the validation of thermal models. Our methodology uses an infrared camera and matches infrared measurements with temperatures coming from models, computing and evaluating any discrepancies between the two. We tested our methodology on two models of the Atom D2700 processors, showing the validity of our approach. Our methodology can be used to assess the accuracy or to fine-tune existing thermal models.

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