Field-Programmable Gate Array Implementation of a Scalable Integral Image Architecture Based on Systolic Arrays

Juan Alberto De la Cruz
Utah State University

Follow this and additional works at: https://digitalcommons.usu.edu/etd

Part of the Computer Engineering Commons

Recommended Citation
De la Cruz, Juan Alberto, "Field-Programmable Gate Array Implementation of a Scalable Integral Image Architecture Based on Systolic Arrays" (2011). All Graduate Theses and Dissertations. 854.
https://digitalcommons.usu.edu/etd/854

This Thesis is brought to you for free and open access by the Graduate Studies at DigitalCommons@USU. It has been accepted for inclusion in All Graduate Theses and Dissertations by an authorized administrator of DigitalCommons@USU. For more information, please contact dylan.burns@usu.edu.
FIELD-PROGRAMMABLE GATE ARRAY IMPLEMENTATION OF A
SCALABLE INTEGRAL IMAGE ARCHITECTURE BASED ON SYSTOLIC
ARRAYS

by

Juan A. De la Cruz

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Computer Engineering

Approved:

Prof. Paul Israelsen
Major Professor

Dr. Jacob Gunther
Committee Member

Dr. Reyhan Baktur
Committee Member

Dr. Byron R. Burnham
Dean of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah
2011
Abstract

Field-Programmable Gate Array Implementation of a Scalable Integral Image Architecture Based on Systolic Arrays

by

Juan A. De la Cruz, Master of Science
Utah State University, 2011

Major Professor: Prof. Paul Israelsen
Department: Electrical and Computer Engineering

The integral image representation of an image is important for a large number of modern image processing algorithms. Integral image representations can reduce computation and increase the operating speed of certain algorithms, improving real-time performance. Due to increasing demand for real-time image processing performance, an integral image architecture capable of accelerating the calculation based on the amount of available resources is presented. Use of the proposed accelerator allows for subsequent stages of a design to have data sooner and execute in parallel. It is shown here how, with some additional resources used in the Field Programmable Gate Array (FPGA), a speed increase is obtained by using a one-dimensional Systolic Array (SA) approach. Additionally, extra guidelines are given for further research in this area.

(61 pages)
Dedicated to my family and beloved ones, especially to my grandfather who always believed in me.
Acknowledgments

The completion of this thesis has been a long journey and would not have been possible without the help and support of many. I would like to acknowledge their extraordinary support in making this research a reality. First, I would like to thank the government of the Dominican Republic and the Ministry of Higher Education for giving me the great opportunity to come and study at Utah State University.

I would like to thank my major professor, Prof. Paul Israelsen, for giving me an opportunity to work under his supervision when I needed it. I specially thank Dr. Aravind Dasu for his dedication, support, and technical guidance along the trajectory of this research, even though he is not part of my final committee. I have to thank my colleagues at the Energy Dynamics Laboratory for all their help, especially to Bruce Christensen for his support. I would also like to thank Dr. Jacob Gunther and Dr. Reyhan Baktur for being part of my committee and for their support and advising.

Thanks to all my friends that stood by my side unconditionally, making my stay at Utah State University memorable. Among them are Omar Rodriguez, Michael Calcaño, Jhonattan Castillo, Dulce Minaya, Abiezer Tejeda, Augusto Rodríguez, and Erick Tejada. Special thanks go to my beloved girlfriend, Iris Bueno, for being so loving and understanding during this life project that concludes.

Last, but not least, I want to thank my family for their support and guidance; they have always had faith in me. I want to give special thanks to my aunt, Ana De la Cruz, who is like a mother to me, and my grandfather, Ramón De la Cruz, who is no longer with us. Also, to my grandmother, Ana Medina, who raised me and took care of me for many years, to my mother, Angela González, my father, Octavio De la Cruz, and all my aunts and uncles that have always treated me like a brother, a son, and a friend.

Juan A. De la Cruz
# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>iii</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>v</td>
</tr>
<tr>
<td>List of Tables</td>
<td>viii</td>
</tr>
<tr>
<td>List of Figures</td>
<td>ix</td>
</tr>
<tr>
<td>Acronyms</td>
<td>xi</td>
</tr>
<tr>
<td>1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Motivation</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Key Contributions</td>
<td>2</td>
</tr>
<tr>
<td>1.3 Thesis Overview</td>
<td>3</td>
</tr>
<tr>
<td>2 Background</td>
<td>4</td>
</tr>
<tr>
<td>2.1 Field Programmable Gate Arrays</td>
<td>4</td>
</tr>
<tr>
<td>2.2 Systolic Arrays</td>
<td>6</td>
</tr>
<tr>
<td>3 Integral Image</td>
<td>11</td>
</tr>
<tr>
<td>3.1 Integral Image Calculation</td>
<td>11</td>
</tr>
<tr>
<td>3.2 Previous Work</td>
<td>13</td>
</tr>
<tr>
<td>4 Implementation</td>
<td>17</td>
</tr>
<tr>
<td>4.1 Sequential Implementation</td>
<td>17</td>
</tr>
<tr>
<td>4.2 Two-dimensional Systolic Array Accelerator</td>
<td>19</td>
</tr>
<tr>
<td>4.3 One-dimensional Systolic Array Accelerator</td>
<td>20</td>
</tr>
<tr>
<td>4.4 Integral Image Accelerator Architecture</td>
<td>24</td>
</tr>
<tr>
<td>4.4.1 Skew - Data Preparation</td>
<td>25</td>
</tr>
<tr>
<td>4.4.2 Master Node</td>
<td>26</td>
</tr>
<tr>
<td>4.4.3 Helper Node</td>
<td>29</td>
</tr>
<tr>
<td>4.4.4 DeSkew - Data Normalization</td>
<td>29</td>
</tr>
<tr>
<td>4.4.5 Controller</td>
<td>31</td>
</tr>
<tr>
<td>4.5 Software Simulation</td>
<td>31</td>
</tr>
<tr>
<td>4.6 Hardware Simulation</td>
<td>34</td>
</tr>
<tr>
<td>5 Results</td>
<td>37</td>
</tr>
<tr>
<td>5.1 Execution Time</td>
<td>37</td>
</tr>
<tr>
<td>5.2 Speed-Up</td>
<td>38</td>
</tr>
<tr>
<td>5.3 Resources</td>
<td>40</td>
</tr>
<tr>
<td>5.4 Resource Estimation</td>
<td>42</td>
</tr>
<tr>
<td>5.5 SAIII Accelerator Model</td>
<td>44</td>
</tr>
</tbody>
</table>
6 Conclusions and Future Work ................................. 46
  6.1 Summary .................................................. 46
  6.2 Future Work ............................................. 47

References ....................................................... 49
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Summary of previous work on integral image acceleration across various platforms.</td>
<td>16</td>
</tr>
<tr>
<td>4.1</td>
<td>Set of equations for SAII accelerator PE nodes.</td>
<td>24</td>
</tr>
<tr>
<td>5.1</td>
<td>Total execution time estimate for the sequential implementation and various sizes of the SAII accelerator. Time estimate based on total clock cycles required to process an image and the maximum clock frequency achievable after synthesis.</td>
<td>38</td>
</tr>
<tr>
<td>5.2</td>
<td>FPGA resources utilized by the sequential approach and the proposed SAII with different number of PEs.</td>
<td>41</td>
</tr>
<tr>
<td>5.3</td>
<td>Maximum number of PE nodes that can be instantiated across several devices. Negative estimations refer to non-capable devices. The minimum of LUT and FF nodes estimates is considered.</td>
<td>44</td>
</tr>
</tbody>
</table>
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 FPGA basic block diagram.</td>
<td>5</td>
</tr>
<tr>
<td>2.2 Mapping of a boolean function to an LUT.</td>
<td>7</td>
</tr>
<tr>
<td>2.3 Comparison between a single PE and multiple PE in a systolic array structure.</td>
<td>8</td>
</tr>
<tr>
<td>2.4 Figure with different topologies for Systolic Arrays.</td>
<td>10</td>
</tr>
<tr>
<td>3.1 Integral calculation of an image region using integral image.</td>
<td>12</td>
</tr>
<tr>
<td>3.2 Multi-row parallel integral image computation.</td>
<td>15</td>
</tr>
<tr>
<td>4.1 Pure sequential integral image implementation.</td>
<td>19</td>
</tr>
<tr>
<td>4.2 Two-dimensional SA integral image.</td>
<td>21</td>
</tr>
<tr>
<td>4.3 One-dimensional SA implementation.</td>
<td>22</td>
</tr>
<tr>
<td>4.4 Incorrect results when number of PEs $\notin {1, 2, $ image width$}$.</td>
<td>23</td>
</tr>
<tr>
<td>4.5 Proposed integral image accelerator structure.</td>
<td>26</td>
</tr>
<tr>
<td>4.6 Skew module inner diagram.</td>
<td>27</td>
</tr>
<tr>
<td>4.7 Master node inner diagram.</td>
<td>28</td>
</tr>
<tr>
<td>4.8 Helper node inner diagram.</td>
<td>30</td>
</tr>
<tr>
<td>4.9 DeSkew module inner diagram.</td>
<td>32</td>
</tr>
<tr>
<td>4.10 Main FSM for SAII controller module.</td>
<td>33</td>
</tr>
<tr>
<td>4.11 Offset adjustment controller FSM.</td>
<td>34</td>
</tr>
<tr>
<td>4.12 Block diagram of top model along with stimulus file read and write results.</td>
<td>35</td>
</tr>
<tr>
<td>4.13 Gray-scale portion of an image along with its pixel values and stimulus representation in bit-set form.</td>
<td>35</td>
</tr>
<tr>
<td>4.14 Hardware simulation flow showing input and output memory along with ChipScope capturing results.</td>
<td>36</td>
</tr>
</tbody>
</table>
5.1  Speed-up obtained by the proposed SAIII accelerator compared to the pure sequential implementation. 40

5.2  Visible overhead on the output of the SAIII accelerator before first valid output. 41

5.3  SAIII performance drop when image size decreases. 42

5.4  Detailed resource usage by individual modules in the SAIII architecture. 43
Acronyms

ASIC  Application Specific Integrated Circuit
BRAM  Block Random Access Memory
CLB   Configurable Logic Block
CPU   Central Processing Unit
DSP   Digital Signal Processing
EDL   Energy Dynamics Laboratory
FF    Flip Flop
FPGA  Field Programmable Gate Array
fps   frames per second
FSM   Finite State Machine
GPU   Graphics Processing Unit
IOB   Input Output Buffer
LUT   Look Up Table
PAR   Place And Route
PE    Processing Element
RAM   Random Access Memory
SA    Systolic Array
SAIi  Systolic Array Integral Image
SM    Switch Matrix
SURF  Speeded-Up Robust Features
VHDL  Very high speed integrated circuits Hardware Description Language
VLSI  Very Large Scale Integration
Chapter 1

Introduction

1.1 Motivation

The ability to capture and analyze human behavior in real time has significant impact on numerous applications such as gaming, retail shopping, high-fidelity lighting/HVAC control, assisted living, and so on and so forth. The general area of computer vision has seen rapid progress in several components of this broad research topic. Within this domain, the ability to reasonably assign the position of an occupant in a room via relative distance/displacement with respect to objects of interest in real-time is a topic that is of interest to the Intelligent Buildings group at Energy Dynamics Laboratory (EDL).

Accurately measuring an occupant’s position in a room has been a topic with a lot of attention from the research community for many years and a lot of work related to the topic can be found in journals and conference papers. Depth information is the key factor when locating a person beyond the camera plane, depth allows for two-dimensional position to be inferred, or at least estimated. The current depth estimation method used at EDL is based on stereo cameras and a relative depth algorithm which makes use of Speeded-Up Robust Features (SURF) [1] for disparity extraction across camera views. The first stage of SURF involves the integral image calculation of the input video frame, making it a high priority stage to avoid bottlenecks further on the process. The need for real-time integral image calculation served as motivation for the design of an accelerator capable of providing the parallelism required for critical image processing applications.

Since the time when Viola and Jones presented their work on rapid object detection [2], the use of integral images has been the preferred way when computing features on an image because of its noticeable reduction in computation time. Integral images use pre-calculated integral values to achieve constant computation time independent of the size of the feature.
This provides a great speed improvement compared to the original and purely sequential implementation, where all pixels had to be summed for every feature evaluation while sliding the filter window across the image. Having the integral image available makes the feature calculation a matter of just using four values to obtain the sum of pixels under any perimeter, instead of constantly summing all pixels. The objective of this thesis is the optimization of the integral image calculation step. With help of a scalable parallel approach, it is possible to accelerate most image processing algorithms that make use of this approach. The throughput of a system can be increased with help of a novel Systolic Array Integral Image (SAII) accelerator, constrained only by memory bandwidth and resources available on chip.

Many image processing algorithms make use of the integral image representation to achieve near real-time execution speeds. Critical applications that expect low response times generally require high frame-rate video inputs, typically in the order of 60 fps and above. However, having hardware capable of processing video with such a throughput while maintaining a small footprint and low power consumption is not a trivial task. This serves as motivation for the Systolic Array (SA) inspired Integral Image accelerator proposed in this thesis. The proposed design will provide a scalable approach capable of providing a high level of parallelism.

1.2 Key Contributions

The main goal was to provide an accelerator capable of calculating multiple integral pixels simultaneously while fully utilizing the memory bandwidth available. Some of the distinguishable features of this architecture are listed below.

- The presented architecture has the advantage of being scalable, meaning that different number of Processing Elements (PEs) can be used.

- The number of PEs can go from one up to the equivalent of the image width, as long as the number of elements is an exact divisor of the image width.
• The number of PEs can be determined by the resources available or the speed required for a particular application.

• The throughput of the accelerator is limited by the memory bandwidth supplying the data to be processed.

• The architecture will compute multiple integral pixels every clock cycle; the number of integral pixels generated will depend on the number of PEs.

• The overhead of the system to produce the first valid output is insignificant compared to the size of the image.

• Processing speed is effectively divided by the number of PEs on the accelerator without resulting in an increase of resources proportional to the number of PEs.

1.3 Thesis Overview

This thesis presents a hardware accelerator for integral image calculation by making use of a systolic array approach. The document has been structured into six chapters for better organization and understanding. In Chapter 1, a motivation is given as to why this problem is of interest and why its application to a relative depth estimation algorithm is currently under implementation. Also, a set of the most noticeable contributions produced by this research are listed in this chapter. In Chapter 2, some background information is given along with details on the relative depth estimation algorithm. Chapter 3 covers integral image calculation basics and includes a literature review with contributions made by other researchers working on the same area. Chapter 4 includes the implementation of the hardware accelerator and simulation methods. Chapter 5 presents the results obtained using the proposed accelerator architecture. Finally, Chapter 6 summarizes the conclusions and future work ideas.
Chapter 2

Background

In this chapter background information is presented for a better understanding of the proposed design and its implementation.

2.1 Field Programmable Gate Arrays

A Field-Programmable Gate Array (FPGA) is a reconfigurable device with the ability of being reprogrammed to satisfy particular requirements. It is comprised of basic elements that can be combined to form highly optimized and high performance systems. The two major manufacturers at the time of writing are Xilinx and Altera. Although their FPGAs have strong differences at the architectural level, their basic operation and functionality is the same. Since the target for this accelerator is a Xilinx device, the rest of the document makes reference to their silicon devices. The basic diagram of an FPGA is presented on Figure 2.1, where the structure has been simplified to show only major components. Input/Output Blocks (IOBs) serve as a way to interconnect the silicon package pins carrying external signals to the internal Configurable Logic Blocks (CLBs). Another crucial element is the Switch Matrix (SM), whose function is to interconnect all elements inside the FPGA. The SM and CLBs are programmable by the user and their configuration is stored in individual Static Random Access Memory (SRAM) cells inside each element.

The CLBs play the most important role; they allow for combinatorial or sequential logic to be generated inside the FPGA. A CLB is typically comprised of slices, each of them including several Look Up Tables (LUTs), carry logic and storage units. An LUT unit can have multiple inputs; the most common is a four input LUT. However, five and six input LUTs can also be found. With an N-input LUT, any boolean logic function with N-inputs can be implemented. In case that the boolean function has more inputs than the number
Fig. 2.1: FPGA basic block diagram.
available in an LUT, multiple LUTs can be connected to gather the required number of inputs. The function is implemented by storing its truth table with the corresponding output value inside the LUT. This way the output takes the value stored based on the combination of inputs. Figure 2.2 shows how a simple boolean function is mapped to LUT by assigning the input values to an output value. Present in slices are also storage elements that can be configured to act as edge-triggered Flip Flops (FF) or latches.

To satisfy memory intensive applications, Block Random Access Memories (BRAMs) are available inside the device to store data and to grant rapid access to it. Each BRAM can store 18Kbits and/or 36Kbits depending on the device, and they can be configured as single or dual port, Random Access Memory (RAM) or Read Only Memory (ROM), depending on the application requirements. Field Programmable Gate arrays are very common in Digital Signal Processing (DSP) applications, therefore the devices already come equipped with special blocks specifically for DSP operations. These modules perform multiplication very efficiently and some even include an accumulator for multiply-accumulate operations. On Xilinx devices, they are referred to as DSP48 blocks. Making use of them provides a better throughput compared to user implementations.

Programming of FPGAs is done with hardware description languages. Although VHDL and Verilog are the preferred ones by industry, others do exist. The process of programming an FPGA, at least for Xilinx devices, starts with synthesizing and optimizing the Verilog/VHDL code. Then the translation and mapping takes place followed by Placement and Routing (PAR) and finally the generation of the bit-stream that is used to configure the device.

### 2.2 Systolic Arrays

A Systolic Array is a set of processors in a regular structured manner, each of them connected to neighbors in a grid-shaped arrangement. Each processor or Processing Element processes the data on its inputs and passes the results to adjacent neighbors. Generally, every PE executes the same operation, however, cases where different types of PE are used in a SA do exist. The major benefit of using Systolic Arrays is the ease of implementation
Fig. 2.2: Mapping of a boolean function to an LUT.

on a VLSI chip, which comes from the regular structure of the arrays and the reuse of PE blocks.

Systolic Arrays are a form of Single Instruction Multiple Data (SIMD) computers, which can operate on multiple data with a single instruction. Data flow inside a systolic array is highly parallelized and pipelined to achieve high throughputs. Every PE is assumed to receive all required inputs simultaneously at the same clock edge, and the outputs are ready in the subsequent cycle. The outputs of a Processing Element are the inputs to neighbor PEs and should be transmitted synchronously.

Introduction of the SA in 1970 caused a great impact in general purpose computing applications [3]. An important advantage of SAs is that the input has to be brought from memory only once and can be used multiple times by the PEs. This is because PEs pass the information between each other instead of going back to memory every time an operation takes place. Kung [4] classified the SAs as semi-SAs and Pure-SAs depending on the way data from memory is propagated to PEs. Semi-SAs are structures where a global data communication is present on all PEs to deliver data requested from memory. In contrast, Pure-SAs do not have a global data bus, and memory data enters the array through a single
PE and is propagated to other PEs every clock cycle until the last PE receives the data. A visual representation of this advantage can be seen in Figure 2.3. Figure 2.3(a) shows how a single PE would have to access memory for every iteration, while Figure 2.3(b) demonstrates how the data from memory can be propagated to every node instead of generating a memory access every time.

Since there was no widely accepted formal definition of Systolic Arrays, it was considered by Moreno and Lang to be a network of processing elements (PEs) with some basic characteristics [5]:

- A linear or two-dimensional structure, comprised of nodes with up to four ports connected with neighbors;
- External communication with Host is only possible from boundaries of the array;
- Communication between cells is uni-directional;
- No capability for broadcasting through cells without delay.

However, most of those characteristics have been modified. Currently it is possible to find PEs with more than four inputs arranged in a three-dimensional structure. To save resources, a uni-directional communication approach is not very attractive; a single PE’s output can be fed back for reprocessing at expense of throughput while using less resources.

![Fig. 2.3: Comparison between a single PE and multiple PE in a systolic array structure.](image)
Broadcasting can be of great benefit if the output data is needed by cells at the beginning of the processing pipeline without additional delay. The integral image architecture proposed in this thesis implements almost all these features, previously considered to violate the definition of a SA, in order to achieve a nearly linear speed-up as a function of the number of PEs used in the structure. Details on the characteristics of the proposed SA will be presented in Chapter 4.

Memory inside PEs is another important topic; a typical systolic processing element has no internal storage besides registers used to save input operands. Data flows through the PEs on every clock cycle without saving any intermediate or previous results. Although some applications require a storage element inside the nodes to save inter-node bandwidth, usually the storage size is small and independent of the type of problem addressed by the SA. This option becomes very handy when executing multiple operations with the input data and stored data on a single clock cycle instead of having to require multiple inputs. Sometimes cells have large storage elements; this helps further reduce the bandwidth between cells, reduce the number of PEs required, or increase the number of operations per clock that a PE can execute by reusing data.

The type of PE is not the only variable when designing a Systolic Array; there are also different topologies that can be implemented depending on the particular application. Figure 2.4 has some of the possible topologies for SAs: rectangular, triangular, and linear.

The basic assumption with an SA is that data flows synchronously across the structure. Each node is assumed to use its inputs and storage to generate an output and store the result if needed in the future. However, in some cases the outputs are not generated on every time step, making the design a pseudo-SA. In the implementation described in this thesis, the PE has a significant amount of storage to reduce the number of nodes, allowing for a simplified structure (one-dimensional) with the same throughput as a more complex two-dimensional implementation. It has to be mentioned that the storage size is independent of the number of PEs instantiated in the design. This is because the total storage required to hold an image row is distributed equivalently between nodes.
Fig. 2.4: Figure with different topologies for Systolic Arrays.
Chapter 3
Integral Image

This chapter contains information related to integral image calculation and previous work in this area.

3.1 Integral Image Calculation

Integral image representation of a gray-scale image allows for the sum of pixels inside a region delimited by a rectangle with corners A, B, C, and D to be computed in constant time, regardless of the size of the rectangle. Calculating the sum in constant time provides for a noticeable speed-up when running box filters and calculating features. This is mainly due to their dependence on the sum of pixel values underneath the variable size filter window while it is displaced across the image. Each pixel in an integral image representation contains the sum of all gray-scale pixels above and to the left as described by equation (3.1), making the computation time dependent on the number of pixels in the image.

\[
I_{\Sigma}(x, y) = \sum_{i=0}^{i \leq x} \sum_{j=0}^{j \leq y} I(i, j) \tag{3.1}
\]

Integral image representation only has to be calculated once and can be used many times afterwards, this is of great advantage for algorithms requiring multiple computations on the same image. Having the integral image representation available makes obtaining the sum under a region of interest a process that only involves three arithmetic operations and four data loads. Consider Figure 3.1 to be the integral image representation of an image \( I \), and A, B, C, and D the corners of a rectangle marking the boundary of the region of interest, then the sum under the rectangle is calculated with \( SUM = D - B - C + A \) in constant time.
Extra attention has to be paid to the address of the four rectangle corners required for calculation. This affects the final result of the pixel sum. Corner A is placed at \((A_x - 1, A_y - 1)\), B at \((B_x, B_y - 1)\), C at \((C_x - 1, C_y)\), and D stays at \((D_x, D_y)\) without any further adjustment. All corners are located with respect to the origin \(O\) positioned at the top left corner of the image, which is taken as the \((0,0)\) coordinate.

Calculating the integral image has a heavy data dependency on previous results. Each integral pixel calculated requires previous results to be available, making the time required to complete this process depend linearly on the number of pixels in the original image. Assuming that \(P = (x, y)\) is a pixel on the original image, \(A\) is the accumulate of pixel in the current row, and \(R = (x, y)\) is a pixel of the resulting integral image. To compute \(R\) at \((x,y)\), the result depends on the previous \(R\) value above, the value \(A\), and current \(P\) value.

\[
R(x, y) = R(x, y - 1) + A + P(x, y)
\]  

(3.2)

Obtaining substantial parallelization at the integral image generation stage will allow subsequent stages to also be parallelized and obtain greater overall speed-up. Several
approaches have been studied to efficiently make the integral image calculation parallel, circumventing the data dependencies present in the purely sequential method.

3.2 Previous Work

The concept behind integral images is considered to be born with the work presented by Crow [6] where the use of pre-calculated intensity tables was introduced. The tables contained the sum of all the pixel intensities from any location on the table to the bottom left corner, which was considered as the origin. Having this kind of table allowed for the average of intensities to be found in constant time, regardless of size of the rectangle of interest. This was specifically applied to make computational cost of texture-maps independent of the texture density and to reduce computation cost.

The term integral image was not introduced until Viola and Jones [2] started using an image representation that they applied to rapid object detection using boosted cascades of simple features. Integral images allowed for Haar features to be evaluated faster and in constant time. They achieved a speed-up of approximately 15 times compared to other approaches by using gray-scale images and the integral image representation.

Many attempts have been made to optimize the performance of integral image computation across a broad repertoire of systems and platforms. Messom and Barczak [7], motivated by the importance of integral images and its use on many image processing algorithms, took advantage of the stream processing capabilities of GPUs (Graphics Processing Units) to improve its performance. The large number of processors on a GPU, compared with the number of processors on a CPU (Central Processing Unit), was exploited to gain a substantial increase in performance. Stream processing refers to the use of many processors in a parallel implementation, where all of them work on a common task. This was used to run a multi-pass prefix sum algorithm on all pixels in an image. The goal was to divide the task into smaller tasks to reduce the total execution time of $N \log_2 N$, where $N$ is the number of data elements to process and $\log_2$ is the number of passes required. By using $P$ number of processors, this is effectively reduced to $\frac{N \log_2 N}{P}$, and achieving significant improvement compared to a serial approach running on a CPU.
A more recent publication by Bilgic et al. [8] also targeted GPUs as a platform for optimizing integral image computation. In this approach, the task of processing the integral image was also delegated to the large quantity of processors in the Graphics Processing Unit (GPU). The main idea behind this approach was to sum rows and columns independently. Rows were first added and then the transpose of the results was obtained to process columns using the same kernel. Images were divided into smaller blocks and distributed across thread blocks on the GPU. The use of single precision floating-point computation has also been evaluated, and achievements close to one order of magnitude improvement in speed are claimed with respect to a sequential approach with a four mega-pixel image as input.

Terraberry et al. [9] introduced a novel approach based on Blelloch’s [10] approach and extended it to compute multi-dimensional parallel prefix sums. The use of their novel two-dimensional implementation and better cache handling, resulted in a 3.6 to 5.5 times speed increase, and was used to accelerate SURF computation on GPU.

Other approaches focused on running the calculation on embedded systems with several optimization techniques. Kisacanin [11] applied recursion and double buffering to the sequential implementation of the integral image calculation running on an embedded system. The use of recursion allowed for the complexity of the algorithm to be reduced significantly, and by using double buffering, data can be pulled from memory in to the first buffer while the processor is working with data from the second buffer. Once the processing is done on that buffer, the process can switch to the first buffer and start filling the second one. A speed-up of five orders of magnitude is claimed using a 720 x 480 image size on a Texas Instrument embedded media processor using this approach.

Multi-core implementations of the integral image computation have also been addressed by several researchers. Zhang [12] studied the calculation of integral images in multi-core processors by using a two-pass approach. First, rows are summed, and on a second pass columns are summed in a parallel fashion, achieving double the speed of the best sequential implementation. It has to be noted that one of the key contributions of this work was the dependency of a chosen algorithm to the processor characteristics, e.g., bus speed, cache
effect, micro-architecture, and the topology of the processor.

Ehsan et al. [13] created a novel hardware algorithm capable of processing multiple integral image rows in parallel. The main goal of this method was to save resources while obtaining a significant increase in speed by starting multiple row processing in a cascaded fashion. In theory they are able to compute four integral image pixels every clock cycle, however, they had not yet implemented it in an FPGA at the moment of this publication. The results of using four simultaneous row processing on a 640 x 480 image can be completed in 76800 clock cycles instead of the 307200 clock cycles required for a sequential implementation. The concept of processing multiple rows simultaneously comes from the Viola-Jones recursive equations and can be better appreciated in Figure 3.2, which resembles the same idea as presented by Ehsan in his work. Colored pixel locations represent positions that can be computed in parallel once their dependencies are met.

Ehsan and McDonald-Maier also studied two word length reduction approaches for integral image calculation [14] and extended the exact method. The assumption is that 96% of all the pixels in a box filter have maximum value and 4% have half the maximum value, compared to the common assumption that all pixels take the maximum value possible (255). This allowed the word length of the integral pixel to be reduced to 21-bits without significant loss in accuracy compared with a full word length implementation. This could reduce the memory requirements on future implementations and allow for simpler hardware to be used. The same problem is addressed by Belt [15] who reduced the word length by involving computation through the overflow and rounding with error diffusion to enabled the algorithm to run on 16-bit processors without significant performance degradation. A more detailed publication by Belt [16] shows more information about the memory reduction.

![Fig. 3.2: Multi-row parallel integral image computation.](image-url)
he achieved.

A summary of all previous work is presented in Table 3.1 which includes the targeted platform, author, image size used, and the achieved speed-up.

Table 3.1: Summary of previous work on integral image acceleration across various platforms.

<table>
<thead>
<tr>
<th>Platform</th>
<th>Author</th>
<th>Approach</th>
<th>Image Size</th>
<th>Speed-Up</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPU</td>
<td>Messon</td>
<td>Multi-pass prefix sum</td>
<td>1024×2048</td>
<td>2×</td>
</tr>
<tr>
<td></td>
<td>Bilgic</td>
<td>Prefix sum on rows, transpose, and prefix sum columns</td>
<td>2048×2048</td>
<td>9×</td>
</tr>
<tr>
<td></td>
<td>Terriberry</td>
<td>Multi-dimensional parallel prefix sum</td>
<td>1280×1024</td>
<td>4.63×</td>
</tr>
<tr>
<td>DSP</td>
<td>Kisacanin</td>
<td>Recursion and double buffering</td>
<td>720×480</td>
<td>63,333×</td>
</tr>
<tr>
<td>CMP</td>
<td>Zhang</td>
<td>Two pass: rows summed first, then cols</td>
<td>900×600</td>
<td>2.12×</td>
</tr>
<tr>
<td>FPGA</td>
<td>Ehsan</td>
<td>Multiple rows in parallel</td>
<td>640×480</td>
<td>4×</td>
</tr>
</tbody>
</table>
Chapter 4
Implementation

The proposed accelerator architecture is designed to target Field Programmable Gate Arrays (FPGAs) or an Application Specific Integrated Circuit (ASIC). The concept behind the architecture was inspired by the effectiveness of Systolic Arrays and how they are able to process large quantities of data synchronously every clock cycle. To ensure an optimal use of memory accesses, it was chosen to process data coming from memory in row major order, which is the way images are commonly stored, therefore requiring no additional memory manipulation. The original design was based on a two-dimensional triangular Systolic Array approach, and was later optimized to just require a one-dimensional structure. The final architecture is structured as a linear Systolic Array that obtains the same speed-up and reduces on-chip resources previously required for a two-dimensional implementation.

The goal of this accelerator is to produce multiple integral pixel results on the edge of every clock cycle if valid data is available to process. An increased throughput on the integral image stage, compared to the na"ıve or sequential implementation, allows for subsequent stages that depend on the integral image results to also execute in parallel if designed with that purpose in mind. More information on both approaches (two-dimensional and one-dimensional), and details on the processing nodes are presented throughout this chapter.

4.1 Sequential Implementation

The most common approach to compute integral image is the sequential approach; it can be found on many applications that require feature evaluation and filtering. The sequential approach is a simpler architecture and can be coded in a shorter time compared to a parallel approach. However, computing the integral image using the sequential approach brings the disadvantage that it is only capable of producing one integral pixel every clock
cycle. If utilized on low speed video feeds or only used on sets of small images, then the pure sequential implementation will suffice to supply the required throughput. For applications that demand real-time execution this might not be enough, therefore requiring other approaches like the one proposed in this thesis. Understanding this architecture will help to understand the parallel architecture proposed in this thesis.

The architecture of the sequential approach can appreciated in Figure 4.1. The input of the system is a single gray-scale pixel every clock cycle, which by definition is an 8-bit number representing a range of intensities from 0-255. The block diagram describes the operation and the flow of control and data signals used to produce an integral pixel every clock cycle. The main components are: the integral image controller (IIC_Controller), previous row of integral image pixels (prev_row), accumulator of gray-scale pixels on current row (Acc), and two adders. The output is a single integral pixel, represented by a 32-bit number, available every clock cycle assuming that input data is also available on every clock.

The main element is the controller, which keeps track of the original image size, synchronization of signals and provides control signals to the rest of the system in the form of last row (last_row) and last column (last_col) signals. As their names suggest, the former becomes high when the last row of the original image is being processed and the latter when the last column is reached. Both control signals in a high state indicate the end of the image and that the integral image calculation is complete.

Input gray-scale pixel is summed with the content of an accumulator and is then added with the integral pixel located above the current one to produce the integral pixel result. The result from the first adder is further stored in the accumulator to be used on subsequent cycles and the result from the second adder is used as a replacement for the previous row pixel at the current index. Therefore, indexing the previous row provides the integral pixel to be added and at the same time serves to store the result of given addition.

Control signals interact with the rest of the modules by resetting the accumulator once the last column flag is set and the previous row array starts filling positions with zeros instead of saving the integral pixel result when the last row flag is set high. Clearing the
previous row to zero sets the conditions for the next image to start processing without delays. It has to be noted that input pixels have to feed in row major order as stored in memory, one row at a time going through all columns before passing to the next row.

4.2 Two-dimensional Systolic Array Accelerator

The first approach towards a parallel implementation of an integral image accelerator was inspired by two-dimensional Systolic Arrays. A common SA structure is the rectangular one, however for our purposes, the triangular one proved to be more appropriate based on the way data has to flow and the operations involved in the computation of integral images.

With some analysis of the data and the way systolic arrays synchronously process data, a two-dimensional implementation was designed. The architecture, as shown in Figure 4.2, has two types of processing elements or nodes. The edge node is always the leftmost node in the structure and only passes its results to the node on the right. The other type of node is a regular Processing Element which takes an input from the top and the left, passing results to the node on its right, and propagating the unaltered input to the one beneath. By using a triangular structure, it is assured that memory is distributed across all nodes and a node is only entitled to store a single previous integral pixel result before handing it
to its neighbors.

The sample image in Figure 4.2 is 4 x 4 pixels and is assumed to have pixel values from 1 - 16 for demonstration purposes only. It is appreciated how the data is placed on the inputs at the top with a skew-like organization to ensure consistency and timing. Observe that the inputs are to be placed in reverse order for the system to produce the correct results. Outputs are also out of order; rows are actually the columns of the output integral image representation, where the first element out of each row forms the first row of the result, the second of each row belong to the second row and so on. Reorganizing the output data is required to maintain addressing consistency along stages.

Data to the Systolic Array has to be provided in a synchronized manner to ensure that data reaches the correct nodes at the right time to produce the correct result. Therefore, data has to be skewed before passing it to the inputs of the Systolic Array. Skewing has to be done in such a way that the first node to the left receives data first, and in the next clock cycle its result has to reach the next node simultaneously with the corresponding input to be processed together. The same propagation behavior happens along the complete structure.

4.3 One-dimensional Systolic Array Accelerator

After having designed the two-dimensional SA accelerator concept and simulated different sizes of images, it was noticed that the same processing could be achieved with a fraction of the resources previously used. This was achieved with the use of a one-dimensional systolic array approach capable of providing the same results with a \( \frac{L+1}{2} \% \) reduction in the number of nodes required. Instead of using \( \frac{L^2+L}{2} \) processing elements or nodes in the two-dimensional architecture, it can be reduced to just \( L \) nodes (where \( L \) is the length of the SAII accelerator). The reduction of nodes does not reduce the amount of inner memory required by the system, therefore the resource savings are not linear with the number of nodes eliminated. Memory actually depends on the width of the image to be processed, this is because the previous row of integral results needs to be kept available to process the rest of the image regardless of the number of PEs.

A representation of the one-dimensional SA implementation is shown in Figure 4.3. It
can be seen that inputs to the system are the same if compared with the two-dimensional implementation. In this approach, the Most Significant Bit (MSB) is always to the left.

However, using this structure the results are only correct in three cases: (i) when only one Processing Element is used, (ii) when two PEs are used, and (iii) when the width of the accelerator equals the image width. Since we want a fully scalable system that can have any number of nodes as required, some improvements were implemented to be able to instantiate any number of nodes without compromising the results.

Figure 4.4 provides an example of how the computation was affected by the number of nodes in the accelerator. The example has a 6 x 6 input image and is processed by an accelerator with three PEs splitting a single row of the original image into two pieces of the same size as the accelerator. Both the original sample image and the correct result are shown on the right, labeled accordingly to identify them. On the expected integral image result, the numbers in bold represent the pixels with unresolved issues that require additional processing. Each emphasized number on the expected result matrix has its corresponding
erroneous value marked on the output of the nodes. For example, \{10, 15, 21\} are the expected values; however, \{4, 9, 15\} are the actual values produced by the nodes. The same happens with the sets \{44, 60, 78\} and \{14, 30, 48\}. The second set needs to be normalized with an offset of 30 and the first with 6. A trend was observed on the erroneous stream of data produced, and it was noticed that erroneous sets were missing an offset value that happens in the future. In the case of 4, 9, and 15, they all require the rightmost value from the previous result row (6) to produce the correct set \(4 + 6 = 10\), \(9 + 6 = 15\), and \(15 + 10 = 21\). On the same figure, offsets have been identified with a bounding box; this allows us to compare the time when this value is produced and the time step when it is needed.

The offset value at the rightmost position of the output vector is separated from \(T_0\) by \(N - 1\) clock cycles, where \(T_0\) is the time step when the value is expected to be available and \(N\) is the number of PEs in the accelerator. To compensate for this problem, an extra stage was added before outputs from the accelerator are final. Data coming out of the PEs requires additional processing (DeSkew) such that data comes out aligned instead of
Fig. 4.4: Incorrect results when number of PEs $\notin \{1, 2, \text{image width} \}$.

having a diagonal arrangement of data. When output data is aligned, the offset required to normalize the current vector of results is only one clock cycle away, making this the optimum point to correct the values produced before. The correction is achieved with a simple array of 32-bit adders (one for each PE lane of results) and a single 32-bit accumulator to store the previous row rightmost value. The only exception to this correction is when the current vector of data is the first set of data of an integral row, as is shown in Figure 4.4; the first elements of every row have the expected values and require no adjustment. It is not shown, however, that exercising the node equations will demonstrate that the first set is always correct regardless of the width of the accelerator. To account for this, the array of adders at the end of the process will skip the beginning of every row of results to maintain the consistency.

PEs are ruled by two different sets of equations listed in Table 4.1, which define the results for each type of node in the accelerator.

As was mentioned before, the number of nodes can be adjusted to control the amount
Table 4.1: Set of equations for SAII accelerator PE nodes.

<table>
<thead>
<tr>
<th>Node Type</th>
<th>Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master Node</td>
<td>Output = Inner_mem(Index) + Input</td>
</tr>
<tr>
<td></td>
<td>Inner_mem(Index) = Inner_mem(Index) + Input</td>
</tr>
<tr>
<td></td>
<td>Feed_Out = Inner_mem(Index) + Input</td>
</tr>
<tr>
<td>Helper Node</td>
<td>Output = Inner_mem(Index) Feed_In + Input</td>
</tr>
<tr>
<td></td>
<td>Inner_mem(Index) = Inner_mem(Index) + Input</td>
</tr>
<tr>
<td></td>
<td>Feed_Out = Inner_mem(Index) Feed_In + Input</td>
</tr>
</tbody>
</table>

of resources dedicated to the accelerator, but the amount of memory required is constant for the same size of the input image. equation (4.1) gives the amount of memory required per node in the SA. More nodes in the system means that the inner memory will be smaller for each node. The total memory depends on the input image width as described by equation (4.2), where requirement is given in bytes assuming a 32-bit integral image result. Attempts to reduce memory requirements exist [14, 16], and could bring this requirement down by having a shorter integral pixel word length.

\[
\text{Node\_memory\_size} = \frac{\text{Image\_width}}{\text{Number\_of\_PE}} \times 4\text{bytes} \quad (4.1)
\]

\[
\text{Total\_memory\_size} = \text{Image\_width} \times 4\text{bytes} \quad (4.2)
\]

With the proposed adjustments, the correct output is produced at all times at the cost of an extra clock cycle without depending on the number of nodes in the SA structure. In the next section the linear Systolic Array Integral Image (SAII) architecture is detailed as a whole, including the control signals that arbitrate the computation of the integral image, ensuring the correct results are produced.

4.4 Integral Image Accelerator Architecture

Having a working Systolic Array architecture correctly processing data individually was the first step; now it needs to be integrated into a system that a user would use and interact with. The proposed core system will be in charge of arranging the input data, arbitrating
PE nodes, preparing results to be presented on the outputs, and adjusting results to obtain the desired results. Having this level of abstraction is important to produce an efficient interface for end users of this type of module. The simplified block diagram for the final architecture is presented in Figure 4.5, where the different components can be appreciated.

The proposed architecture is composed of (i) a Skew block, where the input data is arranged in the correct order for the PEs to process the data synchronously; (ii) a Master Node; (iii) \( N - 1 \) Helper Nodes, where \( N \) is the number of nodes in the accelerator; and (iv) a DeSkew block, which has to ensure that data produced by the nodes arrives to the output in the correct order and also has to perform an offset adjustment before presenting the results to the output of the accelerator.

Each component of the final architecture will be detailed separately in subsequent sections of this chapter, including the controller which is not shown in the main block diagram.

### 4.4.1 Skew - Data Preparation

Prior to any computation, it is of great importance that input data needing to be processed arrives in the correct order to the processing nodes. This will ensure a synchronous and correct operation. If input data was to arrive with wrong timing, the result would not be reliable and subsequent results would also be affected.

To ensure that data is always delivered to the PEs synchronously, a Skew module was designed to properly arrange input data without having the host system worry about input data ordering to use this integral image accelerator. Input data vector contains multiple gray-scale pixel values; each of them needs to be delayed differently such that when the rightmost pixel is processed by its corresponding processing node, the result of all previous pixels are already available for it to use. A graphical representation of this skewed delay method can be appreciated in Figure 4.6. Input data, as labeled in the aforementioned figure, can have \( N \) pixels, and each one is placed in a delay lane with increasing length up to \( N - 1 \). The leftmost pixel is passed to the Master Node without further delay to start the processing sequence. The rest of the pixels will arrive at their corresponding processing
node in subsequent clock cycles, one at a time, in a left to right ordering scheme.

Delay lanes were implemented using Shift Registers (SR) with different lengths and operating under a common clock. The leftmost pixel is not placed in a delay lane, instead it is directly transmitted to the Master Node. This makes the total number of shift registers required \( N - 1 \) where \( N \) is the number of nodes in the accelerator. Length of each shift register is the lane number minus one, leaving the rightmost lane to be also \( N - 1 \) in length. The amount of resources dedicated for shift registers increases when more nodes are added to the architecture; this is because having more nodes means more and longer SRs.

### 4.4.2 Master Node

In the proposed accelerator, it is mandatory to have a single master node regardless of the width of the accelerator. Since a Master Node is only required once, it has a different behavior compared with the rest of the processing nodes. It must be noted that Master Nodes do not have any inputs from other PEs, making the outputs purely dependent on current input values and previous results stored in their inner memory. A block of memory is necessary for all nodes to remember the previous row of results in order to produce subsequent results as described in the integral image equation (3.2). The amount of memory

---

**Fig. 4.5:** Proposed integral image accelerator structure.
required is $\frac{\text{Imagewidth}}{\text{NumberOfNodes}}$ and it only holds results generated by itself. Let's assume that the input image has a width of 24 pixels and the accelerator has four processing nodes; this leaves every node holding $\frac{24}{4} = 6$ integral pixels. With a memory size of six integral pixels (32-bits), the Master Node would hold integral pixel results at positions 1, 5, 9, 13, 17, 21.

The behavior of this node is described by the set of equations (4.3), (4.4), and (4.5).

\[
\text{Output} = \text{Inner\_mem}(\text{Index}) + \text{Input} \quad (4.3)
\]

\[
\text{Inner\_mem}(\text{Index}) = \text{Inner\_mem}(\text{Index}) + \text{Input} \quad (4.4)
\]

\[
\text{Feed\_Out} = \text{Inner\_mem}(\text{Index}) + \text{Input} \quad (4.5)
\]

A visual representation of a Master Node is given in Figure 4.7, where all interface ports and basic inner component representations can be appreciated for a better understanding of the implementation. The node has the typical clk, rst, and ce signals to maintain synchronization with the rest of the system. Besides that, it has an 8-bit input port and a done flag, which tells the Node to clear its memory and outputs in preparation for a new image frame.

Fig. 4.6: Skew module inner diagram.
once the current image has finished processing. On the outputs, it has a 32-bit output and feed out signals, along with a single valid bit that indicates when a valid value is produced by the node. The abstract representation includes some components that help visualize the operations the node undertakes. It has two 32-bit adders and a 32-bit memory block holding previous results as mentioned before. The multiplexer activated by the Done signal allows for the system to start filling the SA with zeros to avoid perturbing the calculations in other nodes.

The naming of both types of nodes comes from the first stages of the design when the Master Node had additional logic that made it more complex. Names stayed unaltered when the Master Node was simplified and the data offset adjustment was moved to a posterior stage of the processing pipeline. The change was due to an inconsistency and incapacity of the system to compute the integral image with accelerator sizes other than 1, 2, and N.
4.4.3 Helper Node

The accelerator is composed of two types of processing nodes. Since only one Master Node is allowed in the proposed design, the rest of the processing power is provided by multiple Helper Nodes. There can be any number of Helper Nodes in the design to expand the accelerator, the only constraint is that there must always be a total number of PEs that exactly divide the width of the image.

A Helper Node is ruled by a different set of equations than the Master Node because of its additional input from neighbor nodes. The set of equations (4.6), (4.7), and (4.8) describe how the outputs and inputs interact to generate the pre-integral pixels. Just as a reminder to the reader, the output from the PEs need further offset adjustment before representing the actual integral image.

\[
\text{Output} = \text{Inner\_mem}(\text{Index}) \times \text{Feed\_In} + \text{Input} \quad (4.6)
\]

\[
\text{Inner\_mem}(\text{Index}) = \text{Inner\_mem}(\text{Index}) + \text{Input} \quad (4.7)
\]

\[
\text{Feed\_Out} = \text{Inner\_mem}(\text{Index}) \times \text{Feed\_In} + \text{Input} \quad (4.8)
\]

By observing Figure 4.8, the reader could be under the impression that a Helper Node takes less resources than a Master Node, but is actually the opposite, as it has more inputs to process. Having an additional input automatically instantiates a three input 32-bit adder instead of a two input one like in the case of a Master Node. The rest of the components are considered to be the same, including the inner memory block, which is the same size on all nodes of an accelerator.

4.4.4 DeSkew - Data Normalization

This module does the opposite of the Skew; it removes the skewed look of the data coming out of the nodes. It also has the task of adjusting the offset of the data going out
of the accelerator. The operation is split in two phases; the one that will ensure that the output of each PE is placed in its corresponding delay lane. The other, which is the offset adjustment, was accomplished with aid of an array of adders and a 32-bit accumulator which stores the previous rightmost output for subsequent additions. Figure 4.9 tries to throw more light on this, to help us understand the final adjustment and the correctly ordered results.

The reordering of results is achieved in the same manner as the input data was prepared for the nodes to process with help of a different length shift register in each lane to serve as a controlled delay. Shift registers are ordered in decrementing length from left to right, and the rightmost has no delay at all. After the values have been restored to proper order, the data is handed to an offset adjustment module that will add the missing offset to each set of data. Offset is taken from the rightmost value of each data set generated by the DeSkew stage and stored in a local register to use on the next iteration. The local register has a storage capacity of 32-bits, assuming that the integral pixel is that size, but it can be reduced if a word length reduction method is used on the integral pixel.
Offset adjustments consist of adding the local register value to all the elements in the output data set and refreshing the value of the register with the most recent result produced. The operation is applied to all outputs with the exception of the first element of each image row which does not need adjustment. Arbitration of the outputs that require adjustment is managed by the controller who emits a bypass signal indicating that the current data requires no further adjustment. The system skips the addition when it sees the bypass flag; however, it does refresh the local register value for future use.

4.4.5 Controller

This is the module that carries the burden of synchronizing the accelerator by using a set of control signals at the appropriate time. The easiest way to explain this controller is to show the Finite State Machine (FSM) diagrams involved in the system behavior. The FSM diagram is presented in Figure 4.10, where all states and their transition conditions are displayed along with the state of control signals.

There is also the requirement to control the offset adjustment module to skip the addition of the register value to the first set of data of each integral image row. The FSM that generates the global bypass signal, as it is called, is described in Figure 4.11.

4.5 Software Simulation

Verification of the design was first completed using a software simulator, and once it was confirmed that all parts of the design worked as expected, the design was implemented on a Virtex 6 device to ensure actual hardware acceleration beyond software simulations.

The simulation software used for verification was GHDL, which is an open source tool developed and maintained by Tristan Gingold [17]. This tool is perfectly capable of simulating complex designs in VHDL language, even if Xilinx Libraries and Primitives are used in the design. However, advanced knowledge and skills are required to setup and use the mentioned libraries due to the fact that it is an open source and Xilinx libraries are proprietary. The SAI accelerator proposed in this thesis makes use of some generated cores.
Fig. 4.9: DeSkew module inner diagram.

by the CoreGen tool provided by Xilinx with their development suite and is important that
the simulator handles them accordingly.

Every module was designed and tested independently until each behaved according to
design specifications and requirements for the accelerator. More detailed information is
provided for the top module simulation, which covers the overall behavior of the system
after all submodules are interconnected. Top module interface is represented by the block
diagram in Figure 4.12, where basic inputs clk, rst, and ce are present, along with the more
specialized inputs and outputs required for the task. Inputs to the top-level module include
the input data as a vector of bits, configuration inputs (image width, image height), and
the usual clock/reset/enable signals; outputs are the integral image data also as a vector of
bits, a valid flag, and a done signal.

For software simulation, input data was fed to the accelerator from a file containing
pixel values from a real gray-scale image. The size of the image and the number of nodes
were manipulated to explore a broad spectrum of possible scenarios and results. Results
produced by the accelerator were written to a file for further comparison with the expected
result.

To generate stimulus data for the accelerator and to read the results and compare them with the expected correct result, a C++ program was created to help with those tasks. The parameters required by the program are: (i) input image file to use as a stimulus to the accelerator, (ii) the width, (iii) height of the final image data, (iv) the number of nodes that will be used to process the data, and (v) the mode (create COE, generate stimulus, or verification data). COE is a format used by Xilinx to initialize blocks of memory; that way the image can be pre-stored in memory blocks before the device is programmed instead of having to download it after. This is of importance to the hardware simulation, as it will be demonstrated in the next section. For software simulation we are just interested in the last two modes, stimulus generation and the verification data. The original image can be of any size; the code will resize it to the size provided on the parameters and work with that size instead. Stimulus data is generated as a bit-set; a sample is shown in Figure 4.13 where a section of a gray-scale image is shown, along with the pixel values and the corresponding stimulus generated from that data, as if they were generated for a two-node accelerator.

GHDL simulation will produce an output file with the same structure as the input stimulus. The verification data from the C++ program has the same structure, therefore

<table>
<thead>
<tr>
<th>STATE</th>
<th>SIGNALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Done : 0</td>
</tr>
<tr>
<td></td>
<td>Bypass : 0</td>
</tr>
<tr>
<td></td>
<td>Count : Count + 1</td>
</tr>
<tr>
<td></td>
<td>Bypassed : 0</td>
</tr>
<tr>
<td>B</td>
<td>Done : 0</td>
</tr>
<tr>
<td></td>
<td>Bypass : 1</td>
</tr>
<tr>
<td></td>
<td>Count : 1</td>
</tr>
<tr>
<td></td>
<td>Bypassed + 1</td>
</tr>
<tr>
<td>C</td>
<td>Done : 1</td>
</tr>
<tr>
<td></td>
<td>Bypass : 1</td>
</tr>
<tr>
<td></td>
<td>Count : 0</td>
</tr>
<tr>
<td></td>
<td>Bypassed : 0</td>
</tr>
<tr>
<td></td>
<td>Overhead : 0</td>
</tr>
</tbody>
</table>

If Overhead < num nodes then
Overhead = Overhead + 1
Valid = 0
Else
Valid = 1
End if

Fig. 4.10: Main FSM for SAI controller module.
both can be compared at a binary level. For this, it was chosen to use the Linux Diff tool, passing the results and the golden verification data for comparison to ensure both were exactly the same in every simulation scenario. GHDL produces a waveform file that can be viewed with Gtkwave to obtain more details of signal transitions and the flow of data every clock cycle. The total number of clock cycles it takes to complete the processing of an input gray-scale image is extracted from the number of lines in the output file created by the simulation. Since the accelerator produces a line every clock cycle (also confirmed on waveform), we can use this information with confidence as long as the binary representation matches the golden verification data produced by the C++ program.

### 4.6 Hardware Simulation

Once the design is verified with help of software tools (GHDL and a self-created C++ program in our case), the design is taken to the hardware realm for the final verification and actual operation of the SAI accelerator under real world conditions.

The proposed SAI accelerator was deployed to an ML605 Development board with a Virtex 6 XC6VLX240T. The board and device were chosen because of their flexibility and abundant resources, in case they were needed for testing and verification purposes. Since the hardware verification could not take place by reading from stimulus files as it was done in the software simulation, the input and output files had to be replaced by blocks of memory.
Fig. 4.12: Block diagram of top model along with stimulus file read and write results.

Fig. 4.13: Gray-scale portion of an image along with its pixel values and stimulus representation in bit-set form.

instantiated using BRAMS in the FPGA as shown in Figure 4.14. Additional memory addressing modules were added to control the loads and stores to outer memory blocks containing the original image and to store the results. Since the focus of this thesis is a novel integral image accelerator, memory interfaces are not of interest and are not discussed in this document. Due to the lack of an interface to fill memory with the original image from outside the FPGA, it was chosen to have memory pre-initialized with the image data before programming the device. Our C++ program has the ability to take the original image file on the host computer and produce a COE compliant file that serves as initialization data.
for the block of memory generated with Xilinx CoreGen.

The results from the accelerator are stored in an output memory block comprised of multiple BRAMs. However, reading that output memory is not possible without additional interface to the host computer. Therefore, Chipscope was used instead to monitor the output of the accelerator and other critical signals that reflect the status of the accelerator. Chipscope is a tool similar to common logic analyzers; however, it currently has a key benefit of being able to debug signals that have no physical connection. Since Chipscope is a module sitting in the inside of the FPGA, it can capture signals that otherwise would be impossible to reach from outside the chip.

Information captured by Chipscope is of great value when looking for timing issues and verifying correct execution of the inner modules of the design. Data can be represented in many formats and plotted in waveform style for a more efficient inspection and better readability.

![Fig. 4.14: Hardware simulation flow showing input and output memory along with ChipScope capturing results.](image-url)
Chapter 5

Results

This chapter presents the results of the proposed Systolic Array Integral Image (SAII) accelerator and comparisons with the purely sequential approach as described in Chapter 3. Based on the fact that the parallel approach by Ehsan et al. [13] to accelerate integral image computation as described in their publication was not implemented in hardware, it can not be compared beyond the number of clock cycles required to complete the calculation. The proposed design is instead compared with the sequential approach running on the same FPGA device as the proposed SAII accelerator. Comparison between approaches considers the number of clock cycles required to process the input image and the maximum frequency achieved by each design after Place and Route (PAR). From those two values, the processing speed is estimated. This is because the purely sequential approach has a different clock frequency than the proposed design due to differences in the design complexity. The difference in clock frequency across implementations affects the outcome of the comparison.

The proposed design will only be compared with the sequential approach as they are the only implementations that share a common target platform (FPGA). However, fps can be easily calculated using the equations provided in this chapter to compare with other platforms. The proposed accelerator was not compared with other target platforms besides FPGAs because of their differences in footprint, power consumption, and other factors that defeat the purpose of having an embedded image processing solution.

The SAII accelerator was implemented in VHDL and synthesized using Xilinx ISE 12.1. The specific target platform for comparisons is a Virtex 6 LX240T FPGA.

5.1 Execution Time

Verification of the design took place with different image sizes (1280x960, 640x480,
320x240, 160x120, 80x60, and 40x30 pixels) and a subset of all the possible number of PEs that the SAI accelerator can have (2, 4, 8, 16, 32 nodes). Various combinations of these parameters were made to analyze the performance of the proposed integral image accelerator under several scenarios. It is already known from Chapter 4 that the purely sequential implementation of an integral image architecture is capable of processing a single gray-scale pixel every clock cycle. Therefore, the total execution time in clock cycles can be calculated with \((ImageWidth) \times (ImageHeight)\) for the sequential implementation. Conversion from total clock cycles to execution time was required to fairly compare the sequential approach and the different sizes of the proposed design (differences exist in the maximum frequency achievable by each approach). Execution times for the sequential and the proposed SAI accelerator architecture are listed in Table 5.1 for comparison purposes. It can be seen that execution time (in microseconds) of the proposed design is lower on all test cases and for all sizes of the SAI accelerator being the difference more pronounced at larger number of PEs as expected.

### 5.2 Speed-Up

Based on the execution time previously presented, speed-up of the proposed accelerator compared with the sequential approach under different scenarios is shown in Figure 5.1. Speed-up is obtained by using the execution time of the sequential implementation as reference. Results not plotted correspond to test scenarios where the input image width

<table>
<thead>
<tr>
<th>Approach \ Image Size</th>
<th>1280x960</th>
<th>640x480</th>
<th>320x240</th>
<th>160x120</th>
<th>80x60</th>
<th>40x30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequential_CPU</td>
<td>15361</td>
<td>4570</td>
<td>1652</td>
<td>239</td>
<td>117</td>
<td>49</td>
</tr>
<tr>
<td>Sequential_FPGA</td>
<td>8610.167</td>
<td>2152.542</td>
<td>538.135</td>
<td>134.534</td>
<td>33.633</td>
<td>8.408</td>
</tr>
<tr>
<td>2 PEs</td>
<td>4331.554</td>
<td>1082.915</td>
<td>270.755</td>
<td>67.715</td>
<td>16.955</td>
<td>4.265</td>
</tr>
<tr>
<td>4 PEs</td>
<td>2132.345</td>
<td>533.123</td>
<td>133.317</td>
<td>33.366</td>
<td>8.378</td>
<td>2.131</td>
</tr>
<tr>
<td>8 PEs</td>
<td>1066.225</td>
<td>266.613</td>
<td>66.711</td>
<td>16.735</td>
<td>4.241</td>
<td>1.118</td>
</tr>
<tr>
<td>16 PEs</td>
<td>533.206</td>
<td>133.400</td>
<td>33.449</td>
<td>8.461</td>
<td>2.214</td>
<td>NA</td>
</tr>
<tr>
<td>32 PEs</td>
<td>266.780</td>
<td>66.877</td>
<td>16.902</td>
<td>4.408</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
was not exactly divisible by the number of nodes in the accelerator.

Figure 5.1 includes a range of image sizes used for the design verification where each integral image was calculated with different numbers of processing elements in the SAII accelerator. It can be appreciated that by using the SAII approach, an average speedup between 1.987 - 32.27X is obtained, depending on the number of processing elements used (2 - 32, respectively). Under some conditions, the proposed accelerator achieves a speed-up greater than the number of PEs used because of the higher operational frequency it achieves over the sequential implementation.

The number of PEs can be increased to further demonstrate the speedup that can be obtained with the proposed accelerator; however, performance is susceptible to a constant overhead delay that depends on the number of PEs in the accelerator. Figure 5.2 shows how the measured overhead is constant for the same number of PEs across all image sizes. Overhead is dependent on the number of nodes in the accelerator, the time it takes to propagate input data from the first node to the last one, and the time it takes to produce the first valid data on the output.

Because of the aforementioned constant overhead for each accelerator size, performance drops when the image width gets closer in size to the overhead value. An example can be observed in Figure 5.3, where an 8 PE accelerator (with an overhead of 11 clock cycles) starts losing performance when the size of the input image starts decreasing, making itself more pronounced as the size approaches 40 x 30 pixels. Small images are frequently used in image processing when working with reduced regions of interest; therefore, it is important to achieve an acceptable speed-up across a wide range of image sizes, including smaller ones. Although performance shows a slight drop with smaller images, the speed-up is still several times higher than with the sequential implementation. Even compared with Ehsan’s approach, where a 4X speed-up is claimed prior to implementation in hardware, almost 8 times more speed-up than Ehsan’s approach is obtained by using the proposed SAII accelerator with 32 PEs when processing small images.
Fig. 5.1: Speed-up obtained by the proposed SAII accelerator compared to the pure sequential implementation.

5.3 Resources

Resource utilization was quantized for each SAII accelerator size and is presented in Table 5.2 for further analysis. Included in that table are the number of Look Up Tables (LUTs) and Flip Flops (FFs) used by sequential implementation, as well as different sizes of the proposed architecture. Additionally, the maximum frequency that each design can achieve was extracted from ISE to fairly compare both approaches. As the number of PEs in the proposed architecture increases, the number of FF also increases. LUT utilization has a different behavior; as the number of PEs increases, the number of LUTs used drops until it reaches eight nodes, then it increases afterwards. This behavior might be due to the effectiveness of PAR tools and the efficient filling of FPGA slices when using key accelerator sizes. The maximum frequency that each design can achieve shows that the proposed architecture is capable of achieving higher operational frequencies compared to the sequential approach on all accelerator sizes, except with two nodes.

To further understand the resource utilization of the proposed accelerator, every module
Fig. 5.2: Visible overhead on the output of the SAIL accelerator before first valid output.

Table 5.2: FPGA resources utilized by the sequential approach and the proposed SAIL with different number of PEs.

<table>
<thead>
<tr>
<th>Implementation</th>
<th>Resources</th>
<th>Sequential</th>
<th>2</th>
<th>4</th>
<th>8</th>
<th>16</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FFs</td>
<td>42047</td>
<td>41401</td>
<td>41710</td>
<td>42261</td>
<td>43397</td>
<td>45653</td>
</tr>
<tr>
<td></td>
<td>LUTs</td>
<td>34289</td>
<td>45573</td>
<td>41363</td>
<td>34201</td>
<td>39638</td>
<td>40783</td>
</tr>
<tr>
<td></td>
<td>Max. Freq. (Mhz)</td>
<td>142.715</td>
<td>141.844</td>
<td>144.07</td>
<td>144.07</td>
<td>144.07</td>
<td>144.07</td>
</tr>
</tbody>
</table>

was analyzed independently. It was observed in Table 5.2 that the LUT utilization was decreasing as the number of nodes increased. Having individual resource measurements allowed for trends to be extracted based on the number of PEs in the accelerator. Results are presented in Figure 5.4 for all major modules of the SAIL accelerator. From the obtained trends several facts can be deduced: (i) Since arithmetic inside both processing elements (PEs) is constant regardless of the size of the accelerator, the reduction of resources is only due to the reduction of inner storage as it becomes distributed across more nodes; (ii) The controller is completely independent of the accelerator size; (iii) Skew and DeSkew resources
5.4 Resource Estimation

Using the trend equations for each accelerator module presented in Figure 5.4, a resource estimation set of equation is presented. These equations can be used to estimate the maximum number of nodes that the SAIi accelerator can have when implemented on other FPGA devices with different number of resources than the device used for this implementation.

The derived equations are presented below:

\[
LUT_{req} = 55276.49N^{-0.99} + (N - 1)(30478.34N^{-0.94}) + 3.95N^{1.22} \\
+ 82.99N^{1.05} + 512.39 \ (LUTs),
\] (5.1)
Fig. 5.4: Detailed resource usage by individual modules in the SAII architecture.
\[ FF_{req} = 40970.19N^{-0.99} + (N - 1)(40809.12N^{-0.98}) + 3.95N^{1.22} \]
\[ + 64N^1 + 181 \ (FFs), \]  
(5.2)

\[ \text{NumberOfNodes}_{aprox} = \frac{LUT_{avail} - 55875.33}{10^{2.28}}, \]  
(5.3)

\[ \text{NumberOfNodes}_{aprox} = \frac{FF_{avail} - 41219.14}{10^{2.23}}. \]  
(5.4)

Using this estimation method, Table 5.3 is presented as an example of how the SAI\( \text{I}\) would look on different FPGA devices. The calculations were made under the assumption that all resources are devoted to the accelerator, which rarely will be the case in a real-world application. However, resources used for estimation can be the ones available for integral image purposes when other designs are also to be placed in the same device.

### 5.5 SAI\( \text{I}\) Accelerator Model

Based on results and design characteristics, a model of the proposed SAI\( \text{I}\) accelerator was extracted. Using the given set of equations, it is possible to extrapolate the design

<table>
<thead>
<tr>
<th>Device</th>
<th>FFs</th>
<th>Nodes</th>
<th>LUTs</th>
<th>Nodes</th>
<th>Estimated Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spartan 3 XC3S1600E</td>
<td>29,504</td>
<td>-69</td>
<td>29,504</td>
<td>-138</td>
<td>-138</td>
</tr>
<tr>
<td>Spartan 6 XC6SLX100</td>
<td>126,576</td>
<td>503</td>
<td>63,288</td>
<td>39</td>
<td>39</td>
</tr>
<tr>
<td>Spartan 6 XC6SLX150</td>
<td>184,304</td>
<td>843</td>
<td>92,152</td>
<td>190</td>
<td>190</td>
</tr>
<tr>
<td>Virtex 4 XC4VLX40</td>
<td>53,248</td>
<td>71</td>
<td>106,496</td>
<td>266</td>
<td>71</td>
</tr>
<tr>
<td>Virtex 4 XC4VLX200</td>
<td>178,176</td>
<td>806</td>
<td>356,352</td>
<td>1577</td>
<td>806</td>
</tr>
<tr>
<td>Virtex 6 XC6VLX130T</td>
<td>160,000</td>
<td>699</td>
<td>80,000</td>
<td>127</td>
<td>127</td>
</tr>
<tr>
<td>Virtex 6 XC6VLX240T</td>
<td>301,440</td>
<td>1532</td>
<td>150,720</td>
<td>498</td>
<td>498</td>
</tr>
<tr>
<td>Virtex 6 XC6VLX760</td>
<td>948,480</td>
<td>5342</td>
<td>474,240</td>
<td>2196</td>
<td>2196</td>
</tr>
<tr>
<td>Artix 7 XC7A105</td>
<td>129,600</td>
<td>520</td>
<td>64,800</td>
<td>47</td>
<td>47</td>
</tr>
<tr>
<td>Artix 7 XC7A335T</td>
<td>440,400</td>
<td>2351</td>
<td>220,200</td>
<td>862</td>
<td>862</td>
</tr>
</tbody>
</table>
to other devices that might have different resource counts, different clock frequencies, or just another performance requirement. \( \text{MaxFrequency}_{SAII} \) is the maximum frequency at which the accelerator can run on a particular device. \( \text{Overhead} \) is the number of clock cycles required until the first valid data is presented to the output. The rest of the parameters should have names clearly related to their meaning, and should not cause confusion.

\[
\text{Overhead} = \text{NumberOfNodes} + 3 \quad \text{(cycles)} \quad (5.5)
\]

\[
\text{Time}_{SAII} = \frac{\text{Cycles}_{\text{total}}}{\text{MaxFrequency}_{SAII}} \quad \text{(seconds)} \quad (5.6)
\]

\[
\text{Cycles}_{\text{total}} = \text{Overhead} + \left[ \frac{\text{ImageWidth}}{\text{NumberOfNodes}} \ast \text{ImageHeight} \right] \quad \text{(cycles)} \quad (5.7)
\]

\[
\text{Speedup} = \frac{(\text{ImageWidth} \ast \text{ImageHeight})}{\text{MaxFrequency}_{\text{seq}}} \quad \text{(X)} \quad (5.8)
\]

\[
fps = (\text{Time}_{SAII})^{-1} \quad \text{(fps)} \quad (5.9)
\]

\[
\text{NumberOfNodes}_{\text{aprox}} = \frac{\text{Cycles}_{\text{total}}}{\text{ImageWidth} \ast \text{ImageHeight}}^{-1} \quad \text{(elements)} \quad (5.10)
\]
Chapter 6

Conclusions and Future Work

This chapter contains the conclusions obtained from simulation results of the proposed architecture and some future work for upcoming research opportunities.

6.1 Summary

A novel scalable integral image accelerator was proposed based on systolic array architectures. Simulations that involved multiple input image sizes and different number of nodes in the accelerator were used to validate the design. The SAII accelerator is capable of achieving a speed-up that depends almost linearly on the number of processing elements instantiated in the architecture having as a limit the availability of resources. Based on the results, an average speed-up of 1.98X – 32.27X was obtained by the proposed architecture over the basic sequential approach when using 2 - 32 PEs in the SAII accelerator.

The system offers scalability by allowing for the number of processing elements in the accelerator to be adjusted as needed. Speed-up is dependent on the number of nodes on the system, assuming that there is enough memory bandwidth to feed all processing nodes with data every clock cycle and resources to instantiate them. In some cases memory bandwidth is not a constraint. For example, images can be entirely downloaded to inner memory blocks and then processing can begin with a larger number of PEs. This is very similar to what a GPU approach does, where the host computer transfers the input image to the GPU’s shared memory and then processes it, and writes it back.

A set of parameterized equations were derived to model the proposed architecture under various scenarios. The model was parameterized with respect to the size of the input image (width and height), total clock cycles, frames per second, desired speed-up, number of Processing Elements (PE), and overhead to first valid data.
By using those equations, it is possible to estimate the maximum speed-up obtainable on FPGAs with different amounts of resources available. A sample of such a projection was shown on previous chapter.

6.2 Future Work

The accelerator proposed in this thesis was designed static in nature and is only viable for known maximum image sizes prior to implementation, as the number of nodes cannot be changed during runtime. Having a static implementation means additional work is needed to determine the optimal number of nodes that can solve all the cases while satisfying the resource constrains established by the design requirements. Extra functionality can be obtained from this design if the accelerator is converted into a dynamic implementation, meaning that the system could adapt the number of nodes to the conditions of a particular task or field application dynamically.

A dynamic implementation would not affect resource utilization, but it would require restructuring memory locations and control signals. In order to make such an approach viable, it would be required that the disabled nodes resources be used for other tasks (for example, Box Filtering) when they were not in use for integral image calculation. This could be done by either having polymorphic nodes or by using Partial Dynamic Reconfiguration (PDR). By using polymorphic nodes, nodes can be instructed to do different tasks while keeping all their inherent functionalities, just using the fraction intended for the active task. Using PDR has its advantages and disadvantages. No resources are wasted by reconfiguring a section of the FPGA for the intended task; however, it takes longer to reconfigure a portion of the FPGA than it takes to just instruct a node to switch tasks. Additionally, PDR requires advanced knowledge in dynamic partial reconfiguration to design interchangeable nodes that can fit in the same footprint.

It would be interesting to see an accelerator like this that is capable of dynamically controlling its throughput based on the demand and priorities of the host system. This would allow for a more flexible and more usable implementation of embedded systems that have a reduced amount of resources but still need the high throughput required to process
real-time video sources. A scheduler that decides which process has higher priority and
resizes the integral image accelerator accordingly to share its resources when needed would
be required to control the dynamic resizing of the accelerator.
References


