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DIGITISATION OF THE ANALOGUE WAVEFORM SYSTEM AT ISIS

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Abstract

The Analogue Waveform System (AWS) at the ISIS Neutron and Muon Source is a distributed system that allows operators to select and monitor analogue waveforms from equipment throughout the facility on oscilloscopes in the Main Control Room (MCR). These signals originate from key accelerator systems in the linear accelerator and synchrotron such as the ion source, magnets, beam diagnostics, and radio frequency (RF) systems. Historical data for ISIS is available on the control system for many relevant channels. However, at present, to avoid disrupting the oscilloscope displays in the MCR, only an hourly image capture of the AWS waveforms is stored. This is largely inadequate for potential data-intensive applications such as anomaly detection, predictive maintenance, post-mortem analysis, or (semi-)automated machine setup, optimization, and control. To address this, a new digital data acquisition (DAQ) system is under development based on the principle of large channel count, simultaneous DAQ. This paper details the proposed architecture of the system and the results of initial prototyping, testing, and commissioning.

INTRODUCTION

The Analogue Waveform System has been a key part of accelerator operations since the inception of the ISIS Neutron and Muon Source in 1984 [1]. At present, it is a distributed analogue waveform switching system that allows operators to select and monitor signals from equipment throughout the facility from the Main Control Room (MCR).

Recently the particle accelerator community has been turning to the increasingly mature fields of machine learning and data science to help manage the inherent complexity of these facilities [2]. Therefore, to modernise the current system in order to meet the data needs of these techniques, a new digital data acquisition system (DAQ), called the Digitised Waveform System (DWS), is under development. The new system aims to increase the signal capacity, improve flexibility, as well as signal integrity of the system. Further benefits are expected from the ability to store and archive descriptive statistics of the waveforms and raw waveforms for specific applications.

EXISTING AWS SYSTEM

The AWS consists of three main cable trunks. Each trunk can, in principle, connect any number of ISIS Controls CPCI System (CPS) crates [3] using a daisy chain topology. Each CPS crate provides 32 analogue inputs to the system. However, at most six signals from all the CPS crates connected on a single trunk can be multiplexed to a bank of Tektronix TDS3014B oscilloscopes in the MCR.

The CPS crates contain a Kontron CP3004-SA CPU board, Pickering PXI switching matrix modules (40-531-022/40-531-023), a custom six channel fully differential amplifier board, and a seven segment I/O display board. Inter-crate communication is over the CompactPCI [4] backplane. The direct analogue trunks provide negligible signal transmission latency but limit the flexibility of the system and make expanding the signal capacity difficult. The fast update rate of the oscilloscopes ensure real-time capture of each 50 Hz acceleration cycle.

There are currently 13 AWS CPS crates installed across the facility, providing 416 inputs to the system. Control and status monitoring of the AWS as well as triggering from the ISIS Timing System is provided by the ISIS Control System [5], based on the VSystem SCADA/HMI toolbox from Vista Control Systems [6] .

DWS SYSTEM OVERVIEW

Hardware

Recent technological developments have brought down the cost of high-performance and high channel count digitisers. This has made possible the option to replace the multiplexed analogue approach with a largely digital paradigm consisting of network connected digitisers. A similar one-digitiser-per-device approach with the DAQ placed as close to the accelerator device as possible has recently been proposed and implemented at the Facility for Antiproton and Ion Research (FAIR) [7].

For the DWS, the selected DAQ hardware is the ACQ2106 carrier units from D-TACQ Solutions fitted with two or three ACQ482 ELF modules [8]. These digitisers provide excellent analogue and digital performance at a competitive cost per channel. In addition, it has built-in EPICS support, providing extensive monitoring, supervisory and control features that reduces integration efforts for the new EPICS based control system at ISIS [9]. Each ACQ482 has 16 differential inputs with an analogue bandwidth of 10 MHz and ADC clock speeds up to 80 MSPS. The bandwidth is sufficient to digitise the ≤1 MHz analogue bandwidth of the existing AWS. The signals from the AWS are connected to the VHDCI input connectors of the ACQ482 with 32 channel dual pin LEMO 1U, 19" panels. A total of nine ACQ2106 units will cover the existing system capacity of 416 channels, with the option to install additional units to cover any future capacity requirements.

The Rear Transition Module (RTM-T) in the ACQ2106 units connects to the DAQ server fitted with AFHBA404 PCI Express Host Bus Adapters via LC terminated OM3

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50/125µm optical fiber. Avago AFBR-709SMZ SFP+ transceiver modules are used for the ACQ2106 and AFHBA404 connections. The AFHBA404 is a standard PCIe x4 Gen 2.0 card which provides four SFP+ transceiver ports at up to 6 Gbps [10]. The DAQ server is a Dell PowerEdge T440 Tower Server configured to be rackmountable fitted with an Intel Xeon Gold 5120 CPU at 2.20 GHz. The server has 256 GB of RAM installed and is fitted with a 3.5 TB SSD. A demonstration system, shown in Fig. 1, has been setup and tested for use with signals from various diagnostics systems at ISIS.

Figure 1: The demonstration system for the DWS connected to signals from various diagnostics systems at ISIS.

The DAQ is triggered and synchronised with the ISIS Timing System (200 kHz timing signals over twisted pair (RS-485)) via in-house CPS Type-T timing cards. An in-house 1U, 19" Timing Trigger Mixer unit is used to convert the differential RS-485 signals on the CPS Type-T BNO connectors to TTL compatible single-ended pulses for use with the external single-pole LEMO trigger input on the ACQ2106s. An overview of the DWS is shown in Fig. 2 and a summary of the specifications for hardware components of the DWS system is shown in Table 1.

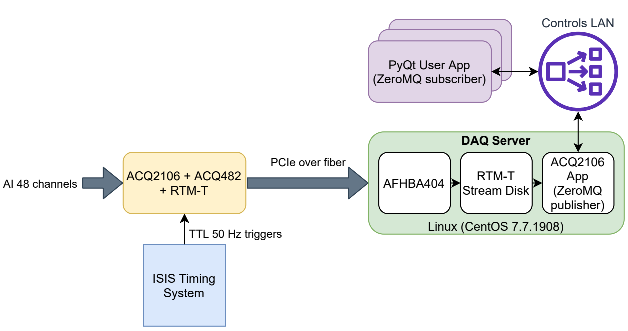

Figure 2: Overview of the DWS.

Software

The DAQ server is set up with CentOS Linux release 7.7.1908 (Core) patched with the real-time Linux kernel.

Table 1: DWS Hardware Specifications

Item	Specification
Dell PowerEdge T440 Tower Server	Intel Xeon Gold 5120 CPU at 2.20 GHz, 14 cores, RAM 256 GB, SSD 3.5 TB.
D-TACQ Solutions ACQ2106, x3 ACQ482, MGT482	48 simultaneously sampled differential analogue inputs, 14-bit, 1 MS/s, ±10 V. PCI-Express over fiber, streaming data over 400 MB/s.
D-TACQ Solutions LEMO Panel	1U 19" rack-mount panel. 32 dual pin LEMO connectors. Differential connection. 100 V Zener diode transient protection.
D-TACQ Solutions AFHBA404	PCIe x4 Gen 2.0 card which provides four SFP+ transceiver ports at up to 6 Gbps.
CPS Type-T, Timing Trigger Mixer	2.5 µs TTL compatible timing trigger pulses at 50 Hz on single-pole LEMO. Remotely configurable delay time with a resolution of 5 µs.

The AFHBA404 Linux device driver is used along side the RTM-T-stream-disk application software [11], both released by D-TACQ Solutions under GNU General Public License v2.0 [12]. The AFHBA404 writes 2 MB buffers directly to memory using DMA operations. Each 2 MB buffer contains 16384 samples, on 48 channels, 16-bit data which corresponds to 16 ms of data on each channel at 1 MS/s. The driver provides the address for the DMA engine to do this. RTM-T-stream-disk creates a series of fixed size binary files in RAM which are overwritten cyclically. The binary data files are consumed by a custom, in-house developed, application that employs the Linux inotify API [13] to monitor the data files and return events when the data files have been written and closed. The data files are then read out in real-time, before they are overwritten by the driver. The ZeroMQ protocol is used for data exchange between the DAQ server and other client applications over controls network using the publish/subscribe messaging pattern to achieve minimum latency. Latency measurements have been performed on the ISIS machine controls network which showed that latency is linearly related to message size. An average latency of 2–6 ms was found for expected message sizes of 30–60 kB. Throughput measurements were also performed over varying message sizes which showed negligible impact on throughput with an approximate throughput of 94 Mbit/s. ZeroMQ was selected as it allowed greater flexibility in terms of client host operating system and programming language, as well as high scalability across multiple machines. Every channel of

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data uses a separate TCP port and is identified with a unique ZeroMQ topic [14]. The data stream is currently started and stopped remotely using the acq400 Host API Python module provided by D-TACQ. The plan is for this to be migrated into the user application in future.

For data visualisation, use of EPICS based Phoebus user displays was investigated. However, it was found that the update rate of approximately 3 Hz was not sufficient for the real-time waveform requirements of the system (4 channels, 16-bit data, 16384 points per waveform at 50 Hz). As a result, a PyQt based application has been developed for real-time user application data visualisation called "DWS Live Viewer" (Fig. 3). The application is a ZeroMQ client that subscribes to selected channels streams and plots them in real-time.

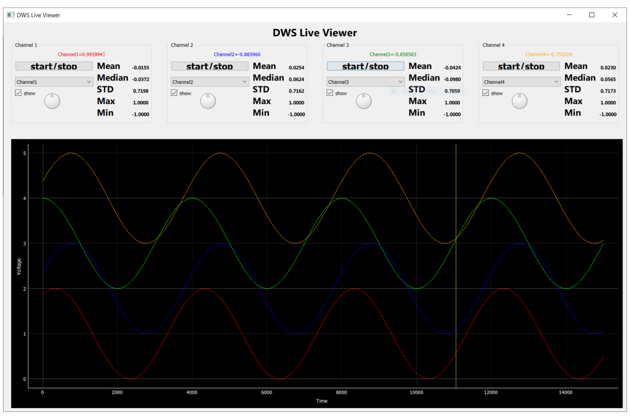

Figure 3: DWS live viewer.

Data Storage Strategy

One of the most important features in the new DWS system is that signals are available in a digital form so digitized waveform storage becomes possible.

An approximate calculation was done to estimate the required storage capacity for 416 signals sampled at 1 MS/s for 16 ms interval synchronised with the machine repetition clock (50 Hz) for 10 weeks run cycle which is around 3.8 petabytes. This volume of data is beyond our capacity to maintain, and therefore the following short-term data storage strategy will be used:

A one minute long ring buffer of raw data for each signal used for diagnostics purposes especially during machine startup and beam commissioning. Another use case is post-mortem data logging. In this case, when an interlock occurs pre-interlock data writing stops and post-interlock data writing starts for a specified amount of time.

For long-term data storage, the proposed solution is to store statistical properties (mean, median, standard deviation, minimum, and maximum) of the raw data rather than storing the waveform data itself.

Raw data from each channel will be received by subscribing to the ZeroMQ stream with the corresponding topic for the channel of interest. Statistical properties will then be calculated and pushed into Telegraf which will aggregate data points into big chunks for efficient data writing into InfluxDB [15]. InfluxDB is a high-performance time-series database optimised for query and visualization of timestamped data . With this solution, a significant reduction in storage capacity and pre-processing overhead can be achieved.

Some applications may require raw waveform data because statistical properties alone aren't sufficient. For cases like this, a ZeroMQ based stream processing pipeline will be implemented to do online data processing rather than batch processing on big data sets of stored raw data.

A summary of the software components of the DWS system is shown in Table 2.

Table 2: DWS Software Specifications

Software	Version	Reference
CentOS Linux	7.9.2009	`https://www.centos.org/`
AFHBA404 Linux device driver	v2.3	`https://github.com/D-TACQ/AFHBA404/`
RTM-T-stream-disk	2.3	`https://github.com/D-TACQ/AFHBA404/tree/master/STREAM`
inotify	Linux kernel ≥2.6.13, glibc ≥2.4	`https://www.man7.org/linux/man-pages/man7/inotify.7.html`
cppzmq	4.8.0	`https://github.com/zeromq/cppzmq`
acq400-hapi	2.8.2	`https://github.com/D-TACQ/acq400_hapi`
PyQt5	5.15.4	`https://riverbankcomputing.com/software/pyqt/`
pyzmq	22.1.0	`https://github.com/zeromq/pyzmq`
pyqtgraph	0.11.1	`https://www.pyqtgraph.org/`
InfluxDB	2.0.8	`https://www.influxdata.com/products/influxdb`
Telegraf	1.20.1	`https://www.influxdata.com/time-series-platform/telegraf`

SUMMARY AND FUTURE WORK

The proposed architecture for a new digital DAQ system for the digitisation, visualisation and storage of waveform signals from the AWS at ISIS has been presented and described. A demonstration system has been setup and tested for use with signals from various diagnostics systems at ISIS. This demonstration system has been newly setup during a long shutdown in ISIS operation. As such, an Agilent 33220A function generator connected to the controls network is currently being used to provide representative waveforms for initial testing and commissioning. Remote control and configuration of the function generator is provided by the PyVISA Python package along with the Keysight IO Library Suite. Waveforms from the existing diagnostics systems will be targeted during the initial beam commissioning prior to the user cycle in January 2022.

Investigations are also underway for two additional tiers of hardware for both low bandwidth signals (< 100 Hz) and those above the bandwidth of the existing AWS (1–500 MHz) that currently sit outside the system. For slow signals a bespoke solution is under development. For the high speed signals, for example from the synchrotron extraction kicker, dedicated digitisers (< 10 channels total) based on MicroTCA [16] will be investigated.

Currently time-stamping of each cycle of data (at 20 ms intervals) is provided on the DAQ server which is synchronised with a NTP server. It is noted that the D-TACQ ACQ2106 digitiser units are White Rabbit (IEEE 1588-2019) [17] compatible and accurate sub-nanosecond time-stamping of the data could be investigated in conjunction with any future development of the ISIS timing system.

The ACQ2106 units are also supplied with calibration data. The calibration data allows client applications to convert raw binary data from the ADC to calibrated voltage readings. So far this has not been implemented but in future the data will be calibrated prior to visualisation.

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