

The Battle of the Giants

A Case Study of GPU vs FPGA Optimisation for Real-time Image Processing

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Abstract: This paper focuses on a thorough comparison of the two main hardware targets for real-time optimization of a computer vision algorithm: GPU and FPGA. Based on a complex case study algorithm for threaded isle detection, implementation on both hardware targets is compared in terms of resulting time performance, code translation effort, hardware cost, power efficiency and integrateability. A real-life case study as described in this paper is a very useful addition to discussions on a more theoretical level, going beyond artificial experiments. In our experiments, we show the speed-up gained by porting our algorithm to FPGA using manually written VHDL and to a heterogeneous GPU/CPU architecture with the OpenCL language. Also, issues and problems occurring during the code porting are detailed.

1 INTRODUCTION

Many applications have high inherent parallelism which can be exploited for substantial execution time speed-ups. Especially for many image processing algorithms, this is the case because of the straightforward data parallelism possibilities on pixel basis. At the same time, execution speed is the heel of Achilles of many vision applications, without real-time performance they can not be practically applied in real life. An example is the endoscopic image enhancement algorithm we describe in this paper, which have to be implemented with minimal latency in order not to impede the surgeon's hand-eye coordination during an operation. Therefore, much effort is put in real-time optimization of image processing algorithms.

The first step is always to perform machine-independent optimisations on the algorithm. A good example is the development of the SURF feature detection method (Bay et al., 2008), as a faster alternative to SIFT (Lowe, 2004), by approximating the filters used by block filters and exploiting tricks like integral image pre-calculation.

If on a standard CPU-based platform the required speed is not reached yet, a next obvious step is implementing the algorithm on specific hardware, at which the inherent parallelism can be exploited. This paper focuses on two frequently used types of parallel hardware, FPGAs and GPUs. FPGAs have shown very high performance in spite of their low operational frequency by fully extracting the parallelism. On the other hand, recent GPUs support a large number of cores, and have a potential for high performance in many applications. However, the cores are grouped, and data transfer between the groups is very limited. Programming tools for FPGA and GPU have been developed, but the prevailing idea is that it is still difficult to achieve high performance on these platforms with limited effort.

Both platforms have very distinct properties. While GPUs excel in raw processing speed in terms of operations per second, FPGAs are the summit of flexibility. In this paper we port one complex image processing algorithm to both platforms to be able to compare the resulting time performance. Another important evaluation criterium will be the effort that is needed for the code translation.

Relevant related work, also comparing GPU and FPGA for image processing algorithms, include the work of Cope *et al.* (Cope et al., 2005) and Asano *et al.* (Asano et al., 2009), which were unfortunately limited to rather simple image processing tasks (color correction and two-dimensional convolution filters), and rather outdated. More recent work is that of da Silva *et al.* (da Silva et al., 2013), which is targeted at combining the power of GPUs with the flexibility of

FPGAs in a hybrid FPGA/GPU platform. Their conclusions are that the usefulness of the combination is limited, because of the confined data bandwidth available between GPU and FPGA. However, in their paper they also report on a comparison where the GPU and the FPGA are used separately. Their results show that the HLS FPGA compiler outperforms handwritten code and offers a performance comparable to the GPU for the application studied.

The remainder of this paper is organised as follows. In section 2, the threaded isle detection algorithm we start from is detailed. After that, our code porting efforts towards both GPU (section 3) and FPGA (section 4) are reported upon. Our results are presented in section 5. We end with an evaluation in section 6 and a conclusion in section 7.

2 ALGORITHM

2.1 Algorithm Overview

The goal of the algorithm studied in this paper is to visually highlight linear structures during videoscopic inspections. An example result is included as Figure 1. The algorithm is a chain of four basic building blocks: preprocessing, feature detection, filtering, and visualization.

2.1.1 Preprocessing

The image is reduced to a grayscale picture which discriminates better between linear structures and the surrounding areas. This step is highly application-specific, but can be methodically optimized with supervised training techniques, using a set of expert-annotated images. In many cases a linear transformation of the RGB or HSV colorspace or a lookup table will yield good results.

2.1.2 Feature Detection

The structures to be highlighted are linear. Hence, any edge or ridge detector can be used to extract these from the preprocessed image. The algorithm uses oriented phase congruency energy features (Kovesi, 1999) which are able to detect both strong and weak edges. This method is based on a convolution of the image with a filter bank of 24 log-Gabor-filters, over 4 scales and 6 orientations. Other edge detecting features such as canny gradient strength were found less appropriate for our intended applications. Of course, different features can be combined for other applications.

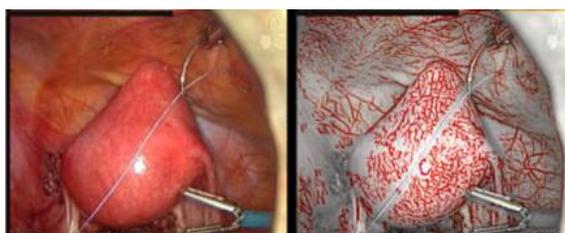


Figure 1: Vascularization highlighting algorithm illustration: (left) input image, (right) output image.

2.1.3 Filtering

The goal of the filtering step is to suppress the detected lines that do not bear visual information with respect to the application at hand. For instance, for the vascularization highlighting application as described in section 2.2, a region where a lot of short vessels go in random directions is probably not pathologic and therefore not interesting for the detection of tumors.

2.1.4 Visualization

In the last step the filtered mask is combined with the original image. This step is probably the least interesting from an image processing point of view, but very important for the optimal transfer of the computed visual information to the human end-user of the application. For the vascularization highlighting application, the saturation of the original image is globally reduced, while the filtered feature map obtained in the previous step non-linearly modulates the saturation locally.

2.2 Applications

Such a general linear structure detection algorithm is useful in a broad range of applications. We detail a few of them below.

The application that spurred the initial development of the line detection algorithm discussed in this paper is real-time vascularization highlighting during endoscopic procedures. Preliminary experiments have shown that this highlighting is very likely to enhance the human detection rate of pathologic tissue, such as endometriosis and tumors. Most malignant tumors are linked with increased vascularization and unregular vessel patterns (Tyrrell et al., 2005), presumably because of a higher demand caused by accelerated growth. The increased vascularization becomes visible around superficial tumors as a star-shaped structure. While the tumor itself may be very small and invisible, the vascularization pattern surrounding it is a valuable visual guide towards it. The

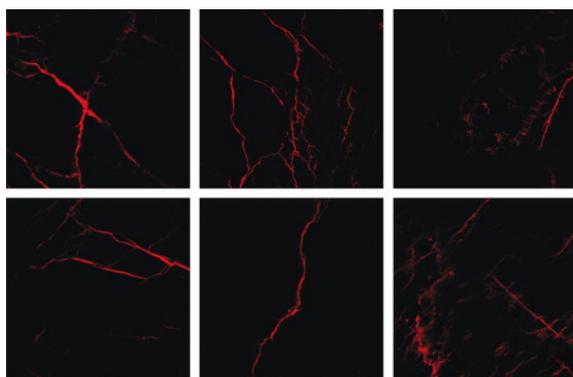


Figure 2: Images of cracks in polished marble acquired by confocal laser microscopic photography.

same holds for endometriosis, which is also characterized with increased angiogenesis, often to be recognized as parallel vessels.

Also in other disciplines like colonoscopy, bronchoscopy, hysteroscopy, vascularization patterns are important for the detection of intestinal, lung, and uterine tumors.

The software implementation of a vascularization highlighting application was already developed by eSaturnus for early tests with a few key users. This prototype can process 3 standard definition video frames per second and per core of an Intel Xeon E3-1200 CPU. The work on hardware-accelerated line detection, as described in this paper, allowed this application to deliver smooth, low-latency filtered video on the same space and power footprint as the original software-only implementation.

Besides medical applications also various industrial applications benefit from real-time line detection. One example is automatic crack detection in various materials, such as natural stone (fig. 2), composites, plastics, metals, glass and concrete. During production or processing of these materials tiny cracks can cause parts to break with high additional costs. Automatic detection of cracks in incoming raw materials using a machine vision system before production can be used to reduce these costs. Another application for fast line detection is automatic alignment or placing objects using robots.

2.3 Code Profiling

As a start, the more complex and time consuming parts of the source code had to be identified. This was done by profiling the code and analysing the result to detect the most time consuming parts. Since the application uses images from a video stream as input, some parts will be run for every frame, while other parts are run only once. The profiling resulted

in one function comprising six time-consuming loops through which were computed over every frame: the six passes of different log-Gabor filters over the image.

A second time-consuming part of the algorithm is the preparation of the log-Gabor filter itself by computing the coefficients. But because these filters are kept fixed during the processing of a video stream they can be precomputed and are not interesting to spend optimisation effort on.

3 GPU OPTIMISATION

As explained above, we will implement this algorithm on two different hardware platforms. This section will detail our GPU implementation, while the next section is about the FPGA implementation.

For the GPU implementation of this algorithm, we chose for the OpenCL language, because of its ability to target heterogeneous hardware platforms and its excellent code portability across different GPU vendors. In the subsections below, we first give an overview of OpenCL and its coding philosophy. After that, the specifics of the code porting OpenCL we did are detailed along with the best practices we learned from this case. Timing results will be given in chapter 5.

3.1 OpenCL

Modern computer platforms include one or more CPUs and GPUs (and even DSPs amongst others). All these hardware types are designed and optimized for a specific type of calculations. OpenCL, Open Computing Language (Khronos, 2011), is a quite novel open standard for heterogeneous computing. It is a framework for writing programs that can use these platforms in an heterogeneous way. This is in great contrast to CUDA, developed by Nvidia, which can exclusively be used for Nvidia GPU hardware. OpenCL allows to write an efficient and portable implementation of an algorithm which exploits the possibilities for parallelizing parts of the algorithm on the most suitable devices (multi-core CPU, GPU, celltype architectures or other parallel processors). Since it is heterogeneous, it is not necessary to know in advance which hardware will be used to execute the algorithm. The used platform can easily be changed by changing an initialisation variable of the program. Since different devices have different instruction sets, the compilation of the OpenCL kernels happens online (during the execution of the program).

The code is written in the form of kernels. A kernel is a block of code, written in a language based

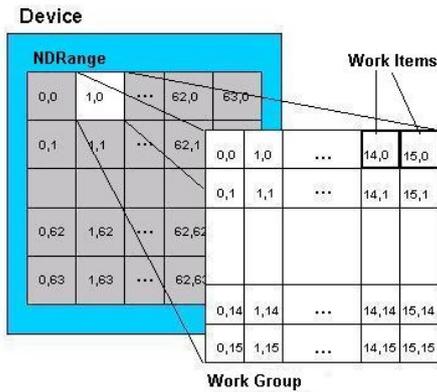


Figure 3: The execution of the kernels is divided in workgroups, which can be subdivided in work items. Each work item executes an instance of the kernel.

on C99, that can be executed in parallel. For example, when each value of a matrix has to be multiplied by a certain value, each kernel contains the code for one multiplication and this kernel will be executed for all elements of the matrix. The execution of the NDRange (all kernels that have to be executed) is subdivided into workgroups. A workgroup is subdivided into work-items, which will execute the kernels in parallel (figure 3). To distinguish between different executing threads, each thread has a unique global id, and within a workgroup each thread has a unique local id. Both are assigned for each dimension.

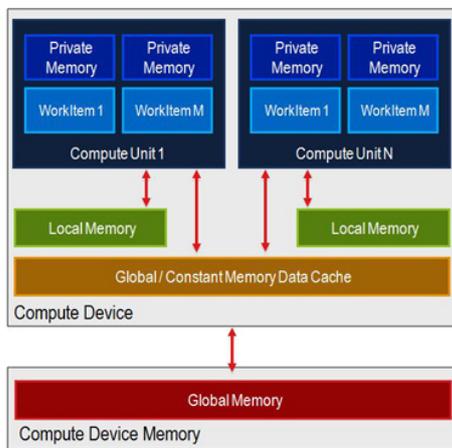


Figure 4: Memory model of a GPU, from slow to fast: Global memory, Local memory, Private memory.

Figure 4 shows the memory model of a GPU device. The memory access times are ranging from the slowest at the bottom (starting with the memory of the host computer) to the fastest at the top (private memory). The global memory of the GPU (and CPU) is shared over all executing work items, the local memory is shared over the work items in the same compute

unit (workgroup) and the private memory is only accessible by the running work item.

3.2 Code Porting to OpenCL

OpenCL has the advantage that it is a middleware built upon C/C++. Hence, porting an algorithm that is already written in C/C++ to OpenCL is not that complex.

The general approach was to identify the code that had to be run for every image frame and search for the loops within that code. Since OpenCL on GPUs is highly parallel, embarrassingly enough, parallel loops that iterate over every image pixel are the most efficient to port to OpenCL for the biggest performance gain.

Porting code to OpenCL can be divided in three parts. First, the different loops must be ported to OpenCL kernels, so they can be run on the GPU. Since the code made use of the highly optimized Intel Integrated Performance Primitives library, step 2 was to find alternatives for these functions and also port those to OpenCL. Included in this step is the merging of several smaller loops into bigger ones. This way, loops 2, 3 and 4 were merged into one, and the Intel IPP functions were included in the loops most adjacent to them. Step 3 is the elimination of data traffic between the host and the GPU, as this is very time consuming over the slow PCI-Express bus.

We encountered some problems during this, although most of them were quickly solved:

- The use of the Intel Integrated Performance Primitives library took some time to get similar functionality that could be ported to the GPU. Since the IPP library makes excellent use of SSE instructions and multiple cores, it was sometimes difficult to beat the performance of these functions. Optimizing the OpenCL code was necessary to getting higher performance on the GPU.
- Different DFT/iDFT libraries yield different results. Since the IPP library isn't very well documented as to how the different functions are implemented, switching to another library caused some problems with the results. AMD has its own OpenCL Math library, called APPML, which can be used as an alternative for Intel's IPP DFT functions. But they too don't share its implementation details with the user.
- Windows/Linux compatibility issues. These issues can mostly be traced back to the different implementation of the `size_t` type. In Windows, this is always four bytes, as in OpenCL. In Linux, on the other hand, it can be eight bytes for a 64-

bit OS, the OpenCL size is still only four bytes though.

The main lesson learned is that the simple technique of GPU-optimizing only the code parts that are identified as the most computationally intensive by the profiler is not a good idea. In many cases, little is gained (or the result is even slower), because of the increased need of CPU-GPU data traffic. Data locality, i.e. keeping data as long as possible on the GPU, is much more important.

3.3 Ease-of-use Evaluation of OpenCL

In this section we will discuss our experiences with the use of OpenCL as a way to optimize an algorithm by running it on GPU. We will comment on the learning curve and give tips and tricks for development.

Learning Curve. Since it is a quite novel standard, the available literature is still growing. The specifications released by the Khronos group (Khronos, 2011) are very valuable as a reference for function calls while developing. It does not only explain how to use the functions, but also gives possible errors and shows how to prevent them. Although it is a great help, it does not contain enough information to exploit the possibilities of OpenCL to produce the best implementation. It is necessary to know how OpenCL works, to fully exploit these opportunities. When we started using OpenCL, the learning was mostly based on examples and a trial and error-approach, which results in a longer learning curve. Now, the available literature (Tsuchiyama et al., 2009; Benedict et al., 2011) offers a more complete range of books which reduces the learning curve drastically and can also teach the reader a correct way of programming for a high performance gain.

Development. OpenCL focuses on heterogeneity. This comes at the cost of a lot of function calls to set up your execution environment (creating a platform, creating devices, creating a program, creating command queues, ...). This can be seen as a disadvantage, but once these functions are written, they can easily be reused in later projects without losing the flexibility it offers. This flexibility allows an easy change of execution device without modifying your kernel code. To make optimal use of the possibilities of OpenCL, it is necessary to understand every detail of the algorithm to implement. Just copy-and-pasting existing source code to kernel code can give a speed up, but this will be small compared to an implementation which exploits the availability of fast memory, the highest parallelization possible and sequen-

tial memory access. The upcoming amount of (public) available libraries of optimized implementations of commonly used functions (matrix multiplication, image filtering, convolution, ...) can limit the developing time, since the developer only needs to focus on the rest of the algorithm.

4 FPGA OPTIMISATION

4.1 Algorithm Adaptation

Since the architecture of an FPGA is completely different than the architecture of a GPU, not all algorithms that can be ported successfully to a GPU can also be successfully ported to an FPGA. If an algorithm can be rewritten such that it can handle streaming data without large memory blocks an FPGA implementation is often possible. Examples of such algorithms include simple image filtering operations, where only a small neighborhood of pixels is necessary at a certain moment. The first step in porting image analysis algorithms into FPGAs is to rewrite the algorithm into a streaming algorithm. In our research first an attempt was made to convert the oriented phase congruency energy features (Kovesi, 1999) used by eSaturnus into a streaming algorithm that fits the proposed FPGA (a Xilinx Spartan6 LX150). The original algorithm uses 24 oriented log-Gabor filters (4 scales, 6 orientations) which are not separable in the spatial domain. Calculation in the frequency domain however introduces the need for 24 parallel inverse Fourier transforms which do not fit on the FPGA. An approximation in the spatial domain using 3 separable Gaussian derivative kernels can be made with good results (illustrated in fig. 5). This is inspired by the DoG approximation of the Laplacian (Mexican Hat function) in e.g. (Lowe, 2004). However, since 3 of these kernels are necessary for each approximation for both the even and odd parts this results in storing 144 separable filter results. With relatively large spatial kernels (e.g. 21×21 pixels) the internal memory of the FPGA for storage of the line buffers is not sufficient on the targeted Spartan 6 FPGA. Not even the largest Virtex 7 FPGAs have the required 2.880 BRAM blocks suitable for such implementations. Moreover, using external memory would cost too much data transfer overhead. Therefore, we switched to an alternative line enhancement algorithm that yields similar results (in terms of PSNR) for the FPGA implementation.

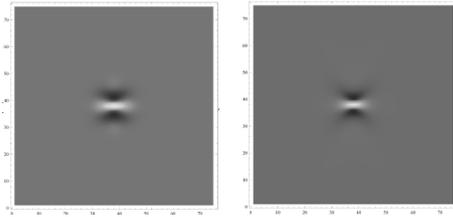


Figure 5: A log-Gabor filter (kernel shown on the left) is approximated by a combination of 3 Gaussian derivative kernels (right).

4.2 Orientation Score Algorithm

The orientation score framework (Kalitzin et al., 1999; Duits and Franken, 2010a; Duits and Franken, 2010b) has been proven very useful for line detection and enhancement. It is also based on a set of oriented filters, similar to the log-Gabor filters used in the phase congruency algorithm. However, instead of calculating phase features in each pixel to enhance lines a simple group convolution (a convolution not only over the spatial domain, but also over the orientation domain) is performed that is very suitable for FPGA implementations. In our experiments 24 filters are used (3 scales, 8 orientations) to have a comparable complexity as the phase congruency algorithm. The filters are not separable in the spatial domain and are similar to the log-Gabor filters. The group convolution is comparable in the number of multiplications and additions to the phase congruency algorithm, but can be better optimized for FPGA implementations.

4.3 FPGA Implementation

The orientation score algorithm is implemented directly in VHDL using simple arithmetic operators, registers, multiplexers and FIFO (First In First Out) buffers. The data is streamlined through a number of registers and FIFO buffers in such a way that at a certain clock cycle all necessary pixels for the $N \times N$ neighborhood are present in registers. Then in parallel the filter operations are performed resulting in all 24 filter results at a certain pixel position in each clock cycle. These results are again streamlined through a number of registers and FIFO buffers to obtain an $M \times M \times 24$ neighborhood of all filter results to perform the group convolution, again resulting in one value per pixel clock. This way, in each clock cycle one pixel is loaded and one pixel result is presented. The maximum clock frequency thus determines the maximum amount of pixels per second that can be processed. All calculations are fixed-point calculations with a flexible position of the point. This is possible without losing accuracy due to the carefully cho-

sen filter values.

5 RESULTS

In this section, we will first examine the timing results of the GPU implementation (5.1) and the FPGA implementation (5.2) respectively.

5.1 GPU Results

First we will present the timing results of our OpenCL-based GPU optimization. In table 1 the different steps of our GPU porting process, as described in part 3.2, and their respective speed gains can be found. Results are generated on an Intel Core i7 950, 6GB RAM, AMD Radeon HD6870 with Windows 7 Professional. The software used is Visual Studio 2010, with the AMD Accelerated Parallel Programming (APP) SDK and AMD APPML (APP Math Library).

Table 1: GPU optimization: processing time/image (in ms) for 720×576 resolution at different steps of the porting process.

	Loop 1	Loop 2,3,4	Loop 5	Loop 6	Total	w/traffic
Ref.	122.0	214.78	7.14	52.28	396.21	408.40
Step 1	106.75	126.38	8.74	4.51	246.39	303.88
Step 2	67.45	5.24	0.071	5.66	78.54	166.18
Step 3	6.81	0.015	0.0026	0.0019	6.83	40.93

In the reference implementation and step 1 of the port, loops 2, 3 and 4 were still separated from each other in loops or different kernels. It is only in step 2 that these kernels were taken together to construct one big OpenCL kernel. Doing this eliminated a lot of data traffic from host to GPU and otherwise, which accounts for the large gain in speed performance. In step 3, the AMD library with FFT implementation in OpenCL was used and all dependencies to the IPP library removed, what resulted in another tremendous speed-up to 41 ms for a 720×576 image frame. Taking also the preprocessing and processing times in account, this boils down to 65 ms, or more than 15 fps.

The resulting processing speed for different image resolutions is given the graph of figure 6. We can see that for smaller images of e.g. 360×288 , the resulting speed is even more impressive: about 14 ms or about 30 fps.

When reducing the number of scales or orientations filtered at, the framerate increases also. At 3 scales (instead of 4), SD video is processed at 18 fps. When the number of orientations is reduced to 4 instead of 6, the framerate is 24 fps.

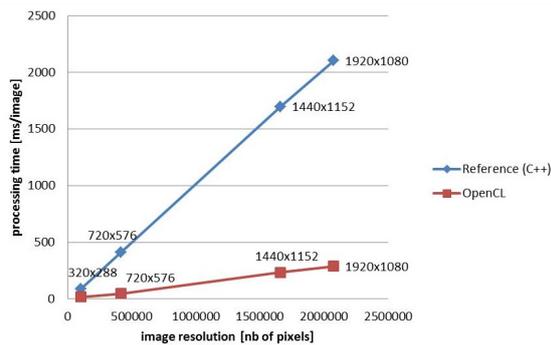


Figure 6: Processing speed results of the GPU implementation as compared to the reference C++ code started from.

5.2 FPGA Results

The VHDL code is synthesized using the Xilinx ISE for a Spartan 6 LX150 FPGA. Using a gigabit Ethernet connection the image data is loaded into the FPGA and the results are sent back to the PC again. The Gigabit Ethernet PHY (Physical layer) runs at 125MHz with 8 bits in parallel. Since we use 8 bits per pixel this results in a pixel clock of 125 Mega Pixel (MP) per second. The VHDL design runs at 125MHz and is thus also capable of processing the image at 125 MP per second. Before the output is valid however, the FIFO buffers need to be filled. The delay between first pixel in and first pixel out is in total a bit over 12000 clock cycles which results of a delay of 96 microseconds. In practice the demonstration unit is limited to the bandwidth of the gigabit Ethernet interface which is below 125 MP per second due to overhead of the packets. A Full HD video stream at 30 frames per second is successfully tested.

6 EVALUATION

As explained above, we evaluated different criteria of the two implementations: speed performance, code translation effort, hardware cost, power efficiency, integrateability and physical space.

6.1 Speed Performance

On GPU, we achieved real-time performance on standard definition (SD) video (15 fps at 720×576 pixels). This is already quite impressive, compared to our initial CPU implementation which only ran at 2 fps at that resolution. But the FPGA implementation surpasses this greatly by showing timing results of 30 fps at HD resolution (1920×1080 pixels).

6.2 Code Translation Effort

While code porting to GPU via OpenCL was straightforward, an implementation on FPGA was much more of a hassle. The only actual issue for the OpenCL implementation was finding OpenCL-versions of proprietary CPU-optimized software libraries. For the FPGA implementation, we were not able to directly port the available algorithm. After spending quite some time searching for approximated filter kernels, this approach proved unfeasible. Therefore, we had to make use of a totally different line detection algorithm for the FPGA version. Moreover, next to the tedious VHDL coding of the FPGA implementation itself, we spent lots of effort to get the CPU-FPGA interface working. Happily enough, both FPGA and GPU developments took about 2-3 man months because of the experiencedness of our FPGA developer at InViso.

6.3 Hardware Cost

The actual hardware cost of the two platforms is comparable. The mainstream AMD GPU board that we used in our demonstrator can be bought for around €160, while the Spartan 6 board is around €200. Note that the compared prices are for evaluation boards only. The naked component cost for self-assembly is also not significantly different.

6.4 Power Efficiency

When measuring the power usage of both platforms (in full function) with a Watt meter, we observed that the GPU consumed 65W extra on top of the 135W of the PC itself, while the FPGA took less than 10W.

6.5 Integrateability

Although the impressive speed gain results of our FPGA implementation, the integration of such a hardware platform in an existing PC-based computing platform showed not obvious. We encountered quite some issues during interfacing between PC and FPGA, which in the end was solved as a UPD Ethernet connection. Moreover, we see that the overall processing speed of the FPGA platform was severely constrained by that interface. For GPU hardware, these problems were non-existent because of the seamless hardware integration and the fact that OpenCL is developed for hybrid CPU/GPU platforms.

6.6 Physical Space

We see that the FPGA solution ended up very efficient in terms of board space: the unit measures only 5cm×4cm. The computational density of the GPU solutions is an order of magnitude worse, because the AMD7850 is a PCB of about 26cm×12cm (with two huge fans), which even does not fit in a standard desk-top case.

7 CONCLUSIONS

In this paper, we have compared the optimal implementation of a complex image processing algorithm on GPU and FPGA. On both target platforms, we achieved an impressive speed-up factor, albeit with quite different amounts of effort.

In general, we can conclude that both FPGA and GPU platforms have important — but different — advantages. While the ultimate flexibility of a FPGA-based system can lead to a speed performance that is an order of magnitude better than the GPU-based platform, the effort spent in developing a FPGA implementation of a certain algorithm boils down to quite more effort as compared to the C/C++ to OpenCL-translation needed for a GPU implementation. Moreover, we saw that the original algorithm was unsuited to be implemented in a FPGA, even after an approximated simplification, which forced us to rethink the algorithm and move to a totally different approach. In terms of physical space and power consumption, the FPGA is certainly the winner.

Nevertheless, because of the ease to integrate the GPU implementation in an existing server installation, eSaturnus chose the latter. At this moment, our GPU code is running in a real hospital in Berlin as a clinical try-out.

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