

SmartCam Design Framework

W. Caarls, P.P. Jonker, and H. Corporaal

{wcaarls, pieter}@ph.tn.tudelft.nl, h.corporaal@tue.nl

Pattern Recognition Group, Department of Electrical Engineering
Delft University of Technology, Eindhoven University of Technology

Abstract—The last few years have seen the advent of *Smart Cameras*, surveillance-camera sized devices with on-board programmable logic. Usually, Digital Signal Processors (DSPs) or general-purpose (GP) microprocessors are used, but obviously the specific field of image processing allows for many architectural optimizations, such as the use of single-instruction multiple-data (SIMD) processors for filtering. Furthermore, intuitive mappings of algorithms on architecture components are used, after the architecture has been determined. It will be clear that this is far from optimal. Finally we foresee a further integration, making a combination of on-chip vision sensor, pixel processing, control, and feature / object processing possible. The result is a low-cost one-chip smart camera (so-called *SmartCam*) solution. This means that research is needed to explore the new architectural opportunities and consequences.

The SmartCam project investigates these new opportunities and contributes to a better and more quantitatively guided design trajectory. This paper describes the design flow as seen by the application developer: the use of *algorithmic skeletons* to exploit data-parallelism, and *design space exploration* to find a suitable board- and processor architecture. We explain how it can lead to smaller, cheaper, and more efficient devices, tailored to a specific application or set of applications.

I. INTRODUCTION

The SMARTCAM [2] project aims to investigate the design of application-specific programmable smart cameras, with integrated sensor, SIMD-, and ILP processors. In such a camera, a lot of vision processing is done on-board, allowing the camera to actuate control systems, raise alarms, or output symbolic information. Single instruction multiple data (SIMD) processors are especially well suited for the pixel and neighbourhood operations common in low-level image processing, while a network of instruction-level parallel (ILP) processors can handle the more coarse-grained and irregular algorithms found in intermediate- and high-level tasks.

We are most interested in quantifying the design flow of such systems via the use of simulation and analysis in a design space exploration (DSE) environment,

and in the development of an intuitive programming model. In this paper, we will first introduce the programming model, which is based on instantiating *algorithmic skeletons* in order to bring parallelism into a sequential code image. Then, we will show how this is integrated in the overall DSE framework, and how this allows a developer to generate the most appropriate architecture for his application.

Section II will review previous work in the field of fast image processing, providing a reference for our architecture template and programming model, described in sections III and IV. We will continue by introducing our DSE framework in section V, and section VI gives an example of the entire design flow. Finally, we will have some concluding remarks.

II. PREVIOUS WORK

The large amounts of data used in image processing, and the speed needed to process this information in a reasonable amount of time, has led the image processing community to look into special computer architectures since the early 1970s [16]. Subsequent miniaturization efforts have brought us to the point where it is possible to integrate an entire vision processing system in a single security-camera sized device.

A. Stand alone systems

Recognising the data parallelism inherent in low-level vision operations such as thresholding and convolution, image processing systems have been designed massively parallel from the start. This has taken many forms, such as multicomputers [6], SIMD processor arrays [10], and pipelines [18]. However, with ever increasing workstation processing speeds, the advent of cheap Beowulf-type commodity clusters [27] and the increase in their communications bandwidth, the other architectures have faded into the background. Pipelines are difficult to program and cannot cope with dynamic control flow, and large SIMD systems, while very much suited to low-level image processing, are just too expensive and specialized.



Fig. 1. UCL CLIP4 SIMD image processing system

The sole survivor is the linear SIMD architecture, that can be found as accelerator board, architecture component in smart cameras and even in a rudimentary form in MMX/SSE/AltiVec instruction sets in general purpose processors.

Clusters are usually programmed using the MPI message passing library [11]. Data-parallel language extensions such as CC++ [4] or the compiler-directive based OpenMP [20] are also used, but the amount of effort required keeps image processing researchers away, except when the added speed is absolutely necessary. Recent efforts have created specific image processing libraries which generate data-parallel [24] or even mixed data/task parallel [26] programs from sequential code images, which go a long way towards providing researchers with the benefits of parallel processing without the hassle.

B. Vision accelerator boards

Because of the increased power and area efficiency, SIMD arrays, and in particular linear processor arrays (*LPAs*), are still frequently used in embedded appli-

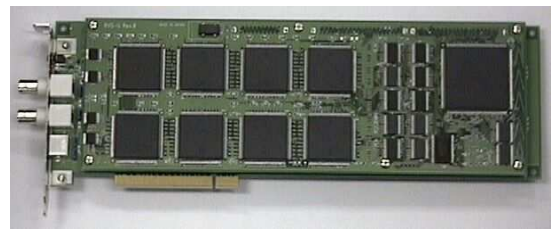


Fig. 2. NEC IMAV-Vision SIMD vision accelerator

cations. Vision accelerator boards are employed in real-time control systems where there is enough room to have a workstation. They contain LPAs (IMAV-Vision [28]), DSPs (FUGA [21]), or GP processors (GenesisPlus [19]).

The IMAV-Vision uses a data-parallel C extension called 1dc [17] to program the LPA, while the FUGA and GenesisPlus are programmable in standard C++. All boards provide optimized library routines for common image processing operations. In addition, the GenesisPlus uses the library routines to interface with a separate neighbourhood processor as well.

The use of an explicitly parallel language makes the IMAV-Vision more difficult to program, but also potentially faster. It occupies a place between assembly language, which is always fastest but not realistically used by image processing researchers, and a completely library based approach, which may shield the programmer too much to make any optimizations. It would seem that a library-based system in which the user can descend to a 1dc-like (parallel) level if necessary is the best approach.

C. Smart cameras

For the even more embedded market, with a need to be very small and power efficient, cameras that integrate sensing and processing are emerging. Again, DSP (Vision Components [13], iMVS [23]) and GP (Legend [25], mvBlueLYNX [12]) solutions are often used, but single-chip LPAs (Xetal [1], added to Inca311 [5]) and even integrated sensor/LPA chips (MAPP2500 [15]) exist as well.

Again, all systems are programmable using an image acquisition and processing library, but the LPAs, because of the simplicity of the processing elements (*PEs*), cannot be programmed in C. Xetal tries to remedy this by providing a C-like macro language, while the MAPP2500 avoids the problem altogether by only providing a few algorithms specific to the expected application domain (range imaging). Both so-



Fig. 3. Philips CFT Inca311 Intelligent Camera

lutions are unsatisfying.

Two of the smart cameras, Inca311 and Legend, are also programmable using graphical programming languages. Both are targeted at industrial inspection, and allow novices in the field of image processing to graphically connect algorithms like sub-pixel edge detection, angle measurements and template matching. Efforts have been made to put such a user interface above a library-based approach, providing another level of abstraction in a single framework.

III. ARCHITECTURE TEMPLATE

In our SMARTCAM DSE environment, an application designer will be able to generate an optimal smart camera hardware configuration for his specific domain, based on his application code and various constraints such as size, cost and power consumption. However, for this approach to be feasible it is necessary to restrict the search space by imposing an architecture template. Based on the previous work described in the previous section, our architecture template will consist of a sensor, LPA(s), instruction-level parallel (ILP) processor(s), memories, and communications peripherals (see figure 4). These will be parameterizable with regard to resolution, number of PEs and PE functionality, data width, the amount and type of functional units, etc. The choice of an LPA is simple, because it is perfectly suited for the data parallelism inherent to low-level image processing operations. ILP processors, such as very long instruction word (VLIW) and *superscalar* processors, can execute multiple independent instructions per cycle, exploiting a finer-grained level of parallelism than LPAs. This is necessary because higher-level vision processing tasks are too irregular to execute on LPAs. Finally, using a network of processors allows us to take advantage of the independence between different im-

age processing tasks, or between different stages in a pipeline.

IV. PROGRAMMING MODEL

Of course, managing such a diverse set of parameterizable processors without putting too great a strain on the programmer requires a unified programming model. The programming languages for the systems described in section II fall in five categories: (parallel) assembly, specialized parallel languages, data-parallel extensions to a sequential language, (generalized) libraries, and graphical programming environments. We think that assembly is too time consuming, and specialized parallel languages require too much effort to learn to gain widespread use in real applications. This leaves us with three viable options; however, as described in [24], any deviation from a standard sequential programming model creates a barrier for adoption, and thus we would like to limit that as much as possible.

Thus, our programming model will consist of a C/C++ image processing library, possibly with a graphical programming environment on top. If the user wants to add library routines, either to accommodate new algorithms or to speed up existing ones, he can do so by using some data-parallel extensions in the form of compiler directives or *pragmas*. Note, though, that because of the possibly limited capabilities of some of the processors in the architectural template, he may have to provide several versions.

A. Algorithmic skeletons

Because extensions to the library should be as infrequent as possible, we will base it around the concept of algorithmic skeletons [7], also called template- or pattern-based parallel programming. This means that the library provides higher-order functions which only implement a certain structure and communication, while the user provides the code for the actual computation (see figure 5). A useful survey of different skeletons and implementations is contained in [3]. In the field of low-level image processing, examples are generalized skeletons for point operations, neighbourhood operations, and global reductions.

By using the algorithmic skeletons, the user is completely shielded from the parallel implementation of his algorithm, providing only the sequential code to process a single datum. The advantage, apart from providing the developer with a sequential interface and avoiding changes to the library, is that this abstraction allows the program to be executed on dif-

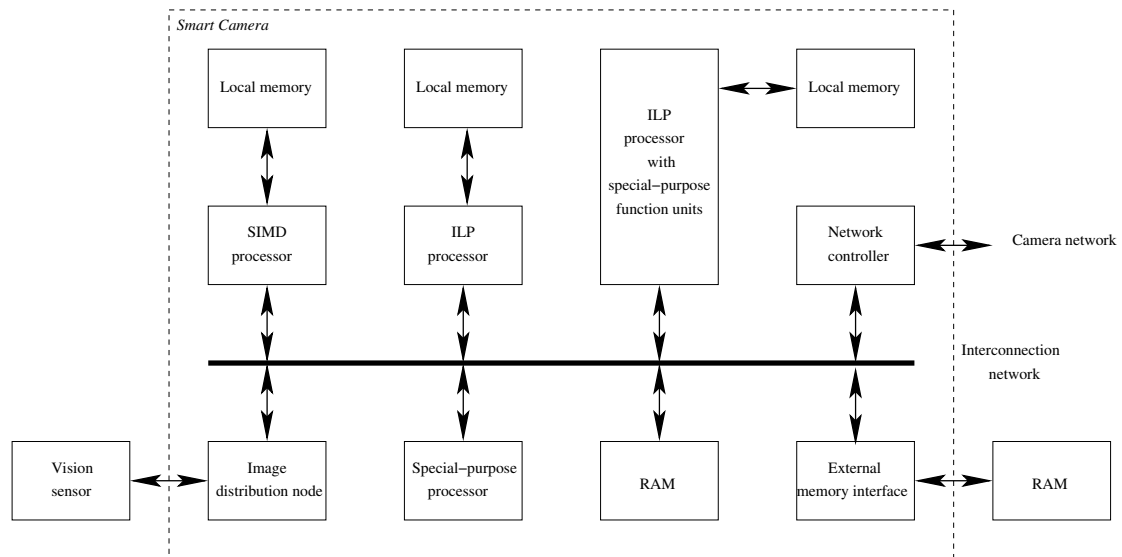


Fig. 4. A possible architecture template for a smart camera device, containing SIMD, ILP, and special-purpose processors. All components, including the interconnection network, are subject to adjustment by the architecture exploration.

A higher-order function is a function which takes another function as input. We can use this to abstract over the structure of a certain computation. Consider the following code:

```

for ( $y=0$ ;  $y<HEIGHT$ ;  $y++$ )
  for ( $x=0$ ;  $x<WIDTH$ ;  $x++$ )
     $out[y][x] = (in[y][x]>128)$ ;
    
```

Using a higher-order function, **PixelToPixelOp**, we can separate the structure from the computation. **PixelToPixelOp** will implement the loops, calling **binarize** every iteration.

```

int binarize( $value$ )
  return ( $value>128$ );
void PixelToPixelOp(int  $in[HEIGHT][WIDTH]$ , int  $out[HEIGHT][WIDTH]$ , int (*op)(int))
  for ( $y=0$ ;  $y<HEIGHT$ ;  $y++$ )
    for ( $x=0$ ;  $x<WIDTH$ ;  $x++$ )
       $out[y][x] = op(in[y][x])$ ;

PixelToPixelOp( $in$ ,  $out$ , binarize);
    
```

Fig. 5. Abstracting over structure using higher-order functions

ferent processor architectures without changes to the user code: once a skeleton implementation has been provided for the architecture, it is possible to run any instantiation of it¹. Skeletons which are not implemented on a certain architecture are simply never scheduled to those processors.

While this abstraction over communication as well

¹Severely limited architectures – like single-ALU processing elements in SIMD systems – may have additional requirements on the skeleton instantiation functions, such as the absence of indirect addressing.

as architecture is very convenient, algorithms which cannot be captured in one of the provided skeletons are executed sequentially. That can be avoided by providing the user with low-level communication primitives, but this might introduce problems with scheduling and maintainability. Therefore, it is better to allow the programmer to create his own skeletons, possibly based on already existing ones. In the ideal case this would be done in an architecture-independent manner, but for some architectures that is either impossible or inefficient. Thus, there are four

levels of abstraction in our programming model:

1. *No abstraction* for the specification of skeletons for restricted architectures or fixed-function blocks.
2. *Abstraction over architecture* for the specification of skeletons for general architectures, such as those capable of executing C.
3. *Abstraction over communication* for the user program that makes use of the skeletons.
4. *Abstraction over syntax* for a graphical programming environment.

V. DSE FRAMEWORK

Writing the application is only the first step in our framework (see figure 6). The compilation trajectory takes the source code, instantiates the skeletons, extracts a macro dataflow graph, schedules the different skeleton instantiations to the available processors in the architecture template instantiation, and finally compiles the scheduled code for the different processor types. The design space exploration environment finds the most suitable processor architecture by structurally simulating and analyzing the application on different processor architectures (intra-processor optimization loop) and different combinations of processors (inter-processor optimization loop). Finally, the developer can also access the results, and use them to tune his program (source code transformation loop).

A. Compilation

The different skeleton instantiations in an image processing application are not fully dependent. Some can be run concurrently, while others can be pipelined. The compiler starts by extracting a macro dataflow graph (*MDG*) from the application in order to analyze the dependencies. It then makes a compromise between data-parallel (within the skeletons) and task-parallel (between the skeletons) execution [22]. It uses a cost model and profiling information to determine the weight of each task.

B. Intra-processor optimization

Our architecture template specifies the type of processors that can be used, but not their exact composition, such as the number and types of functional units. The intra-processor optimization step heuristically iterates over the possibilities. Each iteration the application is simulated, and profiling information is used to steer the exploration of the design space [9].

C. Inter-processor optimization

Because the architecture template allows the use of more than one processor, an inter-processor optimization step is needed to find the best mix, and the interconnection between them. This follows much the same strategy as the intra-processor optimization, but also uses the weights of the edges in the macro dataflow graph in order to determine local interconnections between processors. A rescheduling of the macro dataflow graph is necessary for every iteration.

The result of these two optimization steps is a set of architectures that are optimal with regard to speed, area and power consumption (the pareto-optimal set). Based on his own design considerations, the user can then make the trade-off himself.

D. Source code transformation

Based on feedback from the profiling done in the optimization steps, the user can decide to rewrite parts of his application. For example, when rewriting a legacy application, he can start by replacing the easiest loops by skeleton instantiations in order to make them execute in parallel. If no architecture can be found that meets his requirements, he can replace more difficult constructions. In this way, it is possible to construct a parallel application with the least amount of effort.

VI. DESIGN FLOW EXAMPLE

We will present a simulated design flow example. Suppose that we want to find lines in an image using the Hough transform [14] using as little power as possible, meaning that we want a low clock speed because that allows us to lower the supply voltage. In this case, we are not as interested in the area the processors occupy.

The application first convolves the image with an edge detector, then binarizes on the edge strength, and finally transforms the edges to the (ρ, ϕ) space, where each point corresponds to a possible line. The sequential code might look like this:

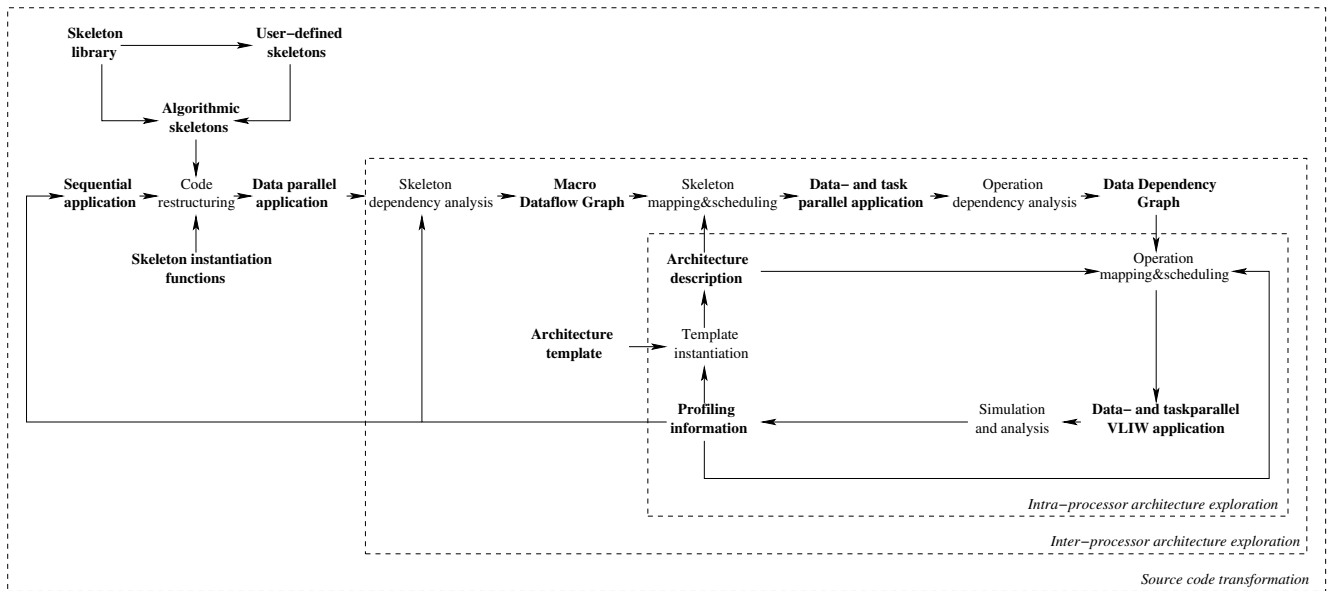


Fig. 6. SmartCam design flow. Note the use of algorithmic skeletons to create data-parallel applications from a sequential code image, and the different types of design space exploration to find a suitable architecture.

```

while (1)
getimage(in);
for (y=1; y < HEIGHT-1; y++)
for (x=1; x < WIDTH-1; x++)
/* Sobel X */
val=abs(-in[y-1][x-1]-2*in[y][x-1]-in[y+1][x-1]
+in[y-1][x+1]+2*in[y][x+1]+in[y+1][x+1]);
/* Sobel Y */
val+=abs(in[y-1][x-1]+2*in[y-1][x]+in[y-1][x+1]
-in[y+1][x-1]-2*in[y+1][x]-in[y+1][x+1]);
trans = {0};
/* Binarization */
if (val > 128)
/* Hough transform */
for (phi=0; phi < PHI_RES; phi++)
trans[phi][abs(x*cos(M_PI*phi/PHI_RES)
+y*sin(M_PI*phi/PHI_RES))];
    
```

Simulating this code on a Transport Triggered Architecture (TTA, [8]) ILP processor with 8 busses (utilizing a lookup-table based Hough transform) results in 5.2 MCycles for a 320x240 image with 32 angles, or 156 MHz for video speed at 30fps (discounting read-out and display). The intra-processor optimization step will find that there is no floating-point math, and instantiate the processor accordingly. If this does not meet the power requirements, the most logical step is to use a neighbourhood skeleton for the edge detector, and a pixel skeleton for the binarization:

```

int sobel(int **nbh)
val = abs(-nbh[-1][-1]-2*nbh[0][-1]-nbh[+1][-1]
+nbh[-1][+1]+2*nbh[0][+1]+nbh[+1][+1]);
val += abs(nbh[-1][-1]+2*nbh[-1][0]+nbh[-1][+1]
-nbh[+1][-1]-2*nbh[+1][0]-nbh[+1][+1]);
return val;
int binarize(int val) return (val > 128);
while (1)
getimage(in);
NeighbourhoodToPixelOp(in, sob, 3, 3, sobel);
PixelToPixelOp(sob, edge, binarize);
trans = {0};
for (y=1; y < HEIGHT-1; y++)
for (x=1; x < WIDTH-1; x++)
if (edge[y][x])
for (phi=0; phi < PHI_RES; phi++)
trans[phi][abs(x*cos(M_PI*phi/PHI_RES)
+y*sin(M_PI*phi/PHI_RES))];
    
```

Within our template, the most energy-efficient way of computing neighbourhood and pixel operations is an LPA, and so the intra-processor optimization step instantiates one with 320 processors. By scheduling the application in a pipelined manner, this reduces the critical path to 4.2 MCycles/image, at the expense of a lot of area.

Most of the computation time is spent in the transform, however, and parallelizing it is necessary if more performance is to be gained:

```

int sobel(int **nbh)
    val = abs(-nbh[-1][-1]-2*nbh[0][-1]-nbh[+1][-1]
    +nbh[-1][+1]+2*nbh[0][+1]+nbh[+1][+1]);
    val += abs(nbh[-1][-1]+2*nbh[-1][0]+nbh[-1][+1]
    -nbh[+1][-1]-2*nbh[+1][0]-nbh[+1][+1]);
    return val;
int binarize(int val) return (val > 128);
int hough(int x, int y, int val, int **trans)
    if (val)
        for (phi=0; phi < PHI_RES; phi++)
            trans[phi][abs(x*cos(M_PI*phi/PHI_RES)
            +y*sin(M_PI*phi/PHI_RES))]++;
int add(int val1, int val2) return (val1+val2);
while (1)
    getimage(in);
    NeighbourhoodToPixelOp(in, sob, 3, 3, sobel);
    PixelToPixelOp(sob, edge, binarize);
    AnisoPixelToGlobalReductionOp(edge, trans,
    hough, add);

```

We assume a skeleton **AnisoPixelToGlobalReductionOp** which in the limit constructs a transform for each pixel, and adds them using a *reduction tree*. Because of the large amounts of communication time (the size of the transform times the depth of the tree) this does not scale well, but at 4 ILP processors it reduces the critical path to 1.2 MCycles/image, which may well suit our requirements.

VII. CONCLUSION

Based on previous work, we have derived an architecture template and programming model for image processing in smart cameras. The architecture contains LPA and ILP processors, while the programming model is based on algorithmic skeletons. We have presented our DSE framework, which finds an optimal instantiation of the template for a particular application. An example has shown the iterative process in which the user transforms his source code to allow parallelization, and the optimizer finds the best quantity and configuration of processors.

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