EVENT-SYNCHRONIZED DATA ACQUISITION SYSTEM OF 5 GIGA-BPS DATA RATE FOR USER EXPERIMENT AT THE XFEL FACILITY, SACLA

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Abstract

We have developed a data acquisition, control, and storage system for user experiments at the X-ray Free Electron Laser facility, SACLA, at the SPring-8 site. The system is designed to handle up to 5.8 Gbps data rate of shot-by-shot data in synchronization with the 60-Hz of beam operation cycle. A partial system for the light source commissioning was released in March 2011. The full system will be released to public users in March 2012.

INTRODUCTION

SPring-8 Angstrom Compact Free Electron Laser (SACLA) has been constructed at the SPring-8 site. SACLA is designed to generate X-ray laser with a wavelength as short as 0.062 nm by using a thermionic electron gun, an 8-GeV linear accelerator, and in-vacuum undulators [1]. The accelerator commissioning began in February 2011. The first lasing at a wavelength of 0.08 nm was achieved in June 2011.

The characteristics of XFEL such as the high-peak brilliance, perfect spacial coherence, and the ultra-fast X-ray pulse shorter than 30 fs are believed to open new opportunity in a variety of scientific fields. SACLA will deliver beam time to public users from March 2012.

DATA ACQUISITION SYSTEM FOR USER EXPERIMENT

Requirements and System Overview

Because the SACLA accelerator is driven with the pulsed operation, the X-ray laser is generated accordingly as the pulsed beam. The X-ray laser is generated by Self-Amplification of Spontaneous Emission (SASE) resulting in the fluctuation of the X-ray laser characteristics such as in the pulse intensity, spectrum, etc. In order to analyze the experimental results taking these fluctuation into account, the data acquisition (DAQ) in the experiment at XFEL must be done shot-by-shot in synchronization with the beam operation cycle. Furthermore, in many of the anticipated experiments, a single shot of the X-ray pulse will damage the sample specimen, the synchronized DAQ is indispensable to correlate the recorded data with the specimen characteristics such as orientation, size etc.

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The most experiments will produce data with one-dimensional (1D) data such as waveform from digitizers, two-dimensional (2D) data from optical camera or multi-port charge-coupled device (MPCCD) for X-ray imaging. The devices installed at SACLA produce the data with a size ranging from 0.5 to 10 MB for each X-ray pulse. With 12 MPCCD sensors operating simultaneously at the 60-Hz operation cycle, which is the maximum number of sensors for the first user-experiment runs, data rate reaches 5.8 Gbps. The beam lime optical components consist of mirrors, a monochromator, attenuators, and beam monitors for intensity, position and arrival time. The control system should be designed so that users can correlate component status as well as monitor data with other detector data.

In order to meet these requirements, we have developed a data acquisition (DAQ) system for SACLA. The DAQ system has dedicated networks to transmit the data from all the instruments, monitors, and detectors. The system is also indirectly connected to the user network via a firewall system so that user can attach their own instruments to operate in a coordinated manner. This will lower the cost in building new experimental setup, and add flexibility to the DAQ system.

The DAQ system has on-line monitoring capability for the prompt examination of the experimental conditions. Raw and preprocessed data can be visualized by Live-View service operating in data-handling servers. In the case of the experiments that demand data preprocessing or data mining by high-performance computer for on-line data evaluation, the DAQ system can transfer the data to a PC cluster with 10 Tflops with high I/O performance (8 GB/s), or to the off-site 10 Pflops supercomputer ”K computer”.

The on-the-fly data compression relaxes the requirements of the bandwidth of data transfer as well as the final storage size to accumulate the experimental data. Embedded data compression for 2D data is available at the front-end Camera Link boards.

Control Framework

For control of the facility equipments, we have selected the MADOCA software framework [2], which has been developed and operated at the SPring-8 accelerator complex. The network-distributed computers are controlled via an RPC call by message-passing system. The system consists of the trigger distributors/counters, data-filling computers, parallel-writing high-speed data storage, and relational databases. Figure 1 shows the schematic of the data-

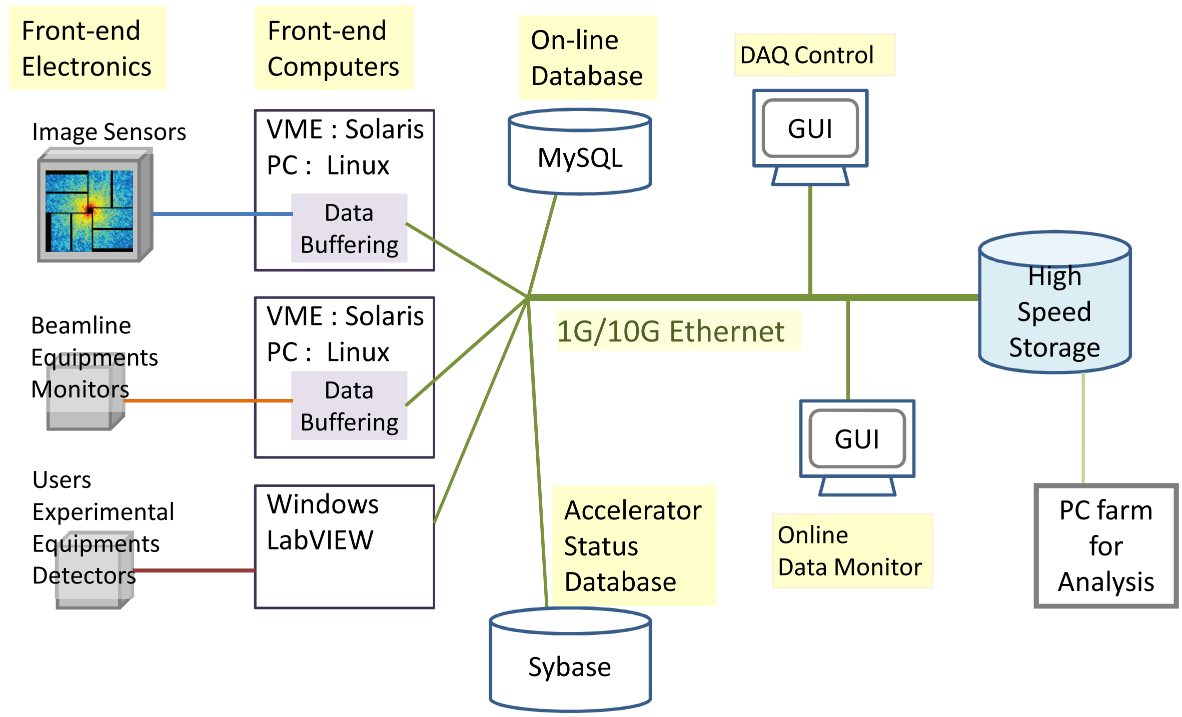

Figure 1: Schematic of the data-acquisition system for SACLA user experiment.

acquisition system for SACLA user experiment.

The original MADOCA has a limitation in the data transfer size. In order to enable a large data transfer for SACLA experiments, a client-server system with TCP socket is implemented to the framework. The large data set is transferred directly via TCP socket system, while the client and server process are controlled by the MADOCA messages. We have demonstrated that 80 % bandwidth of 1 Gbps Ethernet is available for the peer-to-peer data transfer with this system within the modified MADOCA framework.

We introduced the Qt software as the graphical user interface (GUI) for the control tools and data monitoring tools of the facility equipment. The Qt designer software allow us the prompt prototyping of the design of the GUI. The C++ program code of GUI is convenient to call the C API function of MADOCA directly from the GUI itself. So far more than 10 GUIs have been created for our DAQ.

Connectivity to the other software development environment became possible by using the TCP socket data transfer function added in this work. To date, these new functionalities yielded in successful operation of the real-time detector-performance-analysis software implemented on commercial software Igor Pro on Windows platform[3], and of an apparatus to measure the focused X-ray beam running on LabVIEW software on Windows platform.

Front-End System

The most critical part of our DAQ is to collect data from large 1D and 2D data without data loss in synchronization with 60-Hz beam operation cycle.

In the first experimental runs starting from March 2012, we plan simultaneous use of maximum two arrayed MPCCD detectors comprising totally 12 sensors. Each sensor has 0.5 M pixels in size with 16-bit quantized depth. A total throughput of 5.8 Gbps will be required for this sensor. We have chosen Camera Link, which has a transfer rate of more than 2 Gbps, for the interface of the image sensor. The required throughput is achieved by a configuration where each sensor has one Camera Link base-configuration interface. We use Camera Link connections independently for 12 sensors for the convenience of the later data handling. By utilizing an industrial-standard Camera Link interface, quick launch of the data acquisition system was achieved by simply applying a commercial image grabber board on the PC Linux system.

We have also developed a custom Camera Link interface board as a VME module as an upgrade of image acquisition. The module converts the Camera Link protocol to the Ethernet protocol so that the data are directly sent via the network from the front-end VME module to the back-end computers. An on-the-fly data-compression algorithm is implemented in the FPGA on the board so that the data size could be reduced at a very early stage of data acquisition. In the SACLA experiments, decompression speed on CPUs is one of the important performance of compression algorithm. We have developed and implemented a modified Range-Coder compression algorithm on FPGAs, which has superior performance in decompression speed than other standard lossless compression algorithm such as

JPEG 2000. The data size is reduced down to 40-50 % of its original size.

The waveform of the detector, such as in the time-of-flight experiment, is collected by a digitizer at the sampling rate of 4-GHz. The data size of waveform is to be up to 1 MB per X-ray pulse per detector channel before pedestal subtraction, and would be up to 100 kB after pedestal subtraction. A total throughput of up to 1 Gbps will be required. The PCI-express extension board on the PC Linux system is adopted for the digitizer to handle this data rate.

The intensity and the transverse location of the X-ray pulse are measured by monitors equipped with PIN photodiodes. The voltage waveform outputs from preamplifiers are digitized and fitted to Slater function on VME digitizers (MVD-ADC03) to deduce the charge detected by PIN photodiodes. A Solaris 10 operating system runs on the Sanritz SVA041 VME CPU board to control the ADC and other modules in the same VME chassis.

The profile of X-ray beam is observed by the YAG-Ce scintillator screen with a 0.3M pixels CCD camera system. The Camera Link interface board identical to MPCCD sensors is applied for the image acquisition of this CCD camera.

Timing System and Tag Number

The timing signal of the master-trigger system to drive the SACLA accelerator equipment at 60-Hz cycle is also delivered to the DAQ system for user experiment so that the detector could be operated exactly in synchronization with the timing of the X-ray pulse.

In the distributed DAQ system, shot-by-shot data is recorded independently at each front-end computer per X-ray pulse. Each datum must be uniquely identified so that one can collect all the data recorded in the same X-ray pulse to reconstruct the event. We assign a tag number, which is actually a sequential number of the master-trigger signal, to every datum to identify which one is related to which X-ray pulse. Because our master-trigger system does not distribute the encoded trigger number itself, the tag number is counted at each front-end computer node independently by the trigger counter module. All counters are set to the identical number at lease once at a certain point of beam operation to assign the identical tag number for the same X-ray pulse at every node.

Database

Most of the detectors for the facility equipment, such as the beam intensity monitors and beam position monitors, are always in operation when the DAQ system is ready. These data are taken shot-by-shot and are written to the fast relational database MySQL, with a tag number and the timestamp record. These data are shown as the present status of the XFEL beam on the monitoring system at the experimental station. The user can ascertain whether the beam condition satisfies the experimental requirement by this monitoring system. Users can acquire the data such as the beam condition from the database by specifying the tag number or the timestamp. For example, the correlation between the experimental data and the beam condition could be easily analyzed by fetching the data from this database. Access to the database by user programs is also possible via an interface server.

Network and Pipeline Scheme

The most important issue in the network for our DAQ is to guarantee the data transfer without loss. Therefore, in our system, all the data are transmitted via TCP/IP protocol over the standard 1- and 10- Gbps Ethernets to achieve the reliable data transfer by the features of TCP, e.g. ordered data transfer, retransmission of lost packets and error detection, with a reasonable cost.

Because the Ethernet is not capable of the critical real-time operations, we implemented a pipeline FIFO buffering system in the software framework of client-server system of TCP socket connection so that the data would not be lost at the application level even when data transfer is delayed. The FIFO buffer is implemented as a ring-buffer with shared-memory on a Solaris and Linux operating system. Owing to recent progress of information technology, a large memory size of over a gigabyte is available on the computer. We could make the pipeline depth large enough to hold more than 10 seconds of data, which would be sufficient even when the large latency of TCP/IP protocol occurs.

Storage

The 1D and 2D data from the front-ends are finally accumulated to the storage system. It must be able to handle up to 5.8 Gbps of throughput. The total size of data set will reach over 50 TB per day at this maximum rate. For ease of use, a single file system is preferred even for such a large storage.

We have chosen the StorNext single file system on the Data Direct Network (DDN) S2A9900 Storage system to satisfy these requirements. A total of 180 TB of storage is provided by the SAN cluster of the RAID system at over 1 GB/s of total throughput. Five Linux PCs are prepared as the parallel-writing file servers in this SAN system. By distributing the data from the front-end computers into these five file servers in parallel, we have demonstrated that the image and waveform data of up to 5.8 Gbps can be recorded to storage without any data loss.

PRESENT STATUS

Beam tuning of XFEL began in March 2011. During tuning, our DAQ system is intensively used to provide beam intensity data and beam profile data at the beam line components. Stable operation of our DAQ system contributed significantly to efficient and prompt beam tuning.

Several preliminary experiments are planned by internal users of our facility until March 2012. The 8-plates

MPCCD sensor will be used in these experiments. The beam repetition rate until March 2012 will be 10 Hz at maximum as a preliminary operation of SACLA. We will check the performance of the each component of our DAQ system during these preliminary experiments.

FUTURE PROSPECTS

We anticipate that a larger size image sensor will be required for the future experiments using the XFEL. In order to achieve smaller pixel size with higher peak signal and dynamic range, we are developing Multi-Via (MVIA) sensor by using SOI sensor technology [4] as the next-generation X-ray imaging sensor for SACLA. The detector size will be 1.9 M pixels per sensor with 16-bit quantized depth. By assembling 40 MVIA sensors, the total data rate will be 13 times larger than that for the first experimental runs.

An increase of the beam repetition rate from 60 to 120 Hz at SACLA is expected to be rather promising in near future with the present technique. At 120-Hz beam repetition rate, the 40 MVIA sensors will produce 146 Gbps data rate, which is 26 times higher than the present system. To meet these requirements, upgrades of the data transfer networks, front-ends, parallel implementation of the storage system are now under investigation.

SUMMARY

A data acquisition, control, and storage system has been developed for user experiments at the XFEL facility, SACLA, in the SPring-8 site. The shot-by-shot data acquisition in synchronization with the beam operation cycle of up to 60-Hz has been performed in the beam tuning of XFEL laser. The data transfer scheme with the ordinary 1- and 10- Gbps Ethernets has been proved to be reliable enough by introducing the pipeline buffering in the client-server system of TCP socket connection. We have demonstrated that image and waveform data of up to 5.8 Gbps could be recorded in parallel-writing high-speed data storage without any data loss.

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