FROM THE PHYSICAL MODEL TO THE ELECTRONIC SYSTEM — OMTF TRIGGER FOR CMS*

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The paper presents the development of the Overlap Muon Track Finder (OMTF) trigger for the CMS experiment at CERN. The transition from the data produced by the physical model to the algorithm suitable for practical implementation is shown. The paper also concentrates on the problems related to the necessity of continuous adaptation of the algorithm to the changing operating conditions of the detector.

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1. Introduction

The Compact Muon Solenoid (CMS) [1] is an experiment operating at the Large Hadron Collider (LHC) at CERN to study proton–proton, and lead–lead collisions at a designed energy as high as $\sqrt{s} = 14\,\mathrm{TeV}$ (5.5 TeV nucleon–nucleon) and at luminosities up to $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ ($10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the case

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of lead–lead collisions). During the Run 1, the LHC operated at a centre-of-mass energy up to 8 TeV, and at luminosity up to $7.7 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. After the Run 1, the accelerator is subjected to the upgrade which should result in the increase of the LHC luminosity to *ca.* $2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and already reached the centre-of-mass energy of 13 TeV [2]. Those changes require powerful selection of events in the level-1 (L1) trigger, to keep the L1 rate below 100 kHz, which is necessary for the current data acquisition system. The modernisation of the trigger electronic systems is also required due to technology changes which resulted in depleting stocks of spare parts.

The CMS muon trigger upgrade is performed in three areas of the detector separately: as the end-cap track finder, the overlap track finder and the barrel track finder [4]. The Warsaw CMS Group is responsible for implementation of the Muon Trigger in the Overlap area of the detector.

2. OMTF algorithm

In the overlap area, the trigger receives data from three different detectors: Drift Tubes (DT), Cathode Strip Chambers (CSC) and Resistive Plate Chambers (RPC) (see figure 1).

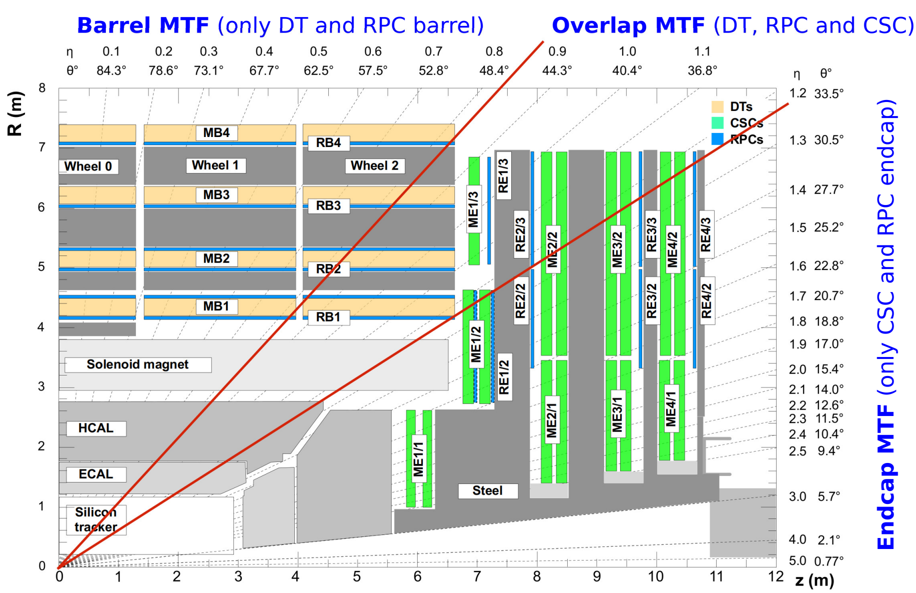

Fig. 1. The longitudinal, schematic view of the quarter of CMS detector. The muon detectors RPC (denoted as RB and RE), CSC (ME) and DT (MB) are marked. In addition, the approximate segmentation into barrel, overlap and endcap partitions is shown [3].

In Run 1 (legacy) system, the signal was processed by the muon sub-triggers [5–7] related to available muon detectors and then combined by the Global Muon Trigger (GMT). In the currently built system proposed for Run 2 and Run 3, the data from muon detectors should be combined as soon as possible in order to provide optimal trigger decision. The new algorithm requires that the data be converted to the common representation and processed in a uniform manner.

In the proposed approach, the CMS detector is treated as a set of 18 "layers", where each layer contains the muon detector of the certain type (CSC, DT or RPC). The muon crossing the detector generates the electrically recorded signal (hit). Each hit is represented by the corresponding azimuthal angle ϕ and the layer number in which it is generated. The trigger algorithm must calculate the transversal momentum p_{T} of the muon (or muons) that generated the received hits.

In the "naive" approach, the hits can be used to find the values of the initial (at vertex) azimuthal angle ϕ_0 and the transversal momentum p_{T}. However, there is no single deterministic muon track for particular p_{T}, and ϕ, due to stochastic effects (multiple scattering and energy losses). It is also necessary to analyse events containing hits generated by more than one muon and detector noise.

As the initial azimuthal angle of the muon ϕ_0 is not known, the reconstruction of the muon track must be started from one of the received hits. Therefore, eight selected layers of the detector, with low noise and good azimuthal resolution are treated as "reference layers". The hit in one of these layers is called a "reference hit" and is used as a starting point to the muon track matching.

The matching process uses patterns generated basing on physics simulations. For each detected range of p_{T}, multiple tracks of muons are generated. The azimuthal angle at which the track crosses the chosen "reference layer" is denoted as ϕ_{ref}. From the histogram of $\Delta\phi_i = \phi_i - \phi_{\mathrm{ref}}$ values in other layers (i is the layer number), the probability density function of $\Delta\phi$ is calculated. Due to cylindrical symmetry of the detector, the obtained set of $\Delta\phi_i$ is independent of the initially chosen ϕ_{ref}. Finally, the logarithm of that probability density function is mapped into 7-bit integer numbers with smaller values truncated at 0. These values are further referred to as PDF. The set of PDF values creates the so-called "Golden Pattern" (GP), for a muon with a p_{T} from particular range. The GP handles information about average muon track propagation and hit spread. Of course, the GPs derived for different "reference layers" are different.

The logarithm of probability that the muon with p_{T} from particular range generated the received set of hits may be assessed in a relatively simple way. First, from the whole set of hits, the reference hits are selected, and

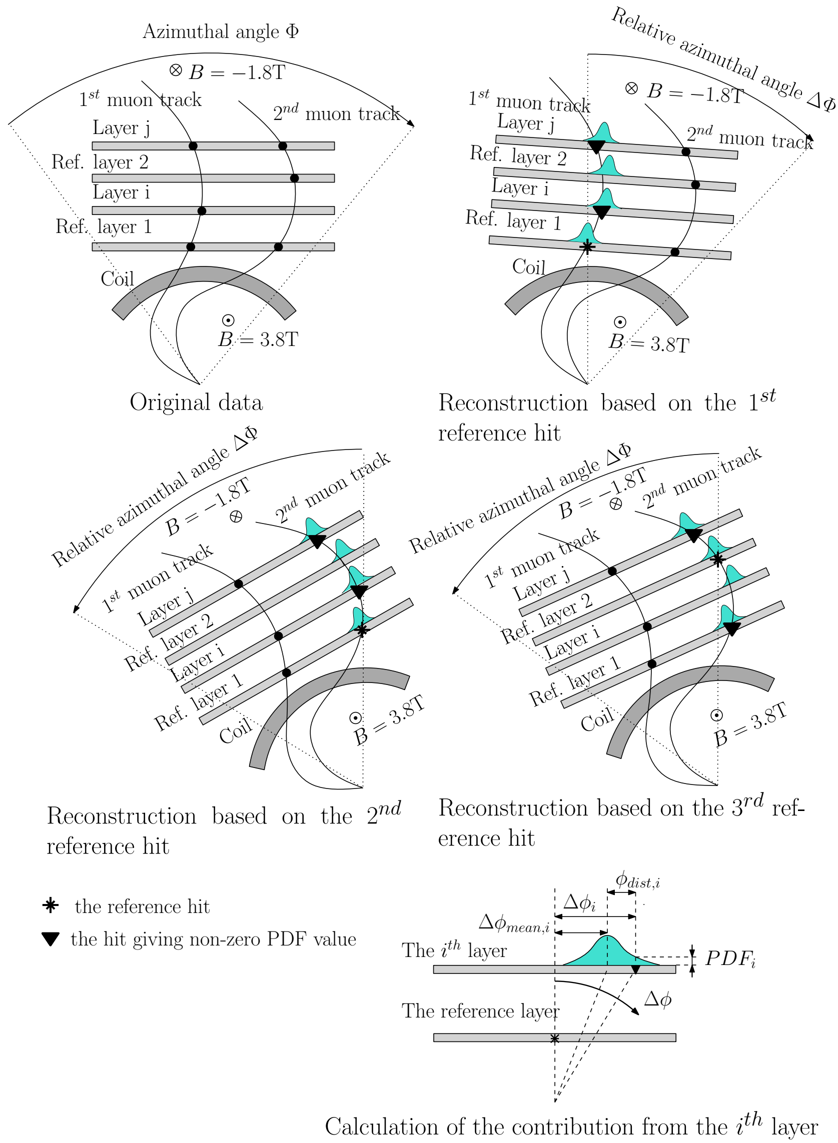

Fig. 2. The principle of operation of the OMTF algorithm. The event contains hits generated by two muons. Three reference hits were available. One of them starts the reconstruction of the track of the first muon. Two others lead to the reconstruction of the track of the second muon. The Ghostbuster algorithm should filter out the repeated detection of the second muon, so that only two muons are reported.

first of them is used as a starting point. The ϕ of this hit ($\phi_{\rm ref}$) is subtracted from the ϕ of all hits in the set, giving the $\Delta\phi$ values. In each layer, the hit with $\Delta\phi$ nearest to the maximum of PDF ($\Delta\phi_{\rm mean}$) is selected, the distance from this maximum ($\Delta\phi$) is calculated, and finally, the corresponding PDF value is found as a PDF contribution. The PDF contributions from all layers are summed, and the derived value (roughly proportional to the logarithm of the analysed probability) is used to measure the degree of matching. The best matched pattern is the one with the highest number of layers with non-zero PDF contributions and the highest sum of PDF contributions from all layers.

The described process is repeated for the next reference hit. In the current design, up to 4 reference hits may be analysed. The possible ranges of $\phi_{\rm ref}$ are ordered to maximize the probability that the consecutive reference hits extracted are generated by different muons in the case of a multi-muon event. The concept of the algorithm and analysis of a sample event is shown in figure 2. Parameters of the best matched patterns, together with the $\phi_{\rm ref}$ are passed to the muon sorter and selector (called Ghostbuster), which removes possible duplicates, and transmits up to 3 best muons matching the quality criteria to the GMT.

3. Hardware implementation of the OMTF algorithm

The algorithm is implemented in the FPGA chip on an MTF7 board, which is the recommended hardware platform for the upgraded CMS trigger [8]. The block diagram of the OMTF trigger is shown in figure 3. The block diagram of a single Golden Pattern Processor (GPP) is shown in figure 4.

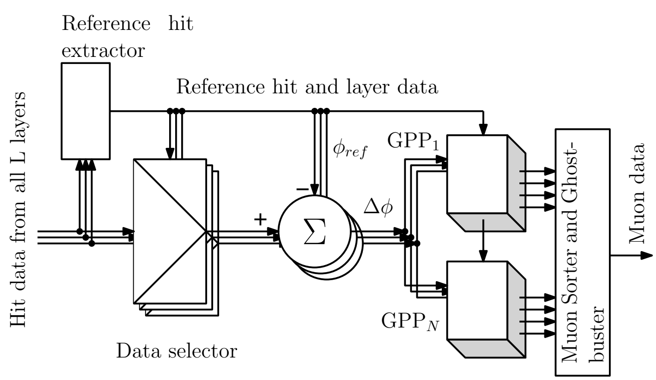

Fig. 3. Block diagram of the OMTF implementation.

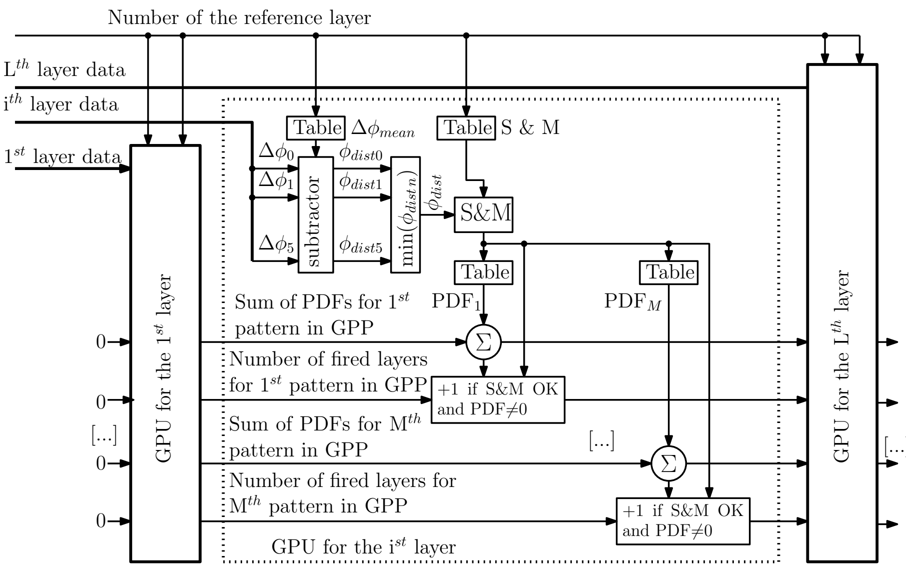

Fig. 4. Implementation of the single GPP handling M patterns. The Golden Pattern Unit (GPU) is the block which analyses hits in a single layer. L is the number of layers, M is the number of patterns handled in the GPP. “S&M” (shift and mask) are the blocks used to scale $\Delta\phi$ depending on the PDF distribution width.

The development and debugging of the algorithm was a complex process requiring multiple iterations, where the results of physics simulations were the source of algorithm concept and parameters, but also the expected output data used to test the resulting design. The FPGA resource consumption and achievable maximum clock frequency were continuously verified, affecting the selected architecture and parameters (*e.g.* the number of patterns). The implemented design was tested both in HDL simulations and in real hardware, and the produced results were compared with expected output data. These tests allowed to identify and fix implementation errors, and to improve the algorithm concept. The flow of the development process is shown in figure 5.

The result of that process was the optimization of the precision of numerical calculations, and architecture of essential blocks (adders and sorters). Additionally, a solution allowing to pack multiple patterns (up to 4) in a single GPP was developed, which increased the achievable precision of p_{T} estimation.

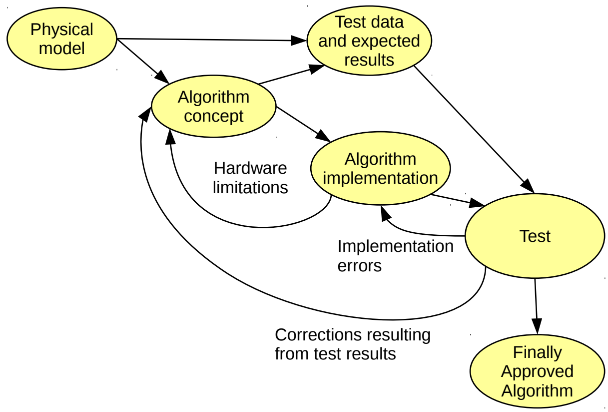

Fig. 5. The process of development and testing of the algorithm.

4. Results and conclusions

The OMTF trigger was successfully implemented in the XC7VX690T chip with the following resource consumption: Slices used: 94.48% (102319 from 108300 available); Slice LUTs: 64.88% (281040 from 433200 available); Slice Registers: 32.87% (284752 from 866400 available); Block RAM tiles: 51.22% (753 from 1470 available).

The algorithm has been successfully tested both in HDL simulations and in the real hardware, but further optimizations are expected.

For the iterative development of the algorithm and its implementation, it is essential that the OMTF algorithm be described with the high level, structured and parametrized behavioural VHDL. The work at implementation and testing of the OMTF has shown that it is a serious multidisciplinary problem requiring the cooperation of professionals from both areas: physics and electronics. In the development of the current form of the algorithm, especially valuable was the participation of persons who combined knowledge about physical phenomena with the understanding of possibilities and limitations of the electronic hardware.

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