Abstract—A multi-board run-time reconfigurable (MRTR) system for evolvable hardware (EHW) is introduced with the aim to implement on hardware the bidirectional incremental evolution (BIE) method. The main features of this digital intrinsic EHW solution rely on the multi-board approach, the variable chromosome length management and the partial configuration of the reconfigurable circuit. These three features provide a high scalability to the solution. The design has been written in VHDL with the concern of not being platform dependant in order to keep a flexibility factor as high as possible. This solution helps tackling the problem of evolving complex task on digital configurable support.

Keywords—Evolvable Hardware, Evolutionary Strategy, multi-board FPGA system.

I. INTRODUCTION

Evolvable hardware (EHW) [1] is the combination of a configurable device and an evolutionary algorithm (EA) [2]. The EA modify the data content which composes the bit string of the configurable device in order to evolve the circuit until it fulfills a task. EHW had been introduced to be applied to real-world applications but up to date only few solutions can deal with relatively large solutions such as [3][12][13]. And nowadays it is mainly seen as a way to automatically design circuits that can be digital, mixed or analogue. Different types of intrinsic EHW implementations have been developed, some based on analogue reconfigurable supports made of transistors [4][5][6] or mixed support (both digital and analogue) application specific integrated circuits (ASIC) [3] others on digital support like programmable logic array [7] or reconfigurable systems based on processors [8].

Most of the digital system development has been made on field programmable gate arrays (FPGA) and almost exclusively on Xilinx products. It appears that this device prevails among the others supports mainly due to its high flexibility. Indeed an FPGA can be reconfigured almost an infinite number of times and this for a reasonable price compare to an ASIC. An FPGA does not need to be design it in infinite number of times and this for a reasonable price and some major drawbacks for EHW lie in the impossibility to reconfigure an FPGA from itself. The important configuration time required is also a major inconvenience to have a successful evolution in the shortest delay. An evolution process in most of the case needs several trials to reach the final solution (cf. Section 2 for further description) therefore in an intrinsic EHW system each trial is downloaded inside the FPGA, in other words the FPGA is configured and the interest is to avoid wasting time during this phase. The method introduced by Layzell to have a configurable system on a top of a FPGA [9] helps bypassing these problems. The FPGA will not be reconfigured for each new generation but the virtual circuit, thus a high amount of time is gained. Some others systems has been carried out following this method such as [10][11] and as much as the authors know they successfully evolved small tasks (up to a ten of inputs).

Sekanina has introduced a way to implement evolvable IP cores [12] thanks to a virtual reconfigurable circuit (VRC) constituted of configurable functional blocks (CFB). In [13] another VRC has been introduced where the array is infinitely extensible regarding the limitation that the support (i.e. FPGA) introduces. These two VRC are extremely promising. In Sekanina one a CFB has been designed as a configurable logic block (CLB) that is present in the Xilinx FPGA [14] so a set of functions can be stored inside a CFB. His VRC is made of an array of column of CFB and the connections between these columns are configurable. In Haddow et al. VRC the Sblock approach allows to configure any connections between each sblock but the functions set capacity seems to limited by the size of the FPGA LUT used to implement the VRC. Therefore if both features are merged and the possibility to configure each cell individually, we could reach a very flexible and highly scalable system.

Section 2 explains the evolutionary algorithm used in the proposed system. Section 3 introduces the proposed solution and details the main components of it. It follows an implementation cost study of the proposed system in section 4 and the document is ended by a conclusion.

II. EVOLUTIONARY ALGORITHM

It has been stated to use a ($\lambda$+1) evolution strategy (ES) because it has been extensively tested for its performances in [15][16][17][18] and has been chosen (Fig. 1) where $\lambda$ reflects the number of individuals composing a population. It has been evaluated that an ES gives good results for an evolution process in a small number of generations for a population constituted of thousands of individuals or in a much higher
number of generations but for a small population [19]. For obvious reason of overall cost the first statement cannot be realized. Therefore it has been established to use a small population and $\lambda$ equals to five have shown some interesting results if we refer to the document previously cited.

A. $(1+\lambda)$ Evolution Strategy

The ES works as follow, after a first generation has been randomly created, each chromosome (= individual) is evaluated. It results one fitness value for each chromosome, the best of them is kept in a memory called best chromosome memory. The fittest chromosome is therefore tested to know if it fully answers to the task i.e. fitness value equals to 100%. Else the best chromosome is mutated five times, one time per new chromosome. It results a mutated population also called new population that replaces the previous one. The process carries on until the fitness value is equal to 100%, the number of generation reaches a maximum allowed number for instance 500,000 or for any other condition introduced by the user for instance in our case a stalling effect of the fitness value i.e. no improvement of the fitness value for a certain amount of time such as 10% of the maximum allowed number of generations.

B. Fitness Evaluation

Each time an individual have been configured by a new generation of population a fitness evaluation is made. This will indicate which chromosome gives the best answer to the task and help to decide if the evolution process as to carry on or if the answer has been found. The evaluation results from a comparison between a set of desired outputs and the outputs of each individual.

In the proposed system each chromosome fitness values are computed one by one. When all of them are known, the best one undergoes a selection with the best chromosome fitness value kept in memory. The following equation (1) illustrates the fitness function used in the MRTR system:

$$F = \sum_{addr=0}^{x} \sum_{out=0}^{x} d \quad \text{where} \quad d = \begin{cases} 0 & \text{if } o \neq e \\ 1 & \text{if } o = e \end{cases}$$

To have a significant fitness value a set of inputs are applied to each individuals of the MRTR. The resulting outputs are compared with another set of desired outputs. These two different sets are located in two memories and organized in truth tables. The fitness value $F$ is thereby expressed by the sum of all the differences $d$ between the desired output $e$ and the output given by an individual $o$. If the individual output is different than the desired one the fitness value does not change else it is incremented by 1. The fitness value is computed for all the outputs ($out$) of each individual through the two truth tables ($addr$).

III. DESCRIPTION OF THE ARCHITECTURE

A detailed description of the system and its main components are exposed in this section.

A. Overview of the MRTR

To have a flexible system it has been decided to use a design coded in VHDL without using any feature belonging to a dedicated FPGA but rather to write a code as generic as possible in order that the system can be implemented on most of the FPGA provided on the market. Moreover to keep a factor of scalability as high as possible the author decided to plan an implementation where each reconfigurable array is on one FPGA. It allows having a high scalability only limited by the size of the support.

The multi-board run-time reconfigurable system is composed of:
- an evolution strategy (ES),
- a fitness evaluation,
- a multiplexer block (Sort) presenting the outputs of each target to the ES for the fitness evaluation,
- two memory blocks containing the values of the input truth tables (ITT) and output truth tables (OTT),
- and finally five reconfigurable arrays.

The Fig. 2 exposes the overview of the MRTR and shows the main data exchanges between the components that composed the system.

The ES, ITT, OTT and Sort components are planned to be implemented on a single FPGA. Each reconfigurable circuit will be implemented on one FPGA. Therefore the whole system will contain six FPGA. Moreover the RC design has been carried out with the VRC as pattern. Bear in mind that the main drawback of this approach relies on the fact that it is very greedy in term of CLB.
B. Reconfigurable Circuit

Each of one the five reconfigurable circuits are made as an array of configurable cells of \( r \) rows and \( c \) columns (Fig. 3).

The Fig. 4 illustrates in detailed the specificities of the three kind of RCell. An RCellA is always located in the first column while an RCellC can solely be located in the last column. An RCellB has the inverse restriction it cannot be a cell of the first or last column of the array. The routing selectors create some connections with the inputs of an RCell. An RCellB for instance can be linked to an output of an RCell or of a previous RCell but as well to an input of the RC. In summary only the RCellC cannot have their inputs connected to the inputs of the cell array. The function selector has a similar role than a Xilinx FPGA LUT i.e. it can be seen as a small memory that contains a set of function (for instance AND, OR, XOR, NOT…). To configure the function of an RCell A or B means to choose one among the pre-loaded functions of their function selector.

As it has been written in the introduction, the RCs are configured by the way of a bit string provided by the ES. The bit string organisation has to reflect the one of the RCs. The Fig. 5 exposes how the RCells are represented in the bit string. As introduced earlier in the document each cell can be addressed independently, partial reconfiguration. Then this feature is translated in the bit string by the data field called Address. In order to address a cell the column and row of this one has to be indicated in @Col and @Row. CConf1 and CConf2 are used to know if the routing selector is dealing with the outputs of the previous cell or with the inputs of the RC. The Functionality & routing field is used to configure the routing and function selectors. Input1 and Input2 are the configuration data of the routing selector while the function selector receives the data from Function. The size of each field has been chosen to have an interesting panel of possible RC shape and size for the simulations of the MRTR. Therefore the full size of the bit string per chromosome will be a multiple of the bit string for one cell by the number

\[ \frac{2^c}{2} \times \frac{2^r}{2} \times 5 \times 5 \times 4 \times 1 \times 1 \times 4 \times 4 = 2^k \times \text{bits} \]

Fig. 5 Bit string representation of a configurable cell (RCell) also called RCell bit string. This organisation is common to the three types of cell
of cell that composes the RCs. The size of a RC is obviously
the number of row by the number of column of this one, see
equation (2).

\[ N_{RC bit} = N_{rows} \times N_{cols} \times RCell bit \text{ string} \]  

(2)

where \( N_{RC bit} \) is the bit string size, \( N_{rows} \) and \( N_{cols} \) are the
number of rows and columns in the reconfigurable target. The
size of RCell bit string is 24 bits.

The bit string format can easily be modified without
interfering in the behavior of the system, by adjusting the
mutation process to the new format.

Each cell can be individually configured, this allows a high
flexibility and thus it offers a good scalability. Indeed it is
possible to increase the size of the reconfigurable array adding
other cells. The size limit of this array is imposed by the
physical support therefore the size of the FPGA on which the
array is implemented. Furthermore, this feature joined with a
variable chromosome length permit to partially configuring an
array as shown in Fig. 4. Bear in mind that modify the size of the
full bit string length is not more than adding or subtracting
some RCell bitstrings. A column of cell, a group of cell or
some isolated cells can thus be configured. Therefore the
finest grain of configuration is a cell.

IV. ESTIMATION AND FIRST RESULTS

In this section, different implementation cost estimation is
introduced. It shows the versatility of the MRTR solution.
Then it is followed by some results pre-synthesis of some
simulations made with the MRTR.

A. Implementation Cost

The MRTR has two main parts:
- the ETP which is the ES along with SORT, ITT and

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
Block & Resource & Used resource \\
\hline
Reconfigurable & Slices & 10147 \\
circuit & Slice Flip Flops & 7896 \\
 & 4 Input LUTs & 18053 \\
 & Slices & 2093 \\
ETP & Slice Flip Flops & 2007 \\
 & 4 Input LUTs & 3653 \\
\hline
\end{tabular}
\caption{Implementation Cost for the Two Main Elements of the MRTR System. ETP Contains the ES, the Input and Output Truth Tables and the Sort Block}
\end{table}

- and the reconfigurable circuits.

The Table I show the amount of slices, slice flip flops and 4
input LUTs needed to implement one RC and the ETP on a
Xilinx XC1000 FPGA.

Several implementations are possible (cf. Table II) such as
one target per FPGA which will require having five XC1000
(82 \% of slices used) and the ETP on a XC300 (70 \% of
slices used). It is obviously an expensive implementation
however other solutions are conceivable for instance an
expensive one could be to implement the whole system on a
single FPGA i.e. XC4VLX160 (78\% of slices used). Any
other solution made of FPGA that can contain this
configuration or an upper one is also suitable.

B. Results of Simulation

Some simulations have been run but none of them have
reached the final solution yet. These simulations were:
- RC 10 rows by 11 columns, clocks 63 MHz and 80 MHz,
  1 and half multiplier i.e. 1 bit by 2 bits and results on 2 bits.
- RC 10 rows by 11 columns, clocks 63 MHz and 80 MHz,
  2 by 2 multiplier i.e. 2 bits by 2 bits and result on 4 bits.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Block & Slices & Available & Percentage & FPGA \\
\hline
Reconfigurable & 25295 & 32440 & 76\% & XC1000 \\
circuit & 12222 & 16724 & 76\% & XC4VLX160 \\
 & 22222 & 32440 & 64\% & XC300 \\
 & 10147 & 12000 & 82\% & XC1000 \\
 & 10025 & 14395 & 70\% & XC300 \\
ETP & 2003 & 3022 & 70\% & XC300 \\
 & 2325 & 3653 & 65\% & XC4VLX150 \\
 & 2019 & 3072 & 69\% & XC4VLX150 \\
 & 2019 & 6144 & 34\% & XC4VLX150 \\
\hline
\end{tabular}
\caption{Implementation Cost for Various Implementations Configurations on Different FPGA. Each RC Are Made of 11 Columns by 10 Rows of RCell}
\end{table}

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\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
RC size (number \ of \ rows \ \times \ number \ of \ columns) & Clocks frequencies & Task to \\
\hline
 & & & Number of bits & Input 1 & Input 2 & Output \\
\hline
10 \times 6 & 60 MHz, 80 MHz & 1 \\ and \\ half & 1 & 2 & 4 & 4.9us \\
 & & multiplier & & & & 4.96us \\
 & & & & & & 30.42us \\
10 \times 11 & 60 MHz, 80 MHz & 2 \\ by \\ 2 & 2 & 2 & 4 & 8.8us \\
 & & multiplier & & & & 8.8us \\
 & & & & & & 48.8us \\
\hline
\end{tabular}
\caption{Initialization, Sending and Mutation Processes Durations}
\end{table}
However it is possible to give the durations of the initialization process, the sending process and the mutation process (Table III). It results that the sending of the bit string to the targets takes only 15% of a generation process. This stressed the interest of having a virtual RC in order to speed up the sending process. Indeed as stated in [14][20][21][22] the maximum frequency range allowed to configure an FPGA is between 50MHz and 100 MHz. Knowing that it is sent by bit frames with some pad bit the configuration time would be much higher than in the current solution (Refer to [23] for more detail).

V. CONCLUSION

A multi-board run-time reconfigurable system has been introduced. Several implementations were proposed. The variable chromosome length, the multi-board approach, and the partial configuration of the reconfigurable circuit offer interesting features to obtain a scalable solution in order to evolve relatively complex tasks. The authors are currently working on the implementation of the system on FPGA. Nevertheless the intermediate results of the simulations are showing us the legitimacy of the solution. Indeed the speed effectiveness and the flexibility and scalability are drastically increased compared to the existing intrinsic digital EHW solutions comporting a virtual RC and an eventual intrinsic EHW working on FPGA without virtual RC.

REFERENCES


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