A DSP BASED CALORIMETER TRIGGER FOR THE DØ EXPERIMENT

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Abstract

We describe the goals, design, implementation, and performance of the DØ Level 1.5 Calorimeter Trigger. This system has been added to the DØ hardware trigger and is based on Digital Signal Processors (DSP's). The Level 1.5 Calorimeter Trigger is a combined hardware and software system which can identify objects (e.g. isolated electrons), or combinations of objects in the calorimeter. The system uses the Level 1 Calorimeter Trigger Tower data and applies filtering algorithms based on neighbor sums of the electromagnetic (EM) and total (EM + hadronic) transverse Energies. Eleven Local DSP's, operating in parallel, process data from overlapping sections of the calorimeter and transfer their results to a Global DSP where the Level 1.5 Calorimeter Trigger decision is made. This decision is then sent to the Level 1.5 Trigger Framework as one of the inputs to the final trigger decision. The average processing time is measured at 136 μs, which implies a maximum input rate of 370 Hz for a 5% deadtime.

More than most hardware trigger processors built for High Energy Physics experiments so far, this project relies on commercial products, and uses them in an application for which they were designed and optimized. The resulting system offers advantages in terms of flexibility and upward migration as improved products become available.

I. Context

The DØ Experiment [1, 2] is a high-energy physics experiment located at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, IL. Fermilab is the world's most powerful collider, with beams of protons and antiprotons crossing every 3.5 μs to produce collisions with an available energy measured as $\sqrt{s}$ = 1.8 TeV. The DØ Detector is located at one of Fermilab's 6 interaction regions. It consists primarily of an 8 meter long cylindrical liquid argon and uranium calorimeter surrounding central tracking chambers, and enclosed by a magnetized iron muon detector. The overall design stresses measurement of parton jets produced at high transverse momentum (high p_T), using the highly segmented, nearly hermetic, calorimeter.

Figure 1: The DØ Trigger Architecture

A subset of the signals collected by the Detector is sent to the DØ Trigger [3], shown in Figure 1. The Trigger, composed of a hardware layer (Levels 1 and 1.5) [4], and a software layer (Level 2) [5], must select events for offline analysis. The goal of the hardware trigger is to process every beam crossing, and initiate, for the most promising events, a high–precision full data readout of the Detector. The software trigger performs detailed analyses of the event on the full data set to obtain further rejection, and makes the final decision to save an event to tape for offline analysis.

The Level 1 Trigger consists of Level 1 Trigger Subsystems and the Level 1 Trigger Framework. Each Level 1 Trigger Subsystem processes detector–specific information and produces, for every beam crossing, an indication of the activity seen by its associated Detector component. These indications are transmitted to the Level 1 Trigger Framework, which determines whether the event is to be rejected, or digitized for further analysis. This decision must be made between beam crossings, before the information is overwritten in the Detector Front-Ends. The Level 1 Trigger Subsystems perform, in hardware, relatively sim-

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ple fixed algorithms with programmable parameters. The Level 1 Trigger accepts about 1 event out of every 300-600 beam crossings.

The Level 1.5 Trigger produces additional rejection by allowing more complex data processing, at the expense of some experiment deadtime. This not only purifies the event sample sent to the software trigger, but also allows for a more efficient usage of the limited bandwidth available in the triggering and data acquisition system. The Level 1.5 Trigger consists of Level 1.5 Trigger Subsystems (again associated with Detector components) and a Level 1.5 Trigger Framework. A maximum of 250 μs is available for the Level 1.5 Trigger Subsystems to produce their triggering information. The Level 1.5 Trigger is used to further qualify a subset of the events which have been accepted by Level 1, and accepts about 1 out of every 5-10 submitted events.

The Level 1 Trigger Framework, Level 1 Calorimeter Trigger, Level 1.5 Trigger Framework, and Level 1.5 Calorimeter Trigger [6] were designed and built at Michigan State University.

II. Level 1 Calorimeter Trigger Limitations and Solutions

The Level 1 Calorimeter Trigger receives signals from Trigger Towers which are 0.2 in pseudo–rapidity (η) by 0.2 in azimuthal coordinate (ϕ). Each Trigger Tower is made of 2 sections identified as EM and Hadronic for a total of 2×1280 Trigger Towers.

Although electron showers are typically smaller than Trigger Towers, the energy deposited is frequently shared between 2 or more neighboring Trigger Towers—the signals from these neighboring Towers must be taken into account to determine the true energy deposit. The Level 1 Calorimeter Trigger does not have this capability. The thresholds that can be safely applied at Level 1, while preserving good efficiency, must thus be set to a fraction of the desired electron signal. For jets, which span many Trigger Towers, this problem is more severe.

This lowering of the thresholds degrades background rejection and leads to high trigger rates. Furthermore, the ability to trigger on multiple electrons or jets is limited.

We designed the Level 1.5 Calorimeter Trigger to allow signals from adjacent Trigger Towers to be combined, providing a more accurate determination of a particle's true energy deposit. Preliminary studies showed that relatively simple algorithms could address the energy sharing problem, and provide rejection factors of 3–10 with greater than 90% efficiency. It also seemed clear that any useful algorithm would only require energy signals from Trigger Towers within $\pm$ 2 Trigger Tower indices of the candidate Tower.

III. Level 1.5 Calorimeter Trigger Implementation

Purely hardware designs were seriously considered, but would have fixed the algorithm in the choice of the architecture. These designs were not very flexible, and would not have allowed the implementation to proceed independently of algorithm development. For these reasons, the DØ Collaboration chose to support the processor–based design presented here.

Early in the design studies, it became clear that the major technical challenge of the Level 1.5 Calorimeter Trigger was *not* in the implementation of a particular algorithm. It was rather in making the Trigger Tower data available to the processing elements. We directed our attention to DSP's since they are, much more than conventional CPU's, optimized for the type of data manipulation needed for this application.

We chose the Texas Instruments TMS320C40 [7, 8], a commercial 32–bit floating–point DSP, to provide the processing power for the Level 1.5 Calorimeter Trigger. The TMS320C40 provides the necessary high I/O bandwidth via its 6 high–speed Communication Ports and associated DMA Channels.

To implement the system we selected commercial VME products. The Hydra-II [9, 10] card offers 4 'C40 processors, and provides external access to 4 Comm Ports for each 'C40, while using the other 2 Comm Ports to ring-connect the processors. Additionally, each Hydra-II provides both VME slave and VSB master interfaces.

The Level 1.5 Calorimeter Trigger processing was decomposed into the following 4 basic steps:

1. Collect all Trigger Tower energy data
2. Scan all 1280 Trigger Towers looking for candidates
3. Use an algorithm to confirm or reject these candidates
4. Combine the results and form a decision based on a global analysis

Fundamental to the architecture of the Level 1.5 Calorimeter Trigger is the realization that the Trigger Tower data need not be examined sequentially. The neighbor energy summing process is a *local* process, requiring data from a contiguous set of Trigger Towers. The calorimeter is therefore partitioned geographically and serviced in parallel by the Local DSP's. Specifically, these Local DSP's are responsible for the collection, scanning, and candidate confirmation phases of the Level 1.5 Calorimeter Trigger processing. They then pass the confirmed objects to a Global DSP, which is responsible for the global analysis processing. A Service CPU oversees the operations of the DSP's, communicates with the rest of the trigger system, and provides error recovery. The architecture of the Level 1.5 Calorimeter Trigger is shown in Figure 2.

Figure 3: Arrangement of DSP's

There are 11 Local DSP's, each of which receives data from all 256 Trigger Towers in a patch of 32 ϕ by 8 η Towers. Each Local DSP is responsible for finding candidates from the central region of 4 η Towers. The 2 η–Tower–wide patches flanking the central region are provided to meet the neighbor range goal described in Section II. These 8 η–Tower–wide patches overlap, such that each Trigger Tower datum is delivered to 2 Local DSP's—it appears in the central candidate region in one Local DSP, and in the flanking neighbor region in another. Special cases at the ends of the Calorimeter are eliminated by providing zero–energy data for the nonexistent neighbors. Figure 3 illustrates the arrangement of the DSP's.

The Trigger Tower data arrive via 4 Comm Ports on each Local DSP (except for the Local DSP's at the ends of the Calorimeter, which only require 2 Comm Ports for Trigger Tower data input). Forty Comm Ports are used in parallel for Trigger Tower data input, providing an overall input data bandwidth of 400 MBytes/sec. The data come from a "hook" that was designed into the Level 1 Calorimeter Trigger, and are captured and transported via custom Energy Readout Paddleboards and Distributor Caps [11].

Each Local DSP passes its confirmed objects to the Global DSP via a Comm Port. However, only four of the Local DSP's have direct connections to the Global DSP. The other seven Local DSP's pass their confirmed candidates to one of the directly connected Local DSP's via the ring–connected Comm Ports.

Figure 2: Level 1.5 Calorimeter Trigger Architecture

The Global DSP performs a global analysis of the confirmed objects (*e.g.* determines if one or more electrons have been found), and returns its results to the Level 1.5 Trigger Framework via the Service CPU. The Level 1.5

Calorimeter Trigger records its results in a Data Block, which is provided to the Level 2 Trigger, and is kept as part of the event's data record.

The Service CPU is assisted in its functions by a small amount of custom peripheral hardware. This hardware provides fast interfaces to the rest of the trigger system (Level 1 and Level 1.5 Trigger Frameworks), to minimize the Level 1.5 Calorimeter Trigger's response time.

The Trigger Control Computer (TCC) [12, 13] that already controls and monitors the Level 1 and 1.5 Frameworks and the Level 1 Calorimeter Trigger also loads the executable images and configures the Level 1.5 Calorimeter Trigger.

IV. Level 1.5 Calorimeter Trigger Software

The tasks of the Level 1.5 Calorimeter Trigger are divided into two classes. Roughly these are: application of an algorithm and movement of data. This is reflected in the division of the Level 1.5 Calorimeter Trigger software into Tool code, responsible for applying an algorithm to confirm or reject candidates, and Frame code, responsible for receiving Trigger Tower energy data, scanning for candidates, calling the Tool for each candidate, building the Data Block, handshaking with the Service CPU, and performing initialization tasks including receiving and checking operating parameters.

We chose to keep the Tool distinct from the Frame, so that the Tool code can be replaced without interfering with the Frame code. The Frame is by far the largest component of the DSP software. All of the DSP code has been written in assembly language.

Although our use does not constitute a traditional DSP application, the powerful data access and manipulation features of the 'C40 are used to efficiently perform the required tasks.

V. Algorithm and Performance

The selected algorithm is designed to find isolated electrons, and was chosen by performing Monte Carlo analyses of several algorithm options. The quality of an algorithm is measured by its:

- Efficiency at confirming "good" events (*i.e.* events which contain an electron)
- Rejection factor for "bad" events (*i.e.* no electron)

The current Tool code implements the 1x2 EM E_t vs. 3x3 Tot E_t "EM Nearest Neighbor" algorithm. In the Local Tool, this algorithm:

- Calculates the 1x2 EM E_t Sum of a candidate Tower plus the most energetic of its 4 neighbors
- Calculates the 3x3 Total E_t Sum centered around this candidate Tower
- Confirms a candidate as an electron if both
  1. 1x2 EM E_t Sum $\geq$ 1x2 EM E_t Energy Threshold
  2. 1x2 EM E_t Sum / 3x3 Total E_t Sum $\geq$ Isolation Ratio Threshold

In the Global Tool, this algorithm:

- Confirms the event if the number of confirmed electrons is $\geq$ Electron Count Threshold

The 1x2 EM E_t Threshold, the Isolation Ratio Threshold, and the Electron Count Threshold are all programmable via TCC and COOR, DØ's overall control system. These 3 thresholds, taken together, are called a Level 1.5 Calorimeter Trigger Parameter Set.

The Level 1.5 Calorimeter Trigger introduces an average deadtime of 136 μs/event. A detailed breakdown of the processing time is given in Table 1.

An offline simulator for the Level 1.5 Calorimeter Trigger was developed in parallel, and has been used both during the algorithm selection phase (as a device to study algorithms before the Level 1.5 Calorimeter Trigger existed) and the commissioning phase of the project. The simulator will also be used as a verification device throughout the life of the Level 1.5 Calorimeter Trigger.

Preliminary tests and results with DØ data indicate that the Level 1.5 Calorimeter Trigger can provide rejection factors of 5 with greater than 95% efficiency in filtering electrons.

Many of the 30 hardware trigger requirements operating in parallel during global physics operation at DØ can benefit from the services of the Level 1.5 Calorimeter Trigger. The DØ collaboration is now following a very careful and conservative approach to include and make use of this newly available service in its triggering strategy. With instantaneous luminosity currently increasing at the Tevatron, the Level 1.5 Calorimeter Trigger is offering a satisfactory solution, and avoids needing to resort to prescaling and losing part of the available signal.

VI. Upgrade Paths

The Level 1.5 Calorimeter Trigger has already been shown to be a flexible system. As we gain experience using the system, we expect to explore two classes of upgrade paths: increasing the performance, and improving the functionality, of the Level 1.5 Calorimeter Trigger.

An examination of Table 1 shows that the largest consumer of processing time is the transfer of objects from the Local DSP's to the Global DSP. We are examining several methods to reduce the time required for this transfer through either software or hardware changes.

Based on commercial hardware, the Level 1.5 Calorimeter Trigger can benefit from industry trends. DSP chips

Level 1.5 Calorimeter Trigger Activity	Step Time (μs)	Elapsed Time with One Tool Call (μs)
Processing request for event n	0	0
All energy data arrives at Local DSP's	18.8	18.8
Local DSP candidate scan (with no Tool calls)	30.7	49.5
Each Local Tool call	6.6	56.1
Local DSP's transfer confirmed objects to Global DSP	56	112.1
Global DSP confirmed object scan	5.5	117.6
Each Global Tool call	0.5	118.1
Answers presented to Level 1.5 Trigger Framework	9.4	127.5
Experiment deadtime ends	8.5	136
Data Block for event n built	252	388

Table 1: Level 1.5 Calorimeter Trigger Timing

are clearly a very active sector of the electronics and computer industry. For example, 60 and 80 MHz versions of the 'C40 have already been announced, and present obvious upgrade opportunities. New DSP architectures, such as the Texas Instruments TMS320C80 [7, 14], with 4 DSP's and a general–purpose processor embedded on one chip, can also become attractive options.

Several ideas for functional improvement are being discussed. The Level 1.5 Calorimeter Trigger was conceived as an electron filter, but its flexible design is open to other possibilities including innovative approaches in electron or jet filtering at the DØ hardware trigger level. The Level 1.5 Calorimeter Trigger could also be duplicated to operate several crates in parallel, but independently, on either the same or different events, while applying different algorithms.

More ambitious functional upgrades could involve importing and correlating information from other DØ Detector components.

VII. Conclusions

We have presented the DØ's Level 1.5 Calorimeter Trigger, a fully programmable trigger based on commercial DSP products. This Trigger was designed and implemented in less than a year by a relatively small design team. It is a flexible system, where the triggering algorithm was kept independent from the architecture.

The Level 1.5 Calorimeter Trigger has been operational at DØ since August 1994, and has caused no down time due to either hardware or software failures since then. It is currently used for electron filtering.

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