AAP Contrats doctoraux en Intelligence artificielle

Cofinancé par l'ANR

Artificial intelligence on FPGAs: a breakthrough for data acquisition in high energy physics experiments and beyond

1. DESCRIPTION OF THE PHD THESIS PROJECT

1.1 OBJECTIVES OF THE PROJECT BASED ON THE CURRENT STATE OF THE ART

Artificial Intelligence (AI) algorithms and machine learning techniques are nowadays one of the most expending fields in research and in the industry. The use of AI in experimental particle physics is not new but these algorithms are only used, for now, in later stages of the data analysis chain such as the analyses leading to the discovery of the Higgs boson coupling to third generation quarks for which the ATLAS CPPM group had a major contribution namely the development of AI techniques for these analyses. For data acquisition and trigger applications, relatively simple algorithms are imbedded in the hardware to process on the fly the huge data flow in a timely manner. However, with the next generation of high-end Field Programmable Gate Arrays (FPGAs), that include large increase of available processing and memory units, it is becoming possible to implement complex AI algorithms inside these FPGAs and process on the fly big data flows with dramatically increased selection performance.

The Large Hadron Collider (LHC) at CERN is currently the world leading scientific program and accelerator in particle physics. The upgrade of the LHC is a crucial part of the European strategy for particle physics. The second phase of the LHC upgrade will happen in 2025 and will increase by an order of magnitude the instantaneous luminosity leading to the High Luminosity LHC (HL-LHC). The increased luminosity puts more stringent requirements on the LHC detectors electronics and data processing. The ATLAS detector, one of the four main detectors located along the LHC accelerator interaction points, will undergo a major update to be adapted to the increasing luminosity at the HL-LHC, hence to the dramatic increase of produced data. In order to treat on the fly with advanced algorithm this huge amount of data (more than 500 Tb/s), we propose to deploy advanced technologies based on state-of-the-art digital electronics running AI algorithms.

The main purpose of this project is to develop AI and machine learning techniques to dramatically improve big data processing effectiveness such the one needed in high pileup environment at the LHC. The main challenge is to efficiently implement these techniques into the dedicated data acquisition electronics, based on FPGAs, which are used for signal processing in particle physics detectors such as the ATLAS Liquid Argon (LAr) calorimeter.

The signals from the LAr calorimeter are processed through a chain of electronic boards in order to extract the energy deposited in the calorimeter. The new electronic chain for the second phase of the LHC upgrade is described in [1]. An excellent resolution on the deposited energy and an accurate detection of the deposited time, in the blurred environment created by the pileup, is crucial for the operation of the calorimeters and of the full ATLAS detector to enhance its physics discovery potential. The computation of the deposited energy and timing is currently done using optimal filtering algorithms [2]. These filter algorithms are perfectly adapted for ideal situations with low noise. However with the increased luminosity and thus the noise from pileup, the performance of the filter algorithms decrease significantly while no further extension nor tuning of those could recover the loss in performance.

AI algorithms have proven to be very powerful tools in data processing and provide the most interesting candidate to recover the performance of filter algorithms in high noise conditions. FPGAs, which are designed to efficiently treat a large amount of data in a very short time, are very much adapted to the online data processing needed at the LHC especially at the trigger level. FPGAs had, up to recently, relatively limited amount of computational resources, however high end FPGAs have now enough resources to accommodate the needs of advanced AI and deep learning algorithms. This allows to combine the performance of AI algorithms with the speed and high bandwidth of the FPGAs to efficiently process the big data flow by electronic boards.

The backend electronic boards for the second phase of the upgrade of the LAr calorimeter (called LASP) will use the next high-end generation of FPGAs. Based on the unique skills and expertise present at CPPM in digital electronics, a prototype of these boards is currently being developed at CPPM and will be finalized in 2020. This prototype will be equipped with two high-end last generation FPGAs from INTEL/ALTERA (Worldwide leader in FPGA production and part of the INTEL group). The research and development (R&D) program of these boards and their production is already financed as part of the government "Très Grandes Infrastructures de Recherche" (TGIR) program for the upgrade of the ATLAS detector. The aim of this project is to take advantage of this unique opportunity to develop the necessary tools enabling the embedding of AI algorithms on these boards and to further explore the outstanding capabilities opened by these developments for new applications. This can prove to be a breakthrough that can extend to many areas facing big data processing in particle physics, especially at the trigger level, and in the industry.

The objectives of this project can be divided into 6 main points:

1. Develop AI methods adapted to the specific problem of signal processing to compute the deposited energy in the calorimeter in high noise conditions.
2. Optimize these methods and compare them with the existing filter algorithms using simulated data that reflect the conditions of the LHC after the upgrade.
3. Adapt the algorithms for processing on FPGAs and optimize the needed processing power while keeping high performance.
4. Investigate and adapt the recent tools that are under developments for converting AI algorithms into HDL code that is used to program FPGAs.
5. Test the performance of the algorithms in-situ using the LASP board prototype currently under construction at CPPM.
6. Generalize the developed tools and study their wider usage for trigger processing and for applications outside the particle physics field including industrial applications.

1.2 METHODOLOGY

The first step of the project will consist of developing and quantifying the performance of AI methods and compare them to the current filter algorithms. Simulated data will be used to train and test several AI algorithms with different architecture. The architecture of the AI will be optimized for the best performance while keeping in mind the requirements for the processing resources that are needed by the algorithms. The performance will be compared with the current filter algorithms in different LHC operation conditions and for various energy ranges. The results of these studies will be published.

The next step is to adapt the AI algorithms to be used inside FPGAs. Tools, such as HLS4ML, that allow to transform an AI algorithm to HDL code that can be used to program FPGAs are very recent and still under development. These tools can also help reducing the needed processing power by trimming the NNs with minimal effects on performance. Existing tools will be adapted to the LASP boards and to the chosen NN architecture, then tested and extended with new developments for the specific needs of this project. The AI algorithms will be tested both in simulation and on the LASP board. Both the performance of the algorithms and the resources needed inside the FPGAs will be quantified. The developed tools will be provided on open platforms and the results of these studies will be published.

1.3 WORK PLAN

This PhD thesis will be part of a more global project involving many physicists and engineers at CPPM. This project is divided into several work packages and the hired PhD student will take part in several tasks as listed below:

1. Studying and optimizing AI algorithms to process the data in simple conditions (no pileup, well separated pulses in the detector). This task will provide the first results about the AI performance for calorimeter pulse shape processing. It will also provide the first algorithms to study the needed processing resources and for exercising the firmware on the FPGAs. [Largely available before the start of the project, further optimization will be studied].

2. Optimize the AI algorithm performance in the presence of pileup. However no special treatment will be used to mitigate dynamically changing pileup conditions. This task will provide a clear understanding of the dependence of the AI on the pileup conditions. [First year of the project].

3. Study and optimize the resources needed by the AI algorithms on FPGAs. Evaluate the performance as function of the used resources. [Second year of the project].

4. Participate with the help of engineers to develop tools, such as HLS4ML, to port the AI algorithms to HDL language to program the FPGAs. [Second year of the project]

5. Study more complex AI algorithms to mitigate the changing pileup conditions. This task will provide the final algorithms that can be used for processing data in realistic conditions and tested on the FPGAs. [Third year of the project].

6. Quantify the effects of the improved energy reconstruction by the chosen algorithm on trigger and physics analysis performance [Third year of the project].

The PhD student will also participate in the various group meeting at CPPM and the ATLAS collaboration meeting at CERN. His/Her work will be presented regularly at these meetings.

WP\Quarter	Q4 2020	Q1 2021	Q2 2021	Q3 2021	Q4 2021	Q1 2022	Q2 2022	Q3 2022	Q4 2022	Q1 2023	Q2 2023	Q3 2023	Q4 2023
WP1													
WP2													
WP3													
WP4													
WP5													
WP6													

1.4 SUPERVISOR AND RESEARCH GROUP DESCRIPTION

This project is structured around a larger project which is the upgrade of the ATLAS LAr calorimeter. The R&D work to produce the boards with the FPGAs, where the artificial intelligence algorithms will run, is already funded by CNRS. The CPPM group working on this project is currently formed of two senior scientists, one junior scientist, three engineers, one postdoc and several students. The CPPM group has leading roles in the upgrade program of the LAr calorimeter:

1. The CPPM group is part of a team of 7 institutes in charge of the development of the firmware for the backend electronics boards for the phase 1 upgrade. In addition, the CPPM is responsible for the integration of these boards with the new data acquisition interface boards from ATLAS (called FELIX).
2. A scientist in the CPPM ATLAS team, **Georges AAD**, is the co-coordinator of the firmware group as well as the co-coordinator of the whole LAr phase 1 project commissioning within ATLAS. He is also the PI of the AMIDEX project. He will be the **co-supervisor** of the student in this project.
3. The CPPM is leading the development of the backend processing board (LASP) for the phase 2 upgrade as part of a consortium of more than 15 institutes worldwide. An engineer at CPPM is responsible of coordinating the ATLAS working group developing the LASP hardware and firmware.
4. A scientist at CPPM, **Emmanuel MONNIER**, is currently the project leader of the ATLAS LAr calorimeter collaboration. He will be the **supervisor** (**monnier@cppm.in2p3.fr**) of the student**.**

Support from the Aix Marseille University Initiative of Excellence program, so-called AMIDEX, is already obtained for this project. Using the AMIDEX funding, a new postdoc joined the CPPM group in January 2020 to work on this project for 2 years.

2. RECENT PUBLICATIONS

[1] The ATLAS Collaboration, Technical Design Report for the Phase-II Upgrade of the ATLAS LAr Calorimeter, CERN-LHCC-2017-018, https://cds.cern.ch/record/2285582

[2] The ATLAS Collaboration, Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector, Phys. Lett. B 784 (2018) 173, arXiv:1806.00425

[3] The ATLAS Collaboration, Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716 (2012) 1, arXiv:1207.7214

[4] The ATLAS Collaboration, ATLAS Liquid Argon Calorimeter Phase-I Upgrade Technical Design Report, CERN-LHCC-2013-017, https://cds.cern.ch/record/1602230

[5] Cleland, W.E. and Stern E.G., Signal processing considerations for liquid ionization calorimeters in a high rate environment. NIM 338 p. 467. 1994

3. EXPECTED PROFILE OF THE CANDIDATE

The hired candidate is expected to have a background in physics, machine learning and programing. An excellent knowledge of the programing languages (especially python) is required. Prior knowledge of Keras and tenserflow is desirable. Knowledge of HDL programing languages is an advantage.

The candidate should be interested in developing machine learning algorithms designed to treat on-the-fly the large amount of data from particle physics detectors. He/she should be capable of working in large group and collaborate with physicist on understanding the physics requirements of the artificial intelligence algorithms and with engineers to understand the constraints of implementing such algorithms on FPGAs.

Good knowledge of English and good communication skills are required. The candidate is also required to travel frequently to CERN to take part of the collaboration meetings and present his/her work.

4. SUPERVISORS' PROFILE

Emmanuel MONNIER (**monnier@cppm.in2p3.fr**) is a permanent senior physicist at CPPM, Centre de Physique des Particules de Marseille, CNRS-IN2P3 and Aix Marseille University.

"Directeur de Recherche" (DR1) at CNRS since 2007, he obtained his PhD in 1991 working at CEA-Saclay on Z to bbar/ccbar decay studies in the ALEPH experiment at LEP, CERN and then worked at Pierre & Marie Curie Paris University as a postdoc on the H1 experiment. He got a permanent position at CPPM in 1992 as "Chargé de Recherche". He actively took part in the development of liquid argon endcap calorimeter prototypes as well as in the definition of the calorimeter for the ATLAS experiment. From 1996 to 1999, he worked at the University of Chicago, as a visiting scholar, on the KTEV experiment at Fermilab contributing to rare decays and CP violation (ε/ε') studies with Kaons and Hyperons and was responsible for the analysis on the discovery of the Xi0 beta decay. At the end of 1999, he continued briefly this rare Kaon decay scientific program on the NA48 experiment until 2002. He got his "HDR - Habilitation to supervise research" in 1997. Since 1999, back to CPPM, he is working on the ATLAS experiment and is the ATLAS calorimetry team responsible. One of the key person in the definition, building and installation of the LAr endcap Calorimeter, he became ATLAS responsible for the commissioning and operation of the ATLAS liquid argon calorimeter and Project Associate at CERN from 2006 to 2009. ATLAS LAr calorimeter detector and operation coordinator, member of the LAr collaboration institute board and of the LAr executive board until February 2019, he is now the LAr Calorimeter Project Leader. Since the start of the LHC physics production phase in 2010, he contributed to data analysis and studies on Top quark properties, Standard Model multi-boson, Higgs and SUSY searches, having supervised more than 15 PhD students. He is author of more than 800 published scientific papers including the discovery of the Higgs and its properties studies.

Fields of research:
Experiments: ATLAS(1992-1996;1999-present), **NA48-2**(1999-2000), **KTeV**(e799/832)(1996-1999), **H1**(1992-1993), **ALEPH**(1989-1991)

Publications > 800 refereed, (about 87000 citations in total with an average of 100 citations/paper), most of them from ATLAS, NA48, KTeV, H1, ALEPH international collaborations. h-index impact of 137 (from inspirehep.net): 16 renowned paper, 34 Famous papers (250-499 citations), 169 Very well-known papers (100-249 citations), 219 Well-known papers (50-99 citations), 320 Known papers (10-49 citations).

PhD supervisor of more than 15 PhD and Co-PhD students from various countries including France China, Romania, as well as many Master and Undergrad students.
Currently supervising a PhD students (09.18 - 09.21) and co-supervising two co-PhDs (09.17 - end 9.20).

VISA DU RESPONSABLE DE L'INSTITUT ET DU DIRECTEUR DE LABORATOIRE CONCERNÉS

Visa du responsable de l'institut,
KAJFASZ Eric

Fait à Marseille, le 14/05/2020

Signature

Eric KAJFASZ
Directeur - IΦU
Institut de Physique de l'Univers

Visa du directeur du laboratoire,
DIACONU Cristinel

Fait à Marseille, le 13/05/2020

Signature

Cristinel DIACONU
Directeur du CPPM