Multi-Grain Reconfiguration for Advanced Adaptivity in Cyber-Physical Systems

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Abstract—The advent of Cyber-Physical Systems (CPS) is putting designers to the test: during operation, such a kind of systems has to meet multiple and variable requirements coming from the environment, the user or the system itself. Runtime adaptivity allows addressing mutable requirements over time by modifying system behavior, and it can be implemented in hardware leveraging on reconfigurable devices operating at different granularities: mainly coarse- and fine-grain. The former is faster but less flexible (minor modifications are applied) than the latter. For modern CPS an advanced adaptivity support providing both the advantages of the two main hardware reconfiguration approaches could be extremely useful. In this work, a novel approach for multi-grain reconfiguration is presented in order to deliver advanced adaptive hardware accelerators to CPS.

Index Terms—Cyber-Physical Systems, Hardware Reconfiguration, Adaptive Systems

I. INTRODUCTION

Cyber-Physical Systems (CPS) are complex systems, characterized by a strong entanglement with the environment and integrating a plethora of different interacting components. These latter should be potentially capable of supporting multiple and distinct behavioral modalities to satisfy adaptation when needed. Both environmental (captured through sensors) and system (captured through monitors) awareness are meant to allow prompt reaction to changes. CPS have to guarantee varying workloads and performance objectives, while continuously optimizing performance goals, i.e. minimizing energy consumption, meeting the available power budget, and so on.

To address adaptivity, computing layers need to be flexible, which may be colliding with performance guarantees. General purpose (i.e. CPUs, GPUs and DSPs) substrates are capable of implementing any application, but they are not specialized, resulting unable to offer high execution efficiency. Application Specific Integrated Circuits (ASICs) boost performance, being customized on the application they are designed for, but they are not flexible. In between, an appealing solution is provided by reconfigurable approaches. They are generally composed by a network of configurable processing elements (PEs), that can compute simple or more complex functions, whose interconnections are also configurable. According to their granularity, reconfigurable systems can be divided in: Fine-Grain (FG) and Coarse-Grain (CG).

FG reconfigurable systems apply reconfiguration at the single bit level, thus offering high flexibility. However, they

involve a large amount of PEs and lots of interconnect points to be configured, so that the configuration bitstream size is big (usually a configuration memory is required instead of few configuration registers) and the related reconfiguration time is long. The most common example of FG architectures are FPGAs. Recently, Dynamic Partial Reconfiguration (DPR) has been proposed to mitigate those drawbacks by limiting the area involved, making it possible to perform it also at runtime. DPR systems usually have a static region that never changes during execution and one or more Reconfigurable Partitions (RP), where different circuits can be allocated at runtime [1]. DPR systems can switch among functionalities: one single highly specialized accelerator is implemented in the FPGA at a time, while the others are stored in a memory and can be implemented via reconfiguration. The deployed accelerator is always optimized in terms of resource usage and frequency, but reconfiguration requires a certain amount of time and an associated power consumption (proportional to the RP size) [2]. DPR-capable floorplans usually involve coarse regions of the FPGA. In the rest of this paper, the adopted terminology refers only to the granularity on which reconfiguration is applied (bit or word level): DPR/FR versus the specific CG presented.

CG reconfigurable (CGR) approaches demonstrated to be a viable solution to provide adaptivity in CPS, trading off functional and non-functional requirements [3]. Contrarily to FG/DPR architectures, CGR engines apply reconfiguration at the word/data level. Computing and interconnecting resources are configured word by word, rather than considering single bits; therefore, reconfiguration can be performed quickly due to the limited configuration stream size, which in turn means less memory to store it [4]. Word level reconfigurability limits flexibility: these systems are able to switch among a limited set of kernels. From the implementation point of view, CGR is virtual: all the resources are available in the substrate, being multiplexed in time while switching among configurations. This affects both operating frequency (multiplexers make the critical path longer) and resource usage (the PEs for all the kernels are always on chip). Commonly, designers use a hardware-to-application approach: a generic CGR structure of homogeneous or heterogeneous PEs with a (potentially) configurable interconnect is made available for mapping different kernels. Such an approach favors flexibility at the price of

the execution efficiency of the single applications [5], [6]. To improve efficiency, the opposite approach (i.e., application-to-hardware) can be used. In this case, the CGR structure involves specialized PEs for the execution of the applications it has been conceived for, but it is not possible to add additional applications afterwards [7].

This work combines the two main hardware reconfiguration approaches, namely FG and CG, to deliver the best of both and better cope with the challenging CPS adaptivity needs. To this end, an automated toolchain has been assembled to foster productivity. The toolchain goes from high-level dataflow specifications of the desired applications (modeling them is the unique effort required to the user) to the FPGA implementation of multi-grain adaptive systems, where different RP of an FPGA are filled in with heterogeneous and irregular application-specific CGR datapaths. The toolchain provides both design-time and run-time support by automating the system generation and its management. As a first proof of concept of the multi-grain reconfigurable architectures generated by the toolchain, a use-case involving two edge detection kernels has been adopted. Experimental results show the potentials of the approach when adaptivity needs change: sometimes a low overhead slight adjustment of the computation through CGR can be enough (e.g. to modify the implemented detector), while other times a strong modification of the system behavior by means of DPR is mandatory (e.g. to maximize execution efficiency when the image size changes).

The rest of this paper is organized as follow: Section II provides background and related works. Section III describes the proposed integrated design flow for multi-grain reconfiguration. Section IV presents assessment results on a use-case exploiting two different algorithms for edge detection.

II. RELATED WORK AND BACKGROUND

This section provides a small overview of state of the art approaches for multi-grain adaptivity (see Section II-A), highlighting what is already available and what is done differently in this work. Moreover, a description of the bases for the proposed architecture and toolchain is also presented (see Section II-B and Section II-C).

A. Literature on Multi-Grain Adaptivity

Different works explored the adoption of both FG and CG reconfigurability on the same substrate to combine their benefits together. Modern FPGAs themselves are actually multi-grain platforms, since they include CG reconfigurable blocks, as BRAMs and DSPs, spread within an FG substrate. Amagasaki et al. [8] proposed the Variable Grain Logic Cell (VGLC) architecture that adjusts computational granularity according to the application. It adopts virtual reconfiguration, leveraging on four configurable units that perform operations such as arithmetic logic, random logic, and multiplexing in any type of application. The HoneyComb architecture [9] is an adaptable dynamically reconfigurable cell array. Cells are composed of a routing and a computing part. Routing

parts, responsible for connecting neighbors, compose the reconfigurable interconnection network. Functional parts can be enabled, disabled, or modified using DPR. The DeSyRe SoC [10] leverages on a multi-grain texture containing different sub-components surrounded by reconfigurable interconnects. Along with functional adaptivity, it also supports repair-oriented one by providing fault tolerance with re-routing, re-targeting functionalities on unused sub-components, or by a functionally-equivalent instance implemented in FG reconfigurable hardware. Yuan et al. [11] presented a multi-grain FPGA aimed for mobile computing and focused on two key steps towards higher efficiency: interconnection network and CG reconfigurable digital signal processors. The chip incorporates FG configurable logic blocks, medium-grain digital signal processors with reconfigurable block RAMs, and two CG kernels.

All the above-mentioned approaches are limited to partially reconfigurable CG arrays, where the PEs are mostly homogeneous and not directly derived from the applications to be accelerated. This lack of specialization may limit performance, which is made even worse if infrastructures with fixed interconnection are used. This work proposes a multi-grain framework flexible enough to be suitable to support functional and non-functional adaptivity. Moreover, with respect to the above-mentioned works in literature, it not only presents a novel architecture, but it also delivers a complete toolchain where user has only to model the desired applications in a high-level dataflow language, while the design and run-time management of the architecture is automated.

B. How to build DPR overlays: the ARTICo³ Architecture

Fig. 1. Schematic view of the ARTICo³ Architecture.

The use of SRAM-based FPGAs has merged the best of two worlds (i.e. hardware and software), enabling systems with software-like flexibility while keeping high-performance benefits of dedicated hardware-based processing. The specific

technology that supports this feature is the DPR. The ARTICo³ architecture exploits DPR in high-performance embedded systems that use a processor-coprocessor approach [12]. However, instead of relying only on one application-specific hardware accelerator for each task, as it has been traditionally done, the computing fabric supports a multi-accelerator based computing scheme. Similarly to embedded GPUs supporting general purpose computing, the ARTICo³ computing fabric usually operates in SIMD-like fashion (Single Instruction Multiple Data), where different copies of a given hardware accelerator work on different sets of input data.

ARTICo³-based hardware accelerators are connected to the communication infrastructure using a custom gateway able to dynamically alter its internal datapath to meet specific requirements of computing performance or energy consumption. The gateway hides custom point-to-point interfaces behind a standard AXI4 interface. Plug-and-play capabilities are enabled in user-defined custom accelerators by instantiating them in wrapper modules embedding a local memory (divided in banks) and a register bank (for configuration purposes). Figure 1 depicts a schematic view of the ARTICo³ architecture with a zoom on the ARTICo³ slot wrapper. The ARTICo³ computing fabric is part of a complete framework able to automatically build the fabric starting from either C/C++ or HDL application specifications (custom accelerators), and manage application execution and computation offloading to the hardware accelerators using its *Runtime Library*. For further details on ARTICo³ computing fabric implementation and management please see [12].

C. How to implement application specific CGR datapaths: The Multi-Dataflow Composer

The Multi-Dataflow Composer (MDC) is an automated framework that, through an application-to-hardware approach, generates heterogeneous and irregular CGR substrates. Applications to be implemented are described as dataflow models [13] and combined together through an iterative datapath-merging algorithm, which shares dataflow actors (PEs) among the different application models, leading to the composition of an irregular computing core containing only the logic and connections necessary to guarantee the correctness of the input applications. The generated CGR accelerator is heterogeneous, PEs are actor-specific rather than homogeneous, and may be manually written or synthesized from the actors by using high-level synthesis techniques [14]. To access shared resources multiplexers, named Switching-Boxes (*SBoxes*), are inserted in the accelerator. Once all the input dataflow models are combined together, MDC generates the corresponding HDL. The user has only to model applications as dataflows, while MDC takes care of automatically generating the corresponding CGR accelerators. Figure 2 depicts an example of the MDC operation with 2 input dataflows whose combination requires the insertion of 4 *SBoxes*, for a resulting configuration pattern size of 4 bits.

MDC offers also the possibility of seamlessly integrating the CGR logic as an adaptive hardware accelerator in a processor-coprocessor system for Xilinx environments [15]. By analyzing the features of the combined dataflow specification suitable wrappers and APIs for different processor-coprocessor communication infrastructures (memory mapped or stream) are automatically provided. Bottom part of Figure 2 shows a scheme of the Xilinx IP generated by MDC.

III. TOOLCHAIN FOR MULTI-GRAIN RECONFIGURATION

As explained in Section II-B, the ARTICo³ architecture offers high flexibility, operating in SIMD-like fashion. However, this flexibility is obtained paying the cost of DPR reconfiguration, that requires long time and high energy consumption. When frequent changes among functionalities are required, this cost may easily become no longer affordable. On the other hand, the MDC Tool provides N:1 composition/synthesis. As described in Section II-C, MDC automatically deploys a heterogeneous and irregular CGR accelerator starting from an input set of dataflow specifications. CGR accelerators generated by MDC offer high-speed low-energy reconfiguration, since here reconfiguration is performed by simply changing the application ID written on a configuration register. However, they are able to implement only the functionalities they have been designed for. Also, being a fixed design, the only way to provide parallelism is instantiating more accelerators in parallel, thus paying the cost of the extra logic if, during computation, parallelism is not required anymore.

Thus, ARTICo³ and the MDC flows clearly show opposite tradeoffs between flexibility and reconfiguration costs when considered individually. A combination of these two approaches would enable adaptive multi-grain reconfigurable

Fig. 2. MDC Design Flow

Fig. 3. Integrated Hardware Design Flow

fabrics exhibiting the benefits of both DPR and CGR. The result is a flexible advanced hardware adaptivity which can meet the changing functional and non-functional requirements of CPS designs. In particular, users would have the flexibility to adopt CGR when the application requires frequent switching between graphs/functionalities with shared resources, while DPR can be used either to change the level of parallelism or to change completely the computing core, when the instantiated CGR logic is no longer required.

In this work, the ARTiCo³ framework and the MDC design flow have been combined in a unique toolchain, capable of automatically implementing and managing multi-grain reconfigurable systems. This flow, starting from the high-level dataflow descriptions of the applications to be accelerated within the configurable logic, derives the multi-grain reconfigurable substrate, placing CGR MDC-compliant datapaths within the DPR slots of the ARTiCo³ architecture as depicted in Figure 3. With respect to the standalone flows, an adaptation step (*Kernel Adapter*) is needed. First, user-driven dataflow specifications are processed by MDC to generate a CGR IP. This IP is modified by the *Kernel Adapter*, which delivers an HDL ARTiCo³-compliant CGR kernel. Finally, the ARTiCo³ framework processes the input HDL CGR kernel to implement the whole reconfigurable processing system.

The ARTiCo³ toolchain already takes care of adding the necessary glue logic to interface each hardware accelerator (located in RP) with the static region. Thus, it requires as input only the core logic of the accelerator. Figure 4 shows an example where an MDC-generated IP, with one input port and one output port, requiring three configuration registers and two memory blocks, is modified through the *Adaptation Flow*. The *Adaptation Flow* parses the MDC CGR IP to remove all interfacing logic (AXI-lite interface, AXI-full interface, local memories and configuration register bank). The remaining logic is instantiated in an HDL wrapper whose external interface is the one required in a standalone ARTiCo³ kernel specification. During this step, the *Adaptation Flow* takes also

Fig. 4. Adaptation Flow from an MDC- to a ARTiCo³-compliant CGR IP.

care of properly connecting the ports of the new HDL wrapper to the internal CGR-kernel logic.

IV. ASSESSMENT

In this Section, as a proof of concept, the proposed multi-grain reconfiguration approach is evaluated through an edge detection application involving two different algorithms: *Sobel* and *Roberts*. This use-case enables the possibility of evaluating the advanced adaptivity features regarding functional (changing the edge detection algorithm) and non-functional (tradeoff in terms of execution time and the power) requirements, acting as a prototype example of CPS behavior. Assessment results have been collected using a custom Zynq-7000 board, based on the XC7Z020CLG484-1 device, with integrated power monitoring circuitry.

A. Test Case: Edge Detection - Sobel and Roberts algorithms

Edge detection algorithms estimate the magnitude and the orientation of edges on a greyscale image [16]. They are adopted in several application fields, such as image segmentation, image compression, computer vision and security. Edge detectors are usually computationally intensive tasks that are accelerated in hardware. The simplest techniques involve discrete first-order differentiation operators. Indeed, the boundary of an object is the difference of the intensity levels in its pixels with respect to the surrounding pixels. To assess the proposed architecture, Sobel and Roberts detectors have been used. These operators are applied to evaluate the gradient image $G = k * A$, given by the convolution of the kernel k with the source image A (k is 3×3 for Sobel and 2×2 for Roberts).

The G function, corresponding to the magnitude of the edge, is calculated as $G = \sqrt{G_x^2 + G_y^2}$, where G_x and G_y are obtained as:

$$G_x = \begin{bmatrix} 1 & 0 & -1 \\ 2 & 0 & -2 \\ 1 & 0 & -1 \end{bmatrix} * A, \quad G_y = \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix} * A$$

for the Sobel case [17], and as:

$$G_x = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} * A, \quad G_y = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} * A$$

for the Roberts case [18]. The magnitude of the edge, G , can be approximated as $(|G_x| + |G_y|)/2^n$, where n is a scaling factor. As soon as the magnitude is evaluated, a thresholding stage (the threshold value depends on the specific context of application) compares the magnitude with a desired value, to determine whether the edge is present or not.

The Roberts edge detector is the simplest gradient-based edge detector, due to the reduced convolution kernel matrix. It requires a bit less computation, resulting in limited footprint when implemented in hardware, with respect to Sobel [19]. However, this simplicity is paid in terms of detection effectiveness and noise robustness: Roberts is able to detect a smaller set of edges [20], and it is more sensitive to noise than Sobel [21]. Due to these characteristics, implementing both Sobel and Roberts edge detectors on the same device can be useful to achieve non-functional adaptivity. Sobel and Roberts kernels may correspond to different working points, each featuring a different tradeoff in terms of performance and detection power: Roberts constitutes the fastest but less accurate detection, while Sobel pushes detection quality at the price of a slower execution. Such kind of changing behaviors could be suitable for CPS contexts, where the system has to monitor the environment, the user demand and its internal state to promptly adapt the exhibited behavior. For example, if the battery level of the system is lower than a certain threshold, it can switch from a more consuming detector (Sobel) to a less power-hungry one (Roberts). In the same way, if the incoming images are not so noisy, a low quality detector (Roberts) can be sufficient and more energy efficient, while, if the image source is noisy, Sobel is preferable. Note that, such approach can also be exploited to achieve functional adaptation, when Sobel and Roberts have to be adopted in the same application, such as for airport runway tracking on infra-red images [22].

B. Designs Under Tests

As described in Section III, in order to foster design automation and ease the development of hardware accelerators, in the proposed design flow dataflow models are adopted for the specification of applications behavior. In this use-case, dataflow models have been described in CAPH language [23].

Figure 5 depicts simplified graphs of the dataflows representing Sobel and Roberts kernels, according to the algorithm described in Section IV-A. In particular, *line buffer* actors are adopted to store previous rows of the image, while *delay* actors are in charge of memorizing one previous pixel within a row. In such a way, once these actors are filled with proper numbers of rows and pixels, the convolution actors can start computing the horizontal and vertical gradients. Actor *abs sum* finalizes the magnitude computation step by summing up the absolute values of the horizontal and vertical gradients and by right-shifting the result for a given scaling factor n . Lastly, the thresholding actor *thr* sets to 255 all the magnitudes that are above a certain threshold (it has been fixed to 80), while setting to 0 the others.

These networks are kept separated (*Sobel* and *Roberts* kernels) or merged together by MDC to derive the corre-

Fig. 5. Simplified dataflow graphs implementing the Sobel and the Roberts edge detection computational kernels.

sponding reconfigurable multi-dataflow model (*reconfigurable* kernel). The convolution actors (*sobel_x*, *sobel_y*, *roberts_x* and *roberts_y*) are not shareable, since they correspond to the different convolution kernel matrices applied on the input image. In this case, the actors that can be re-used between the two networks are related to the magnitude computation step (*line buffer*, *delay* and *abs sum*) and to the thresholding step (*thr*). In summary, *Sobel* and *Roberts* kernels involve respectively 14 and 7 actors (two more than the simplified version in Figure 5), while *reconfigurable* kernel has 14 *SBoxes* and 18 overall actors, among which 5 are shared between the Sobel and Roberts datapaths, and 13 not.

On the bases of the described *Sobel*, *Roberts* and *reconfigurable* kernels, three different designs are considered:

- *fine-grain* - a standard DPR-based ARTICo³ architecture where *Sobel* and *Roberts* kernels can be freely instantiated within a number of slots going from 1 to 4.
- *coarse-grain* - an MDC-compliant reconfigurable accelerator built around the *reconfigurable* computational kernel, able to switch between Sobel and Roberts algorithms. Contrarily to ARTICo³, MDC cannot tune the number of accelerators to be used in parallel at runtime, so that a worst case configuration with 4 accelerators in parallel is adopted.
- *multi-grain* - following the approach proposed in this work, this implementation is composed of heterogeneous reconfigurable MDC-generated *reconfigurable* kernels instantiated within the slots of the ARTICo³ architecture. The number of slots ranges from 1 to 4.

Designs are labeled according to the granularity level of the reconfiguration behind them (e.g. *fine* is used when single bit connections are changed). Nevertheless, please note that both ARTICo³ and MDC cores act on coarse areas of the FPGA. ARTICo³ slots, from a chip occupation perspective, are larger than MDC multi-flow datapaths, but they are reconfigured at bit level using DPR, which is why the standalone ARTICo³ designs are labeled as *fine-grain*.

TABLE I

EXPERIMENTAL RESULTS FOR ALL THE CONFIGURATIONS OF THE CONSIDERED DESIGNS. *IN THE FORM OF Nkk , WHERE N IS THE NUMBER OF PARALLEL ACCELERATORS (SLOTS) AND kk IS THE KIND OF COMPUTATIONAL KERNEL OF EACH ACCELERATOR: FIXED *Sobel* (FS) AND *Roberts* (FR), OR *reconfigurable* EXECUTING SOBEL (RS) OR ROBERTS (RR) ALGORITHM (E.G. $4fs$ IS THE FIXED, MEANT AS NOT RECONFIGURABLE, SOBEL PARALLELIZED IN 4 SLOTS; WHILE $4rr$ IS THE RECONFIGURABLE ACCELERATOR, COMPUTING ROBERTS FUNCTIONALITY, PARALLELIZED IN 4 SLOTS). **COMING FROM REAL ON-BOARD POWER MEASUREMENTS. DATA IN BRACKETS SHOW THE PERCENTAGE VARIATION OF OF THE CONFIGURATIONS WITH RESPECT TO THE CASE WHERE ONLY ONE SLOT IS EXPLOITED.

config*	fps (for different image sizes)				energy** [mJ] (for different image sizes)			
	256x256	512x512	1024x1024	2048x2048	256x256	512x512	1024x1024	2048x2048
fine-grain								
<i>1fs</i>	26.95	6.61	1.65	0.42	33.47	130.32	532.13	2132.95
<i>2fs</i>	33.35 (+24%)	8.31 (+26%)	2.11 (+28%)	0.53 (+25%)	28.61 (-14%)	107.27 (-17%)	437.37 (-17%)	1756.8 (-17%)
<i>3fs</i>	34.57 (+28%)	9.01 (+36%)	2.26 (+37%)	0.57 (+34%)	26.76 (-20%)	102.38 (-21%)	406.44 (-23%)	1628.57 (-23%)
<i>4fs</i>	36.96 (+37%)	9.50 (+44%)	2.39 (+44%)	0.59 (+40%)	25.26 (-24%)	99.01 (-24%)	397.11 (-25%)	1562.94 (-26%)
<i>1fr</i>	26.91	6.64	1.70	0.42	32.36	131.76	526.17	2106.31
<i>2fr</i>	33.48 (+24%)	8.43 (+27%)	2.12 (+25%)	0.53 (+25%)	27.23 (-15%)	106.58 (-19%)	429.57 (-18%)	1729.04 (-17%)
<i>3fr</i>	34.58 (+29%)	9.00 (+35%)	2.28 (+34%)	0.57 (+35%)	26.93 (-16%)	100.42 (-23%)	402.62 (-23%)	1603.06 (-23%)
<i>4fr</i>	35.98 (+34%)	9.42 (+42%)	2.37 (+40%)	0.60 (+42%)	25.29 (-21%)	96.08 (-27%)	387.19 (-26%)	1537 (-27%)
coarse-grain								
<i>4rs</i>	36.90	9.52	2.39	0.60	28.44	97.89	397.4	1578.09
<i>4rr</i>	36.96	9.52	2.40	0.60	25.42	97.22	399.73	1570.45
multi-grain								
<i>1rs</i>	26.85	6.74	1.69	0.42	33.04	133.66	529.74	2136.26
<i>2rs</i>	33.19 (+24%)	8.38 (+24%)	2.12 (+25%)	0.53 (+25%)	26.98 (-18%)	109.63 (-17%)	440.38 (-16%)	1751.99 (-17%)
<i>3rs</i>	34.45 (+28%)	8.96 (+33%)	2.23 (+32%)	0.57 (+35%)	27.82 (-15%)	102.26 (-23%)	412.56 (-22%)	1636.79 (-23%)
<i>4rs</i>	36.90 (+37%)	9.52 (+41%)	2.39 (+41%)	0.60 (+42%)	28.44 (-13%)	97.89 (-26%)	397.4 (-24%)	1578.09 (-26%)
<i>1rr</i>	26.90	6.62	1.70	0.42	32.11	131.02	527.9	2128.85
<i>2rr</i>	33.06 (+23%)	8.42 (+27%)	2.12 (+24%)	0.53 (+25%)	27.01 (-15%)	107.24 (-18%)	435.99 (-17%)	1755.22 (-17%)
<i>3rr</i>	34.37 (+28%)	8.10 (+36%)	2.28 (+34%)	0.57 (+34%)	26.36 (-17%)	103.15 (-21%)	406.78 (-22%)	1631.55 (-23%)
<i>4rr</i>	36.96 (+37%)	9.52 (+44%)	2.40 (+41%)	0.60 (+42%)	25.42 (-20%)	97.22 (-25%)	399.73 (-24%)	1570.45 (-26%)

C. Experimental Results

To evaluate the proposed approach, experimental results obtained with the considered designs under test are hereafter discussed. The target device for all the reported data is the Xilinx XC7Z020CLG484-1 available on the custom Zynq-7000 board used, and the operating frequency has been set to 100 MHz. Note that energy numbers come from real on-board power measurements during execution. For the evaluation of the designs, several metrics will be taken into account:

- *LUT*, *FF* - resource occupancy of the design (for all its possible configurations) within the targeted device;
- *fps* - frames per second of the design (for all its possible configurations) while processing images;
- *E* - energy consumption of the design (for all its possible configurations) while processing images;
- Reconfiguration overhead, evaluated in terms of:
 - *B* - memory footprint of the reconfiguration data;
 - *T* - time required for the reconfiguration phase;
 - *E* - energy consumption during the reconfiguration phase;
 - *F* - penalty on the achievable maximum operating frequency when CG reconfiguration is provided;

1) *Processing Evaluation*: Table I depicts hardware processing results for each possible configuration of the different designs. In terms of processing time, it shows resulting *fps* for different image sizes and for different degrees in terms of parallelism. With respect to the parallelism, both *fine-grain* and *multi-grain* designs show the same trend, increasing the processed *fps* up to 40% going from 1 to 4 slots. No appreciable difference between *Sobel* and *Roberts* kernel execution in

terms of *fps* seems to be present. Note also that performance does not increase linearly, as it would be expected. The main reason behind this is the communication overhead introduced by the ARTICo³ architecture, and its predominance with respect to the real computing time (less than 10% of the overall time per block). To comply with the required data-parallel execution model, the image processing application requires partitioning the total workload in a given set of data-independent sub-workloads that are executed in rounds. The size of the local workload has been fixed to process 32x32 image blocks, and the *Runtime Library* dispatches processing rounds in as many slots as available. Adopting more complex computational kernels or over-clocking data transfers could highlight differences between different kernels and executions with different number of slots.

Table I also shows the measured energy consumption for all configurations. As occurs for performance, the energy efficiency increases when using more accelerators (power consumption increase is less significant than the saving in terms of execution time), reaching reduction values of up to 27%. Comparing the *fine-grain* and the *multi-grain* approaches, it is possible to see that energy consumption is similar. This means that, in an application scenario in which both edge detectors need to be present, the *multi-grain* accelerator provides a solution that is more energy efficient, since both datapaths are already available in the accelerator core logic (otherwise, two *fine-grain* accelerators would need to be present in the FPGA, or switched using DPR, which also adds an energy overhead as discussed in the following section). Note that,

as for the *fps* metric, in terms of energy there is not a real difference between *Sobel* and *Roberts* kernel execution, meaning that CGR, in this very simple case, is not able to provide non-functional (fps/energy driven) adaptivity, but only a functional (i.e., algorithm-driven) one. The predominance of DMA transfers is also playing a role in terms of energy, flattening differences between the two kernels and among the different slot configurations.

2) *Reconfiguration Granularity Analysis*: Flexibility, as we already mentioned in the introduction, has a cost especially in terms of memory utilization, timing and consumed energy. Table II depicts overhead results of both *fine-grain* and *coarse-grain* reconfigurations, in terms of memory footprint (size [B]), timing (time [ms]) and energy consumption (energy [mJ]). As expected, the reconfiguration overhead of *coarse-grain* designs is much lower than the overhead of *fine-grain* ones. This is due to the fact that MDC-based reconfiguration requires writing a single configuration register for each accelerator to switch from one detector to another, while the DPR in ARTICo³ slots requires downloading a new bitstream for the whole region. In the presented scenario, the CG reconfiguration of four parallel accelerators requires around 1000 times less reconfiguration time (0.09 ms versus 106.14 ms) and around 850 times less reconfiguration energy consumption (0.11 mJ versus 94.11 mJ) with respect to FG reconfiguration of four slots. The price to be paid for this advantage in terms of timing and energy is that *coarse-grain* designs are less flexible. It is possible to switch among the kernels to be executed, which are already implemented on the system, by simply multiplexing them in time. However, an infrastructure providing only CGR does not allow playing with the degree of parallelism or re-writing completely the functionality with a bitstream not originally considered at design time.

A *multi-grain* adaptive design combines the best of both, offering a fast low-power consuming reconfiguration when changing among functionalities is needed, and the performance trade-off (throughput versus energy consumption) given by the flexible parallelism offered by the DPR-based ARTICo³ architecture. In such a way, for the considered proof of concept involving *Sobel* and *Roberts* algorithms, MDC-based reconfiguration can be exploited to change the functionality of each slot in a lightweight manner, while the DPR approach behind ARTICo³ takes care of fps/energy by playing with the number of accelerators.

TABLE II
RECONFIGURATION OVERHEAD. *N IS THE NUMBER OF PARALLEL ACCELERATORS (SLOTS). **REAL ON-BOARD POWER MEASUREMENTS.

design	config*	size [B]	time [ms]	energy** [mJ]
<i>fine-grain</i>	1	858k	16.42	15.18
<i>fine-grain</i>	2	1715k	47.62	41.91
<i>fine-grain</i>	3	2573k	75.95	67.1
<i>fine-grain</i>	4	3430k	106.14	94.11
<i>coarse-grain</i>	4	2	0.09	0.11

3) *Impact of CGR*: The coarse-grain reconfiguration, which is used both in *coarse-grain* and *multi-grain* designs of this

experimental evaluation, has an implementation overhead. As seen in Section II-C, the MDC tool merges together the input dataflow applications, in this case the *Sobel* and *Roberts* models depicted in Figure 5, sharing the common actors and making them accessible by means of multiplexers (*SBoxes*) inserted in the crossroads of common paths of data. This means that, when configured for the execution of the *Sobel* or *Roberts* edge detector and with respect to the standalone *Sobel* or *Roberts* kernels, the *reconfigurable* kernel pays a resource overhead given by the fact that the non-shared actors (belonging to the detector that is not currently executed) plus the *SBoxes* need to be considered. This overhead is clearly visible in Table III, where *Sobel* and *Roberts* occupy respectively 10% and 55% less LUT and FF than the *reconfigurable* kernel. If the two isolated kernels are instantiated in parallel (see the *Sobel+Roberts* row in Table III), thus allowing runtime switching among detection algorithms (without any additional overhead), the *reconfigurable* kernel saves more than 20% of the same resources, meaning that sharing actors is convenient and that the *SBoxes* overhead is affordable, according to the considered metric. However, the insertion of the switching modules has also another drawback: it can negatively affect the operating frequency. *SBoxes* are fully combinatorial; therefore, their presence may lengthen the critical path of the system, thus lowering the highest achievable frequency. In this case, non-reconfigurable *Sobel* and *Roberts* kernels support respectively 5% and 57% higher operating frequency than the *reconfigurable* one. For the parallel *Sobel+Roberts* solution, if a worst-case frequency has to be selected (that is also the case of *reconfigurable* kernel), the maximum frequency estimated for *Sobel* need to be considered.

TABLE III
CG RECONFIGURATION OVERHEAD (AFFECTING *coarse-grain* AND *multi-grain* DESIGNS IN SECTION IV-A). IN BRACKETS PERCENTAGES OF VARIATION OF EACH METRIC WRT CG *reconfigurable* DESIGN.

kernel	resources (@100 MHz)		Fmax [MHz]
	LUT	FF	
<i>reconfigurable</i>	2225	2360	108.39
<i>Sobel</i>	1817 (-18%)	2076 (-12%)	113.92 (+5%)
<i>Roberts</i>	922 (-59%)	1048 (-56%)	170.13 (+57%)
<i>Sobel+Roberts</i>	2739 (+23%)	3124 (+32%)	113.92 (+5%)

4) *Usage of the Proposed Flow*: Previous discussions demonstrated the effectiveness of multi-grain reconfiguration, showing the advantage, in terms of timing and energy consumption, of mixing both ARTICo³ and MDC reconfiguration approaches. It is important to highlight also the effectiveness of the proposed flow in terms of design time and effort. The proposed toolchain speeds the design of multi-grain systems up by automatically mapping different input specifications in one MDC multi-flow datapath compliant with the DPR-Based ARTICo³ slots. Users only need to define the applications behavior through abstract high level input dataflow specifications; then, the toolchain takes care of the complete process from dataflow to multi-grain systems. Please, refer to [12], [14] for further evaluation of the single components of the

integrated toolchain (e.g., automation level, user friendliness, stability, flexibility, etc.).

The effort of designing the dataflows is application-specific and cannot be evaluated. However, it is necessary to be highlighted, as the usage of dataflow specifications allows the exploitation of HLS dataflow-to-hardware tools (such as CAPH [23]), which not only speed the design process up by automating HDL generation, but also allow developers that are not expert in hardware design to adopt the proposed design flow.

Furthermore, the proposed toolchain facilitates the management of the generated multi-grain system, since the *Runtime Library* of the ARTICo³ architecture is capable of transparently managing the application execution and computation offloading to the hardware accelerators also when these are CGR accelerators.

V. CONCLUSIONS

In this paper, a multi-grain reconfiguration approach that relies on both coarse-grain (time-multiplexing of available datapaths) and fine-grain (time-multiplexing of FPGA resources) reconfiguration mechanisms has been proposed. The combination of these mechanisms, eased by the use of ARTICo³ and MDC, can be used to enable advanced functional and non-functional adaptivity support in CPS. The presented toolchain supports the automatic development, from specification down to implementation, of multi-grain reconfigurable systems, speeding up the design process and facilitating their deployment and run-time management.

A proof of concept test case involving two edge detection kernels has been used to evaluate the proposed reconfiguration infrastructure. Experimental results demonstrate the potential of the approach in terms of FPGA resources, timing and energy efficiency. Drawbacks and strengths of the different reconfiguration granularities have been highlighted, and the advantages of leveraging on a multi-grain reconfigurable architecture have been revealed. The proposed methodology can be particularly useful in CPS contexts, where variability is common due to the involvement of user (e.g. image resolution), environment (e.g. speed of the objects whose edges have to be detected) or system (e.g. remnant battery) requirements.

With the proposed proof of concept, a limited set of the adaptivity potential for the proposed approach has been shown. In the considered scenario, lightweight MDC-based adaptation provides functional adaptation but, in cases where the implemented computational kernels differ substantially, it can be used to provide also non-functional adaptation with performance/energy tradeoffs [3]. Similarly, ARTICo³-based adaptivity could achieve better results with scalability for more complex applications or could provide fault tolerance [12]. In the future, a deeper validation of the proposed architecture is to be performed by adopting a larger set of applications and/or more complex ones, such as Gaussian edge detectors like Canny, or by considering error-affected scenarios and approximate computing.

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