Evolving the DAQ and Analysis Software of the AIDA Telescope: Toward high rates and *one-trigger-per-particle* Operation

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Abstract

A high resolution ($\sigma \approx 2\,\mu\text{m}$) beam telescope based on monolithic active pixel sensors was developed within the EUDET collaboration. It has become the primary in-beam tool for many high-energy physics groups, largely due to its precise spatial resolution, reliable operation and DAQ integration capabilities. For the telescope to deliver this excellent performance, two software packages play a central role: EUDAQ, a multi-platform data acquisition system that allows easy integration of the device-under-test, and EUTelescope, a group of processors running in ILCSoft's Marlin framework that allows the spatial reconstruction of particle tracks and the final data analysis.

In parallel to their successful operation in test beams for many years, both software packages are under constant development: from the integration of new device types and use-cases, to improvements to usability and flexibility, and the support of new features such as the high-rate capabilities of the next-generation pixel beam telescope developed within the European detector infrastructure project AIDA.

In this contribution, we present the features of the current releases of both EUDAQ and EUTelescope and discuss the plans for further development toward an easy-to-use software stack with the capability for high particle and data rates within the AIDA work package 9.3.

1 Introduction

Beam tests of future tracking devices are crucial to determine their characteristics under realistic operating conditions. By determining the track of a charged particle in a test beam to high precision using a beam telescope, one can perform detailed studies of newly developed detectors.

Originally built at DESY within the EUDET JRA1 project for detector R&D toward the International Linear Colider (ILC), the EUDET beam telescope [1] was designed as an easy-to-use system with well-defined interfaces allowing test beam studies on a short time scale.

Since the first EUDET telescope has been used in beam tests in 2007, it has become the primary beam tool for many groups, largely due to its precise pointing resolution of $\sim 2\,\mu m$, reliable operation and DAQ integration capabilities.

For the telescope to deliver this excellent performance, two software packages play a central role:

- EUDAQ [2], a multi-platform data acquisition (DAQ) system that allows easy integration of the device-under-test, and
- EUTelescope [3], a library that provides tools for the spatial reconstruction of particle tracks and the final data analysis.

Based on the EUDET telescope, a next generation telescope is being developed within work package 9.3 of the European AIDA project to better fulfill the evolving requirements of the user community. It will provide more than two orders of magnitude higher trigger rates of up to 1 MHz, precise time-stamping in the sub-nanosecond range, and large-area sensor planes of $4 \times 4\,\mathrm{cm}^2$. This is made possible by a new trigger logic unit (TLU) with both faster discriminators and a simplified, shared-clock interface to the connected devices and by replacing one of the two telescope arms consisting of a triplet of MIMOSA26 sensors with three MIMOSA28 quad-planes. Both of these hardware developments are described in detail in [4] and [4], respectively.

To fully exploit the new hardware capabilities, both the DAQ framework and the analysis framework have to be extended to be able to deal with a significant increase in data rates, to support time stamping and multiple triggers per device readout, and to allow for a more challenging (offline) alignment of sensor planes composed of several individual devices.

An ongoing effort is made to incorporate these features and which are foreseen to be released as versions EUDAQ 2.0 and EUTelescope 1.0 later this year.

2 EUDAQ 2.0 – A Flexible High-Rate Capable DAQ Framework

EUDAQ is a generic DAQ framework that has been successfully used in testbeams with the EUDET-family of beam telescopes since 2007. It allows the easy (but optional) integration of the device-under-test and its DAQ into the telescope data stream and gives the user a central interface to control and monitor the operation of the full system. EUDAQ features a very modular design in which individual components communicate via TCP/IP and can run on different networked machines.

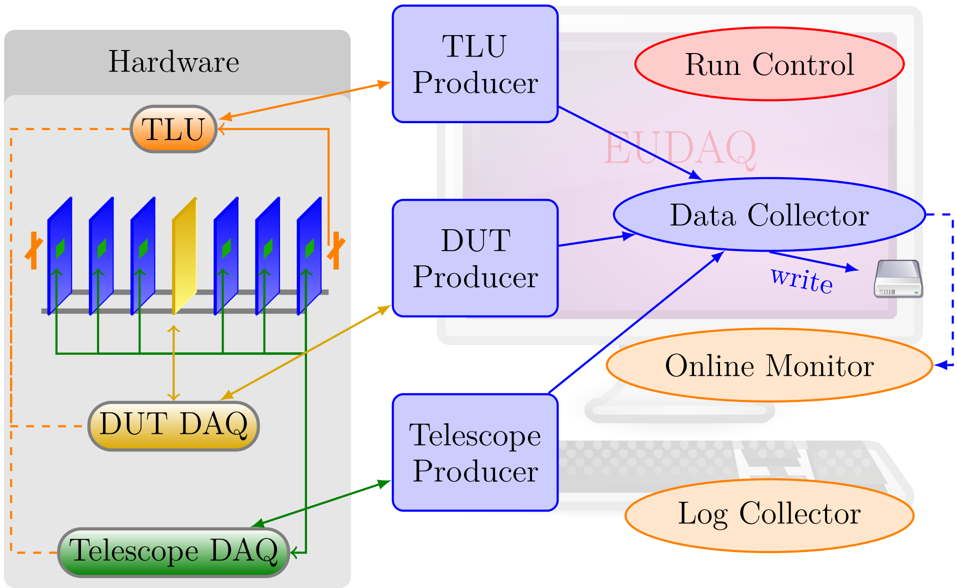

Figure 2.1: Schematic layout of the components of the EUDAQ framework and the data flow from the hardware DAQ systems through their *Producers* to the *DataCollector* which finally stores the data to disk.

The central authority is called *RunControl*. It provides the user with a choice of either a graphical or console-based interface with status information on the current operation and allows to configure, start or stop the data taking. The actual device-hardware interaction with the telescope or the device-under-test is performed by independent *Producers* as illustrated in figure 2.1. Well-documented examples are provided to make the integration as easy and straightforward as possible. All Producers send their raw or already-decoded data to a *DataCollector* which stores it to disk.

EUDAQ will also be the DAQ framework of choice for the AIDA telescope. However, in order to make use of the capabilities of the newly developed AIDA TLU and to support the high data rates expected from large-area telescope planes and the increased trigger rates, modifications to both the underlying data format and the data flow are necessary.

2.1 New EUDAQ data format: *Packets* instead of *Events*

Instead of sending the data in *Events* which correspond to a device readout matching a single trigger, a Producer in EUDAQ 2.0 can record and send the data in units "natural" to its operation (e.g. a set of frames for Mimosas) and store them in *Packets*. These can

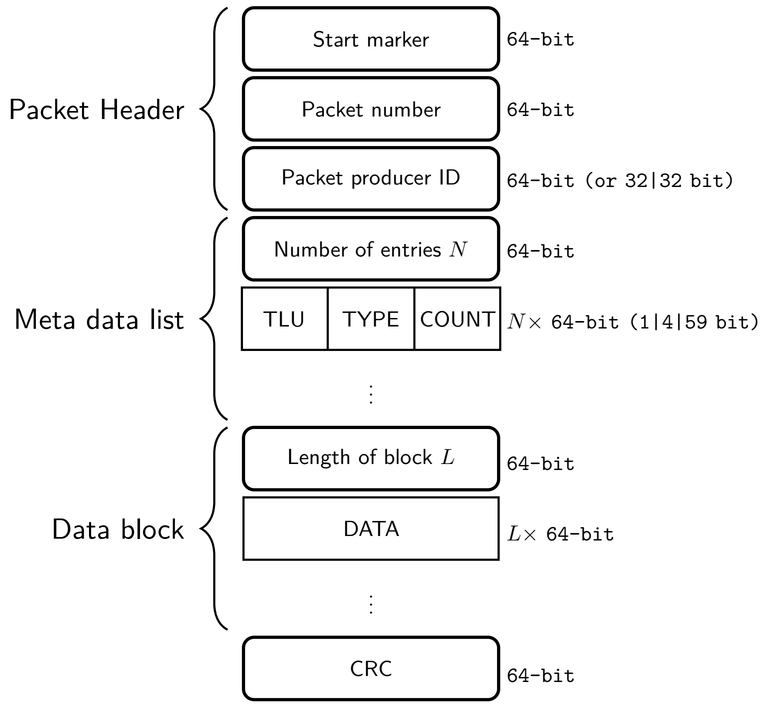

Figure 2.2: The new data format: packets structured into list of meta data (timestamps/counter values) which describes trigger and/or time ranges and the corresponding block of data.

not only cover arbitrary number of triggers and/or time ranges but also include additional meta information that allow to identify packets from different producers corresponding to the same trigger without having to decode the actual data.

The new Packet data format makes it significantly easier to integrate a diverse range of DAQ concepts into EUDAQ, such as untriggered or data-driven devices. Furthermore, the meta data format is designed to allow partial data merging on the fly during data taking (as discussed in section 2.3).

As illustrated in figure 2.2, the Packets consist of a packet header, a body containing meta data and the actual payload data, and a trailer. The **packet header** is composed of:

- a start marker,
- the *packet number* is set by each producer for every data block send to the data collector (starting at 1 for every run), and
- a (unique) producer ID field that describes the detector/producer from which the data originate and which decoder to use; this field is divided into a major and a sub field, each 32-bit wide.

TYPE	**description**
0000	internal trigger – *reserved for internal TLU usuage*
0001	external trigger
0010	shutter falling
0011	shutter rising
0100	edge falling
0101	edge rising
0110	spill off
0111	spill on
1011	start/end of packet data recording
1111	first/last trigger *number* contained in packet

Table 2.1: Codification of the meta data *TYPE* field in the new packet format based on TLU signals[4]. The specific value defines how the *COUNT* field of the meta data entry is interpreted. An additional *TLU* bit indicates whether or not the counter value is based on the central clock provided by the AIDA TLU.

The **meta data** to each packet consists of a length field and a list of counter entries with three fields:

- *TLU* bit to indicate whether or not this counter corresponds to a TLU signal,
- a *TYPE* ID with a width of 4-bit which indicates the nature of the counter, e.g. trigger number, clock count (i.e. timestamp) of a TLU-event, or timestamp of begin/end of packet as detailed in table 2.1, and
- the 59-bit wide counter value.

This allows to store as meta data:

- a list of trigger numbers,
- a range in time during which the data was recorded, and/or
- a list of trigger timestamps.

And finally, the **trailer** is a 64-bit field designated for storing an (optional) *check sum* over the full packet.

In order to keep backward-compatibility, the former Events can be wrapped within the new Packet structure; this is foreseen to happen transparent to the Producer, so that existing device integrations do not need to be modified as long as the performance limitations of the old format and data taking are acceptable to the user.

2.2 Spreading the load: multiple data collectors

In order to cope with the high data rates expected from the increased trigger rates and the large-area sensor planes, EUDAQ 2.0 will allow to run multiple DataCollectors simultaneously[1]. Each DataCollector can be assigned to a single Producer and can run locally on the same physical machine as the Producer itself. This makes the setup more flexible and avoids bandwidth bottlenecks such as slow network connections.

2.3 Online data integrity checks, selected data packet reading, and online monitoring

As described in the previous sections, EUDAQ 2.0 will allow devices to record their data in asynchronous data streams that is stored on different physical machines. This poses additional challenges for online consistency checks and online monitoring which typically provides e.g. correlation plots to allow the user to verify the correct operation of all DAQ systems.

By relying on online checks based on the trigger information that each device's Producer stores in the meta information of its Packets and a separate data quality monitoring (DQM) system, EUDAQ 2.0 will be able to provide more thorough and flexible online verification and monitoring than previous releases.

For devices that make use of the new synchronous TLU interface, the correct and synchronous operation can be assessed based on the trigger and clock information that is expected to be common between all devices. Since the time stamped trigger information is stored within the meta information field of each corresponding Packet, the verification of this data between devices and the matching of Packets belonging to the same trigger can be done by meta data alone.

The task will be performed by a central *Run Monitor* processor while the retrieval of the packets will be performed by *Reader* processors as shown in figure 2.3. These collect packets (or optionally their meta-data only) by accessing the files written by the data collectors and retrieving specific trigger and clock ranges. For this purpose, the a copy of

[1]This feature is available as of EUDAQ version 1.3, as described in section 3.2.3 of the manual[5]

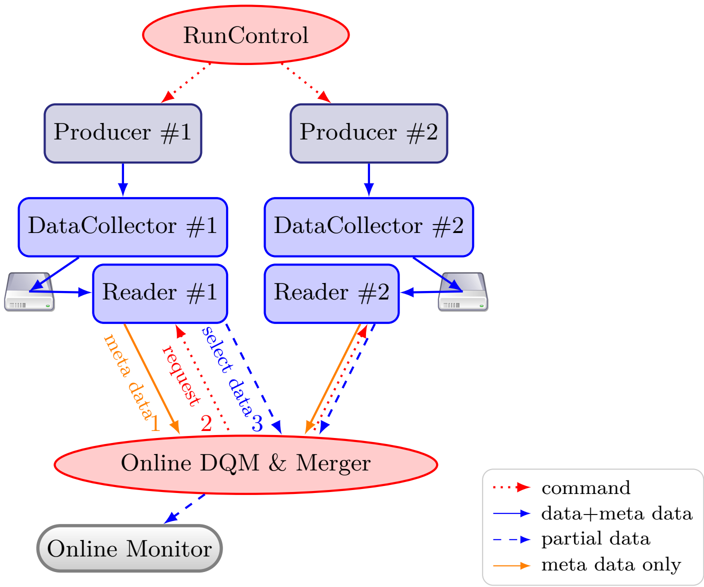

Figure 2.3: A schematic overview of the components of EUDAQ and the foreseen data flow for version 2.0. Shown is the communication between components when writing data from multiple data sources (devices/Producers) to local data sinks (DataCollectors) and monitoring the system online based on a partial sub-set of the stored data merged by a central data quality monitoring process (Online DQM & Merger).

each Packet's meta data and the offset within the data file is stored in an *index file* to speed up the search for specific Packets.

The run monitor can write the thus retrieved Packets to disk, creating a locally available sub-set of the full data corresponding to a specific trigger range and that would be suited for further processing by the existing online monitor or an immediate offline analysis based e.g. on EUTelescope.

All components of the DQM system will be operating separately from the central DAQ modules to minimize interference and allow for a later startup. However, the components will be based on and part of the EUDAQ classes and will be using the same network communication interfaces.

3 EUTelescope 1.0 – A Powerful Toolset for Track Reconstruction

EUTelescope is a generic set of processors that run in ILCSoft's Marlin framework providing tools for clustering, alignment, track reconstruction, and data analysis. Originally developed for the EUDET telescope, it has since been used in other setups such as the

CMS Pixel telescope [6].

Especially when analyzing data recorded at low-energy beams such as the DESY-II or ELSA testbeam facilities, it is important to take into account effects of multiple scattering. Therefore, the upcoming 1.0 release of EUTelescope will provide tracking based on General Broken Lines (GBL) [7] which treats scattering more accurately in all materials present. GBL also offers alignment capabilities using a direct interface to Millepede-II.

Furthermore, a new geometric clustering algorithm allowing for generic pixel shapes and combinations has been developed together with a simplified geometry core based on ROOT::TGeo.

These changes significantly simplify the analysis flow, easily allow for an iterative alignment strategy, and improve the usability and run-time speed. EUTelescope 1.0 will therefore be better suited for immediate offline-analysis directly after online merging in EUDAQ, providing a powerful semi-online monitoring facility.

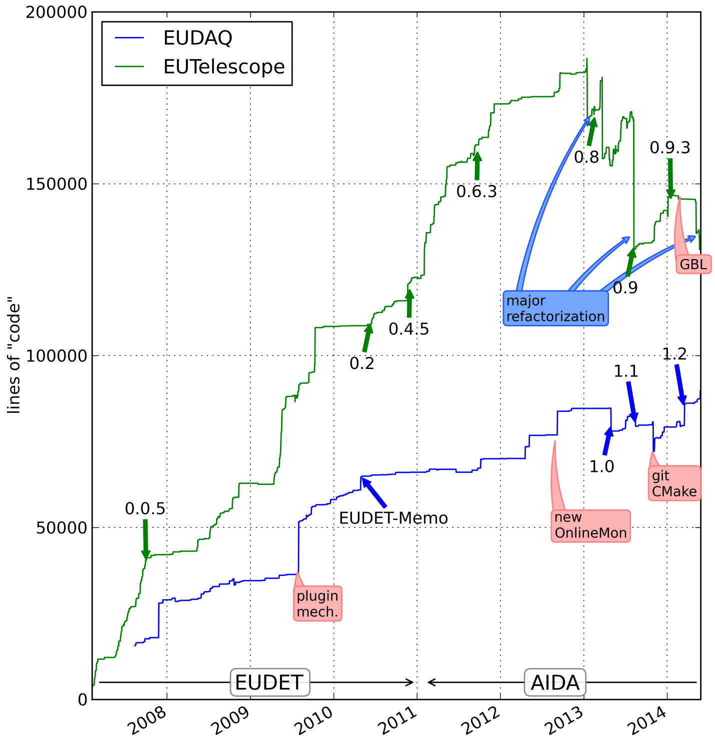

Figure 3.1: Total number of lines of “code” (including comments, documentation and helper scripts) of the two software frameworks versus time. Selected major feature additions (red boxes), releases (arrows) and refactorizations (blue box) have been highlighted.

4 Continuous Operation Needs Active Development

With the successful usuage of the first EUDET telescope for testbeam studies since 2007, four additional copies have been produced and are being operated in various beams around the world. This results in a constantly growing user base with evolving needs. These have been the focus particularly of recent releases of EUDAQ and EUTelescope, by constantly extending the available documentation and examples, by providing support through online forums and workshops, and by making the installation easy and straightforward.

The quickly progressing development over the past years as illustrated in figure /ref-fig:loc has been made possible by the open development model followed for both software frameworks which encourages external contributions. With open source code managed through *git* and hosted on GitHub, new functionality has been integrated in close collaboration with developers from many different institutes. Using automated nightly builds based on the CMake/CTest toolset, problems can be identified and fixed early in the development cycle. Furthermore, data-driven regression tests are used to constantly verify the output of the frameworks against a set of known good references. This ensures the stability and continued validity of the results.

5 Summary

EUDAQ and EUTelescope are central software components of the EUDET beam telescopes and a key factor in their success. They offer the user a ready-to-use framework for DAQ integration and testbeam data analysis and are constantly being evolved to meet the user's needs. For the next-generation AIDA telescope, both EUDAQ and EUTelescopes are being extended to be able to cope with higher data rates, to provide an extended data format and to handle more challenging offline synchronization and alignment tasks.

Specifically the additional meta data available in EUDAQ will make more thorough consistency checks and online verification possible: as devices obtain their clock directly from the TLU, synchronization loss and missed triggers can be reliably detected online. For this purpose, the meta data only will be collected and verified by a central data quality monitoring process. Additionally, the data can be (partially) merged online by requesting packets containing specific trigger ranges – this allows to generate e.g. correlation plots online or even run the data analysis on a sub-set of the data while the recording is ongoing.

Even with these fundamental changes to the data-handling concept of EUDAQ, a lot of effort has been invested to make the modifications backward-compatible in order to preserve existing device integrations by the users.

6 Acknowledgments

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the views of its authors and not those of the European Commission and no warranty expressed or implied is made with regard to such information or its use.

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