A Survey about Intelligent Solutions for Autonomous Vehicles based on FPGA

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Abstract—Safe driving and reducing the number of accidents victims have been the main motivations for researchers and automotive companies for decades. Today, humanity is very close to make the old dream of fully autonomous vehicles a reality, thanks to the rapid spread of AI (artificial intelligence) and the evolution of semiconductor technologies. But the real problem here is the increasing demand for computational power and that of course will increase power requirements, hence it will not be suitable for autonomous driving applications. GPU is not suitable for solving this problem due to its power consumption as well as heat generation. On the other hand, CPU also does not satisfy the performance requirements. For the above condition, FPGA (Field Programmable Gate Array) has drawn attention as a hardware accelerator since it features high performance with low power consumption. This paper reviews the common solutions involving artificial intelligence implemented on FPGA for autonomous vehicle applications. Research, development, and current trends related to the topic are emphasized.

Keywords— *FPGA, AI, Autonomous Vehicles, HW Acceleration, Coprocessing*

I. INTRODUCTION

FPGA (Field-Programmable Gate Array) is an integrated circuit designed to be configured by the designer after its manufacture, as it contains a large array of programmable blocks and reconfigurable interconnects which give it high

flexibility in many applications. The history of FPGA goes back to 1985 when Ross Freeman and Bernard Vonderschmitt invented the viable field-programmable gate array. Because of its high performance and low power consumption, many companies have started to use FPGA to accelerate the performance of their systems. One of the most interesting fields that FPGA is starting to take part in is the industry of autonomous vehicles. Table I shows that the automotive industry is the third most important sector in the market. Autonomous vehicles that drive us instead of us driving them will be a reality soon and that will increase road safety since accidents related to impaired driving could be reduced as cars cannot get drunk or be distracted by a text message or by another passenger. Thus, if we remove humans from the equation, autonomous vehicles will make the roads safer.

Autonomous vehicles are equipped with multiple sensors such as cameras, radars, and LiDARs, to perceive the surrounding environment.

These sensors generate huge data, hence real-time processing this data requires high performance computing systems. Instead of using CPUs and GPUs for implementing AI (Artificial Intelligence), FPGAs are adopted since they feature high performance with low power consumption. This article presents the latest solutions for autonomous vehicles involving AI implemented on FPGAs.

TABLE I. GLOBAL FPGA MARKET SHARE ESTIMATION IN 2019 [1]

Field	Telecom.	Ind.	Auto.	Consum.	Milit.	DP	Others
Market Share	32	18	16	14	9	7	4

Telecom. (Telecommunication), Ind. (Industrial), Auto. (Automotive), Consum. (Consumer Electronics), Milit. (Military & Aerospace), DP (Data Processing)

II. IMPLEMENTATION METHODS

Few years ago, FPGA designs were quasi-exclusively performed by electrical engineers since the implementation tools were low level of abstraction. It was hard to design complex solutions using HDL (Hardware Description Language), thus the increase of the design productivity gap. The considerable progress of the implementation tools including reusable IPs (Intellectual Properties) increases the popularity of FPGAs allowing a large variety of engineers (from hardware to software engineers) to develop FPGA-based systems.

There are many ways to deploy algorithms on FPGAs:

HDL: Using VHDL (Very High-Speed Integrated Circuit Hardware Description Language), an implementation of a vehicle collision avoidance solution has been proposed considering a PID (Proportional–Integral–Derivative) controller based on fuzzy logic [2]. A HW/SW (Hardware/Software) codesign to implement an ADAS (Advanced Driver-Assistance Systems) was presented in [3]. The hardware accelerator, performing an ANFIS (Adaptive Neuro-Fuzzy Inference System) clustering in the PL (Programmable Logic) side of the Zynq SoC (System on Chip), was implemented in VHDL.

HLS (C/C++): Vivado HLS (High Level Synthesis) has been used in [4] to deploy C/C++ code into a Xilinx FPGA to implement a white line detector where the single line search method gives better results than Hough transform in terms of processing time.

Python: One of the latest trends on FPGA development is the use of Python. The authors in [5] presented an implementation on FPGA/Python of lane line detection system. The results show that the execution time of FPGA/Python is 6.34 times faster than OpenCV considering the implementation of median blur, adaptive threshold, and accumulation of Hough transform.

MicroBlaze: The classification of traffic signs is an important aspect in autonomous driving. In [6] is presented an implementation method for traffic sign detection using HW/SW codesign. The classification is processed on a MicroBlaze soft core and the preprocessing is performed on hardware.

PS+PL vs. MB+IP: Xilinx SoCs are made of two major parts, PS (Processing System) and PL, which can be exploited to have HW/SW codesign based systems. The authors in [7] show that implementing a TSR (Traffic Sign Recognition) system on a Xilinx SoC gives better results than its implementation in an MicroBlaze + IP based system

XSG (Xilinx System Generator): is a powerful development tool to implement FPGA designs as it is suitable for DSP (Digital Signal Processing) applications. The authors in [8] used XSG to model, simulate and implement a traffic signs detection system which presents promising results.

HDL coder: is a tool provided by MATLAB that helps to deploy MATLAB/SIMULINK models into FPGAs after automatic generation of HDL code. An MPC (Model Predictive Control) controller has been implemented on SoC using HDL Coder for automated steering of vehicles [9].

III. BACKGROUND

An autonomous driving system is implemented on hybrid computational technologies GPU-FPGA, where the GPU's primary job is self-driving and the FPGA's job is to perform some subtasks such as pedestrian and traffic lights detection [10]. An end-to-end solution for the design of self-driving cars based on Xilinx PYNQ-Z2 board is proposed in [11]. The most important characteristic of this design is the presence of the DPU (Data Process Unit) that accelerates the deep learning process. FPGA is faster than the CPU and consumes less power than the GPU when it comes to accelerate the CNN (Convolutional Neural Networks) process [12]. The proposed architecture permits to reduce the execution time and energy consumption comparing to the CPU.

The accuracy and delay of autonomous driving systems have a major impact on how the vehicle handles the surrounding environment. To make the delay, resulting from data inputs, deterministic a solution is proposed in [13] considering bypassing the CPU from the input data path as shown in Fig. 1.

Fig. 1. Line 1 has more deterministic delay from line 2 [13]

The biggest challenge when implementing AI algorithms in FPGAs is the difficulty of the hardware design. H. Bingo [14] proposes a solution to this problem applying PYNQ board which allows the use of Python for its wide range libraries, especially in AI and Image processing. O. Chang-song and Y. Jong-min [15] discuss the most popular technologies to accelerate deep learning processes for autonomous cars industry. Some steps are introduced to avoid collisions in the air for UAV (Unmanned Aerial Vehicle) using four cameras based on FPGA SoC (System on Chip) [16]. The collision avoidance algorithm has already been implemented in GPU-based system, but the solution is not practical as it requires high energy. Road segmentation is a very important process in self-driving cars which identifies and describes the drivable parts of the roads. The problem with this process is the need of high computational resources. A model based on FPGA is suggested in [17] to perform a real-time and low power road segmentation. The authors suggest the use of LiDAR (Light Detection and Ranging) than the use of traditional cameras since they suffer from image unclarity in poor lighting conditions. FPGA is used for scene perception based on CNN. It took about 16.9 ms to accomplish a CNN operation using Xilinx UltraScale XCKU115 FPGA.

In self-driving cars environment, if there is more than one car starting from the same place and going to the same destination, the decision-making system will choose the same

optimal path for all cars. There will be one busy road/track and other uncrowded as shown in Fig. 2. To solve this issue, paper [18] proposes a solution implemented on FPGA applying game theory. This solution relies on direct communication between vehicles to apply game theory instead of using the cloud. The author of [19] relies on the use of two FPGA board. PYNQ-Z1 to deal with detecting obstacles and pedestrians by implementing light weight BNN (Binarized Neural Networks) and Zynq- Xc7Z010 to recognize traffic lights and detect road lines. The two FPGA boards were connected to each other using Ethernet to be able to communicate. Execution time is reduced and accuracy in identifying obstacles is increased by this architecture.

The authors of the article [20] suggest a hybrid method in which the computing problem of machine learning is solved. The machine learning process should contain two phases: Training phase and inference phase. A machine learning platform was built so that the training phase takes place in the GPU and inference phase in FPGA as shown in Fig. 3. This platform is user friendly and has greatly improved performance. In [21] a tool is provided to accelerate and improve the performance of applying Deep Neural Network (DNN) on FPGA. The proposed design used two different methods to manage the on-chip FPGA memory.

The first one is to store the complete feature maps on the chip in order to reduce the complexity of the data movements. The second technique is to automatically generate buffers to overcome the data shortage when the processes are fetching data from the external memory. The proposed design provides real-time performance for processing HD videos and deliver a higher efficiency (up to 4.35x) than the GPU-based solutions. FpgaConvNet is a framework and tool to automatically implement CNN on FPGA (presented in [22]). The provided tool applies analytical synchronous data flow and the parallelism processing across the CNN layers without constraints on the model size. FpgaConvNet provides hardware optimization by considering the latency as the core

Fig. 2. All autonomous cars will choose path 1 since it is the optimal path and that will make it crowded [18]

Fig. 3. The architecture of the hybrid machine learning platform [20]

of optimization and achieves a performance up to 6.65x comparing with the optimized GPUs. The paper also suggests a method to be used by the CascadeCNN which has two stages as shown in Fig. 4. In the first one, a quick classification is performed based on very low precision processor. In the second phase, the estimation of the prediction confidence is performed. The samples which are wrongly classified are reprocessed using a high precision processor to reach the required accuracy level and that improves the performance up to 48%.

The article [23] presented multi-core processing units capable of increasing the level of automation in Urban Air Mobility (UAM) aircraft by using a parallel sensor fusion structure to increase accuracy and safety during landing. These processing units are based on FLS (Fuzzy Logic System), Which interacts with several sensors that have different in frequency ranges and spatially separated. The proposed method was designed and tested using MATLAB and VHDL on Intel Altera OpenVINO FPGA board. The proposed FLS processing units are capable of achieving a computational speed of 25.3 GOPS (Giga Operations per Seconds).

The architecture offers five Hybrid Obstacle Avoidance (HOA) units to control height as shown in Fig. 5. Landing decisions will be based on the fused information coming from these units. Each node contains two different types of sensors each one works on a different frequency spectrum that will increase immunity to noise.

Fig. 4. CascadeCNN's high-level architecture [22]

Fig. 5. HOA units constellation on the bottom Side of an UAM [23]

One of the advantages of this design is that the FLS core does not depend on any external memory, thus increasing the security against cyberattacks, in addition to the low power consumption reaching less than 20 mW when working at the maximum frequency of 283 MHz. The need to recognize and process sequential data such as video streaming has made LSTM (long short-term memory) networks an important requirement for AI models. However, this LSTM needs high memory requirements, and this will cause many challenges in time sensitive applications.

Paper [24] presents an FPGA-based method for optimizing LSTM functionality in a critical-time environment. The proposed architecture gives a similar output in quality compared to a traditional LSTM, but in terms of speed it is 415x faster. This method proposes an approximate computing scheme that enables the calibration of the QoR (Quality of Result) in exchange for an increase in performance. This model approximates the weight arrays in a neural network using low-rank SVD (Singular-Value Decomposition) in addition to the distribution of weights arrays based on the importance of their components. These techniques allow to restructure the calculations for LSTM and design computing system that carries out the most important operations first, to get peak QoR within time constraints. Table II resumes recent implementation results of different algorithms that can be useful for autonomous vehicles solutions. The implementations are performed in FPGA (or SoC), and some are performed in GPU for comparison. It is clearly noticeable that the power performances provided by the FPGA are significantly better than in GPU. However, in terms of time

performance, both hardware targets present close results that depend on the size of the processed images and the implemented algorithm. CPU based implementations have not been considered in the Table II since they show low performances in all cases.

CONCLUSION

In the present paper, we introduced the latest proposed FPGA-based solutions to accelerate AI processes dedicated to autonomous vehicles. It is doubtless that reaching fully autonomous and safe cars requires overcoming many challenges, for instance real-time processing of the huge data coming from multiple sensors, considering the energy consumption in addition to the safety issues. Exploiting reconfigurable computational technologies significantly enhance the performance of the solutions that especially involve artificial intelligence and autonomous vehicles since they require parallel computing. Depending on the solutions discussed in the paper, we are about to witness fully autonomous and safe vehicles in the next few years considering embeddability requirements.

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TABLE II. COMPARISON OF DIFFERENT IMPLEMENTATIONS FOR IMAGE PROCESSING ALGORITHMS THAT ARE USEFUL FOR AUTONOMOUS VEHICLES

Source	[25]		[26]		[27]		[28]	[29]
Purpose	Canny Edge Detector		STOP Sign Detection		Speed-Limit Sign Recognition		Roberts Edge Detector	Lane Detection
Platform	FPGA (Intel Arria V 5AGXFB3)	GPU (GeForce GTX 580)	SoC (Xilinx ZC706)	GPU (GRID K520)	FPGA (Intel Arria 10 GX)	GPU (NVIDIA GTX1060)	SoC (Intel Cyclone V 5CSEMA6F31A7)	FPGA (Intel Stratix IV EP4SGX230KF40C2)
Resolution	3936 x 3936		1920 x 180		640 x 240		481 x 321 (grayscale)	1024 x 768
Processing Time (ms/frame)	64.16	59.94	7.9	24.3	33.3	30.3	0.85	5.4
Power (W)	1.5	251	5.2	72	12.5	19	0.433	-
Frequency (MHz)	242	772	100	745	-	-	100	200
Accuracy (%)	-	-	99.8	99.8	90	90	98.9	-
Frame rate (fps)	15.58	16.68	126.58	41.17	30	33	1175	185.18

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