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A versatile digital camera trigger for telescopes in the Cherenkov Telescope Array

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ABSTRACT

This paper describes the concept of an FPGA-based digital camera trigger for imaging atmospheric Cherenkov telescopes, developed for the future Cherenkov Telescope Array (CTA). The proposed camera trigger is designed to select images initiated by the Cherenkov emission of extended air showers from very-high energy (VHE, $E > 20$ GeV) photons and charged particles while suppressing signatures from background light. The trigger comprises three stages. A first stage employs programmable discriminators to digitize the signals arriving from the camera channels (pixels). At the second stage, a grid of low-cost FPGAs is used to process the digitized signals for camera regions with 37 pixels. At the third stage, trigger conditions found independently in any of the overlapping 37-pixel regions are combined into a global camera trigger by few central FPGAs. Trigger prototype boards based on Xilinx FPGAs have been designed, built and tested and were shown to function properly. Using these components a full camera trigger with a power consumption and price per channel of about 0.5 W and 19 €, respectively, can be built. With the described design the camera trigger algorithm can take advantage of pixel information in both the space and the time domain allowing, for example, the creation of triggers sensitive to the time-gradient of a shower image; the time information could also be exploited to online adjust the time window of the acquisition system for pixel data. Combining the results of the parallel execution of different trigger algorithms (optimized, for example, for the lowest and highest energies, respectively) on each FPGA can result in a better response over all photons energies (as demonstrated by Monte Carlo simulation in this work).

1. Introduction

The proposed Cherenkov Telescope Array (CTA, [1]) is a large installation of Cherenkov telescopes of different sizes for the detection of very high-energy (VHE, $E > 20$ GeV) γ-rays. CTA will cover the energy range from few tens of GeV up to hundreds of TeV with a sensitivity at 1 TeV that is a factor of 10 better than achieved by the current-generation experiments H.E.S.S.,[1] MAGIC,[2] and VERITAS.[3] It will also provide a good energy (about 10–15%) and angular resolution (on the arcmin scale) for reconstructed photons.

Currently considered array designs (see, for example, [2]) deploy a mixture of large-size telescopes (LSTs), medium-size telescopes (MSTs), and small-size telescopes (SSTs), with typical reflector diameters of 23 m, 12 m, and 4 m, respectively, on an area of roughly 1–10 km^2 in order to ensure good performance over four orders of magnitude in photon energy. The enlarged instrumented area and telescope field of view (FOV) along with the wider energy range (when compared to current-generation experiments) imply a particular challenge for the trigger and data-acquisition systems which have to deal with a cosmic-ray-induced array trigger rate of O(10 kHz), typically an order of magnitude higher than in current installations.

CTA trigger designs typically comprise two trigger levels. At the telescope level, the proposed Cherenkov cameras (equipped with 1000–10,000 pixels with diameters corresponding to about 0.3°–0.1°) are expected to provide local camera triggers for γ-ray and cosmic-ray showers while efficiently suppressing the background. Typical γ-rays generate a Cherenkov light-flash of a few nanosecond duration in spatially neighbouring pixels, but at high energies ($\gg 1$ TeV) and large impact distances of the shower with respect to the telescope the camera image acquires a substantial time-gradient [3] and can last several 10 ns. The background is dominated by the diffuse night-sky background (NSB) light from natural and artificial light sources, resulting in pixel count rates of O(100 MHz) at single photoelectron (p.e.) threshold, and by large-amplitude afterpulses mimicking Cherenkov signals in a pixel. Further suppression can be

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[1] http://www.mpi-hd.mpg.de/hfm/HESS
[2] http://wwwmagic.mpp.mpg.de
[3] http://veritas.sao.arizona.edu

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gained at the inter-telescope level where triggers can combine the information from spatially neighbouring telescopes or even from all telescopes in the array. Array-level or inter-telescope triggers typically require a coincidence of at least two telescopes in a time window of several 10 ns duration [4,5] or make sure that the camera images are compatible with the origin from a γ-ray shower [6]. Such triggers reject, in particular, NSB triggers and events where a single muon from a hadronic shower hit a telescope and generated a camera trigger due to its Cherenkov emission.

At the telescope level, a versatile camera trigger is needed to select γ-rays over the full targeted energy range with good efficiency. Ideally, the trigger hardware should be applicable largely independent of the telescope type and the trigger should also provide guidance to the camera-readout system how much of the image should be kept (both in space and, in particular in the presence of a large time-gradient in the image, in time [7]). This paper describes the concept of a digital camera trigger based on Field Programmable Gate Arrays (FPGAs). Section 2 presents the design and a possible hardware implementation of the trigger. Section 3 discusses test results with prototype trigger boards. The impact of the proper choice of the camera trigger algorithms is illustrated in Section 4 using the results of a Monte Carlo simulation with the `trigsim` program (described in the appendix). Conclusions are presented in Section 5.

2. A digital camera trigger for CTA

2.1. Camera trigger strategies

Camera trigger strategies employed in current-generation experiments [8,9] are either based on the topological distribution of pixel hits (i.e. pixels with a signal above a discriminator threshold) or on the analogue sum of pixel signals. In the first approach (referred to as *majority trigger*) one requires at least N_{maj} (for example 3) pixels above a certain threshold (a few p.e.) in a coincidence window of few nanosecond length. Such trigger designs differ in the definition of pixel groups (out of which N_{maj} pixels must be above threshold) and in the required hit pattern (pixels neighbouring or not). In the second approach (the *sum trigger*), the analogue sum of all signals in a pixel group (trigger patch) must be greater than a value DT_{sum} (around 20 p.e.). To suppress the impact of afterpulses the pixel signals are often clipped (for example at 6 p.e.) before the summation. For both majority and sum triggers the used pixel groups are usually overlapping in space to avoid losses of shower images that occur at the boundaries of two pixel groups.

The implementation of majority triggers can be done in an analogue or digital fashion alike, and also mixed concepts (for example the fast analogue summation of comparator output signals in a pixel group [4,10]) have been used. The implementation of an analogue sum trigger was instrumental in lowering the trigger threshold for pulsar studies [11], but it is clear that also an approximation of such a trigger can be built using digital electronics. For CTA, with its increased number of telescopes and different Cherenkov camera types, aspects of the camera trigger like costs per channel, robustness, adaptability to the camera geometry and the energy range targeted with a certain telescope type are particularly important. In this sense, fully digital camera triggers based, for example, on fast, freely reprogrammable FPGAs may offer advantages over analogue solutions where the trigger logics has been hardwired. The algorithm executed in such a trigger scheme can be modified and adapted easily, and it is also possible to run several trigger algorithms in parallel and to combine their results to obtain a higher photon efficiency.

For definiteness, the case of an MST with about 2000 photomultiplier tube (PMT) pixels that are arranged in a specific geometry will be considered in the following. It is clear that the general trigger concept can be adapted to other telescopes sizes and photon detection technologies (e.g. silicon photomultipliers or multi-anode PMTs).

2.2. The FPGA trigger

The digital FPGA trigger described here is based on the idea to generate digital camera images with a depth of e.g. 1 bit at a rate of e.g. 1 GHz and to process the images with one type of rather inexpensive FPGA which can look for pixel coincidences in time and space. Full image coverage is ensured by the processing of overlapping camera regions. The envisaged trigger scheme comprises three levels, L0–L2:

The L0 stage (Section 3.1): imposes a basic signal threshold and digitizes the preamplified PMT signals with the help of a programmable comparator. With some further signal processing, the length of the digital signal can be used to encode the time over threshold (TOT) of the PMT pulse or an estimate of the signal amplitude derived from the TOT.

The L1 stage (Section 3.2): consists of FPGAs each of which receives the L0 signals from a camera region that is large enough to contain a good fraction of a possible shower image (at most 49 pixels). Overlap of the camera regions is ensured by an exchange of L0 signals with neighbouring FPGAs. Each FPGA executes freely programmable trigger algorithms in time slices of about 1 ns length and generates a L1 trigger signal for its camera region.

The L2 stage (Sections 3.3 and 3.4): combines the L1 trigger signals from all overlapping camera regions and generates a camera trigger.

2.3. Trigger architecture

The computing power of low-cost FPGAs, the number of allowed input/output (I/O) channels and the speed of the links between PMTs and FPGA must be balanced with the size and the required overlap of camera regions. Some CTA camera designs define a group of 7 pixels (one central pixel and the six surrounding pixels) as a basic building block that can be handled and exchanged independently of other pixels in a camera. Besides the PMT pixels such a so-called *cluster* contains also the needed infrastructure (high and low voltages), front-end electronics (preamplifiers, data buffers), and trigger boards. Each cluster has six direct neighbours, and a complete CTA camera can be built up by combining some hundred clusters as illustrated in Fig. 1 for an MST camera with 1897 pixels in 271 clusters. An arrangement of seven clusters (49 pixels) is referred to as *super-cluster* and subtends an angle of O(1°), i.e. it covers a good fraction of even the largest shower images. One cluster FPGA is assigned to each cluster and can receive up to 7 L0 signals from each of the 6 surrounding clusters by means of fast serial links. At the same time up to 7 L0 signals can be transmitted to each of the 6 surrounding clusters. Every cluster FPGA is thus the central engine of a super-cluster. In the design described here, there are 8 LVDS input and 8 LVDS output connections between any two cluster FPGAs. Each cluster FGPA utilizes 7 inputs from the local cluster and 5 of the 7 inputs from each of the six neighbouring clusters, cf. the inset in Fig. 1, i.e. the presently implemented firmware exchanges only 5 L0 signals with the surrounding clusters. Every cluster FPGA has thus 37 inputs, except for clusters that are located at the camera boundary and have therefore fewer inputs. This mapping allows the execution of trigger algorithms on the central 37 pixels of a super-cluster and creates a sufficient overlap of the super-clusters. The unused 3×2 fast LVDS channels per connection extend the flexibility of the