Real-time motion control and data acquisition system for scanning X-ray microscopy using programmable hardware

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Abstract. We developed a real-time motion control and measurement system for a scanning transmission X-ray microscope. The system was designed with an FPGA (field-programmable gate array), which is a programmable, reconfigurable circuit for real-time feature modification. This system enabled specimen stage control driven by a piezoelectric element and precise stage position measurement with a laser interferometer. Programmable hardware processing with FPGA realized high-speed control and measurement that cannot be handled by software processing. This system enables very high-speed control and measurement such as “on the fly” measurement.

1. Introduction
A scanning transmission X-ray microscope (STXM) [1] using synchrotron radiation is an attractive apparatus for magnetic domain observation of rare earth magnets and local component analysis for rare metal resources. [2] STXM uses an X-ray optic element called Fresnel zone plate (FZP) to converge radiated light into nanometer spot sizes and scan specimens to obtain chemical and magnetic images. To obtain high-resolution images, a large volume of sampling data is required. When a measurement takes a long time, it is difficult to use limited beam time effectively. Moreover, data deterioration by external factors such as drift of the specimen becomes more pronounced over time. For quick measurements, high counting rate X-ray detectors, real-time high-speed position control, and a capable measurement and data processing system is crucial. In addition, for nanometer scale X-ray absorption spectrum measurements, very precise position control on the order of nanometers, including beam stability and feedback control, is necessary. For scanning microscope systems in particular, real-time position control and measurement data acquisition is essential. PC-driven control systems and software can’t guarantee real-time functionality, so it is essential to develop hardware-based real-time control and measurement systems. We developed a real-time control and measurement system for a STXM using a programmable, reconfigurable FPGA (field-programmable gate array), capable of producing images with 100 nm resolution.

2. Methods
The block diagram for a real-time motion control and data acquisition system for an STXM is shown in figure 1. We adopted two ways to detect X-ray photons. A photodiode (PD) IRD AXUV (Opto Diode Corporation) is employed in the detection for higher intensity X-rays above approximately 10 MHz. The PD signal to a real-time controller was amplified and converted from current to voltage by an electric current amplifier (Amp.). An avalanche photodiode (APD) is also used as the X-ray photon
pulse detector [4] below the 10 MHz rate for measurement of a wide dynamic range. The APD signal to the real-time controller with a pulse counter by an FPGA circuit was amplified by a high frequency amplifier and rectified by a digitizer.

A sample stage was moved by piezoelectric positioners (ECS3030, attocube systems AG) for large movements in the XYZ directions, and by a piezoelectric scanner (ANSxy100, attocube systems AG) for fine movement in the XY directions. The positioner range was 20 mm with a 50 nm minimum step, and the scanner range was 50 μm with sub nm resolution. The positioner was controlled by an ANC 350 multi-functional controller (attocube system AG) with a standard PC, and the scanner was controlled by an ANC300 (attocube system AG) with an FPGA controller. The positioner had a built-in optical encoder, whereas the scanner had not. The scanner performed the fine control of the sample stage position using a laser interferometer (FPS3010, attocube systems AG). The laser interferometer had a position resolution of 30 pm and output bandwidth of 10 MHz. It supported two types of outputs: quadrature signal with low voltage differential signaling (LVDS) and high-speed serial link (HSSL) with low voltage TTL (LVTTL). In this study we used HSSL to record absolute position.

It is usually necessary that a customized printed-circuit board equipped with FPGA programs be used for building a control and measurement system. In particular, designing a data transmission system to connect with a PC for control and data collection can be difficult. However, with a National Instruments CompactRIO (NI cRIO) 9075, this communication system was easily implemented. The NI cRIO was employed as the FPGA-based system for real-time control and measurement. It was equipped with a Spartan6 LX25 FPGA and a built-in 40 MHz on-board clock. It also supported real-time OS and could process signal without the PC. The NI cRIO 9075 was connected to a PC equipped with a 100Base-TX through a network hub. Each network port was assigned a private IP address. The PC and the NI cRIO were connected via TCP/IP. However, since LabVIEW on a PC communicates via an FPGA I/O node, we didn’t need to consider handling TCP/IP protocol or string processing, making data transmission easier.

The NI cRIO series was equipped with slots for modules such as digital I/O and analog I/O. The NI cRIO 9075 had four module slots. In this study, we installed a NI 9264 analog output module to drive the piezoelectric positioner, a NI 9402 high-speed digital I/O module to handle the digital pulse from the laser interferometer, a NI 9205 analog input module to acquire measurements, and a NI9402 high-speed digital I/O module to count X-ray pulses.

LabVIEW FPGA running on PC was used for the FPGA programming of the NI cRIO. Although the available functions were limited due to the hardware circuitry, such as clock timing, LabVIEW FPGA could handle most of the same functions as LabVIEW for PC. It was a big advantage of LabVIEW FPGA that it could handle hardware circuit in the same manner as LabVIEW software processing.
3. Results

3.1. Analog output for stage control
To move the sample stage, an analog voltage signal was sent to the ANC350 that controlled the piezoelectric positioner and drove the piezoelectric scanner ANSxy100. A voltage spike of 0 to +10 V was sent to the ANC350 that drove the piezoelectric scanner. The laser interferometer controlled the position with high accuracy. LabVIEW on the PC was controlled via the LabVIEW FPGA I/O node.

3.2. Digital input for HSSL signal
High precision position measurement with laser interferometer was achieved using digital input to the FPS3010. From FPS3010, clock signals in batches of 48 pulses (48 bits) and HSSL position information signal were output (figure 2 [3]), and synchronized with the clock signal. When the clock

![Diagram](image1.png)

**Figure 2.** Schematic of clock HSSL signal from FPS3010 laser interferometer.

![Diagram](image2.png)

**Figure 3.** Diagram of the LabVIEW FPGA program for FPS3010 laser interferometer.
signal was inactive, no HSSL pulse was output. The clock signal consisted of two parts; pulse signals at even intervals and intervals without pulse signals for a defined period. In this study we set the clock signal width to 200 ns and the clock signal frequency to 5 MHz for a pulse signal duration of 200 ns $\times$ 48 bit = 9.6 $\mu$s. We adjusted the period such that the interval without pulse signals equaled the signal duration.

Figure 3 shows the LabVIEW FPGA diagram for HSSL signal analysis. The main processing routine processed a loop synchronized with an on-board clock. The clock signal processing routine monitored and counted periods without clock pulse signal. When a clock pulse was input, the counter was reset and deserialization of the HSSL signal was initiated to convert the serial signal of HSSL to 48 bits value. The HSSL signal handling routine continued deserialization while the clock pulse was input. When the clock signal went into the blank period and the next clock pulse was input, the position value from HSSL was sent to the output HSSL signal. The pulse processing of the clock HSSL signal by this LabVIEW FPGA program was of the positive edge type.

3.3. Microscopy application
The STXM observation program was integrated in LabVIEW on a PC with the above elements. Figure 4 shows an STXM image of the KEK and Photon Factory logos patterned on a W thin film by a focused ion beam system. The X-ray beam energy used for the observation was 350 eV. The logos on the microscope image have a resolution of about 100 nm, and were obtained using the FZP with an outer most zone width of 30 nm.

4. Summary
We developed a real-time motion control and data acquisition system for STXM using the FPGA-based system for real-time control and measurement. It processed the position control of a specimen stage through a piezoelectric positioner and stage position measurement by laser interferometer. The performance of this system is sufficient to control and measure the stage position for STXM.

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