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FPGA-BASED MOTION CONTROL SYSTEM FOR MEDICAL LINEAR ACCELERATOR DEVELOPMENT AT SLRI

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Abstract

Linear accelerator technology has been widely applied to radiotherapy machines and there has been an increasing demand of the machines in Thailand over the recent years. An attempt to increase the availability of the low-cost machines has been proposed for the domestic use purposes. Currently, the prototype of the 6 MeV medical linear accelerator is under development at Synchrotron Light Research Institute (SLRI) in Nakhon Ratchasima, Thailand.

For beam shaping purposes a so-called secondary collimator is utilized with different size arrangement of the collimator jaws. The collimator motion control is one of the necessary machine subsystems for producing the desired field size of the beam. In this paper, the FPGA-based motion control system of the machine prototype is presented. The programmable logic part of the hardware is designed in VHDL for digital processing. The main motion control algorithm is implemented in the main processor of Zedboard FPGA. Communication between the motion control subsystem and the main control system software of the machine is also described.

INTRODUCTION

Cancer is one of the leading diseases that causes death all over the world including Thailand. The demand of cancer treatment machines has been increasing over the recent years to serve the country's need as the number of patients increases every year. The choice of choosing a radiotherapy machine for cancer treatment has been increased accordingly. In addition to saving patient's life from choosing the radiotherapy machine, it maintains a quality of life as the use of radiotherapy preserves a number of functions of human organs, for example, female breast (for cosmesis), prostate (for better sexual function), bladder (for more convenient urination) [1].

Linear accelerator has been widely utilized in radiotherapy machines. An attempt to increase the availability of the low-cost machines has been proposed for the domestic use. Currently, SLRI has developed a prototype of the 6 MeV medical linear accelerator (medical linac) for cancer treatment. Reverse engineering approach has been employed in this research and development via a donated machine. The prototype consists of a linear accelerating structure of the S-band standing wave type at 2,998 MHz operating frequency, a 3.1 MW magnetron driven by a solid-state modulator, and a hot-cathode electron gun [2]. A brief technical specification of the prototype is listed in Table 1.

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Table 1: Parameters of the Medical Linac [2]

Parameter	Value
X-ray beam energy [MV]	6
X-ray dose rate [MU/min]	400 - 600 Maximum
Field size [cm^2]	0x0 to 40x40
Linac frequency [MHz]	2,998
Type of accelerator	Standing wave
Gantry rotation	Vertically fixed

A drive stand and a gantry of the prototype provide housing for a modulator cabinet and its control system for magnetron and electron gun. An automatic frequency control (AFC) system is also installed in the drive stand.

A linac treatment head consists of an X-ray target attached to the end of the accelerating structure. A transmission ionization chamber is installed to measure a beam dose. A dosimetry control system is designed to monitor and control the beam by processing the signals from the ionization chamber. To confine the shape and size of the radiated beam, three-stage treatment beam collimators are used, fixed primary collimators, secondary collimators or so-called beam limiting jaws, and a multi-leaf collimator (MLC). A timing system is used to link various subsystems of the machine in order to provide proper synchronization in X-ray beam generation.

A central control system software is designed to interface with all subsystems for proper operation. It is run on the Main Control System with a display monitor and GUI. All subsystems are connected to the Main Control System in a private network as shown in Figure 1.

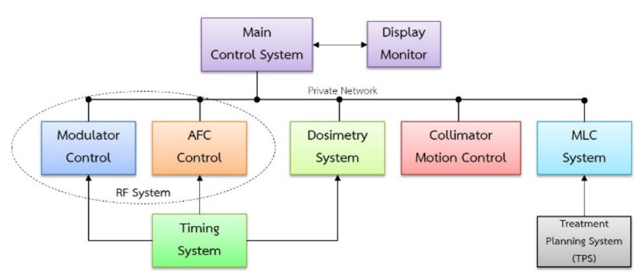

Figure 1: Network diagram of the machine prototype.

This paper describes a motion control system of the secondary collimators for radiotherapy machine. Secondary collimators consist of two adjustable pairs of jaws. They are installed in the linac treatment head. One pair is above the other and at right angles. Control system design, both

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hardware and software, is discussed in the next section. The following section presents some result and discussion. Concluding remark is presented in the final section.

CONTROL SYSTEM DESIGN

In order to control the movement of the secondary collimators, hardware and software of the system need to be designed carefully. This section describes various parts of the control system design. The main hardware part consists of the secondary collimators and electronic boards. The software part includes the design of digital circuits, the implementation of feedback controllers, and the interface with users from the PC.

Secondary Collimators

There are two adjustable pairs of jaws installed in the treatment head with one pair above the other and at right angles. The upper collimators or Y-Jaws can be opened or closed to define the size of the treatment field along one axis. Similarly, the lower collimators or X-Jaws define the size of the treatment field along the axis perpendicular to the one defined by the Y-Jaws. Both collimator jaws can be operated to give symmetric and asymmetric fields depending on the position of each jaw. The jaw openings can be adjusted so that a projected square or rectangular field shape at the target-to-surface distance of the machine ranges from 0x0 cm^2 to 40x40 cm^2.

Each collimator jaw is driven by a brushless dc (BLDC) motor with gears. Traditional H-Bridge circuit is used to provide appropriate voltage level to control the speed of the motor. The pulse width modulation (PWM) that drives the H-Bridge together with motion direction is provided by the FPGA. An in-house PWM drive PCB is designed for motor and FPGA interface and it is shown in Figure 2. For feedback control purpose, a readout potentiometer is used to provide position data, in a form of bipolar dc voltage ranging from -10 volts to 10 volts, to the FPGA controller. Since the system has four collimator jaws together with their double potentiometers for redundancy, this contributes to the total of eight collimator position signals.

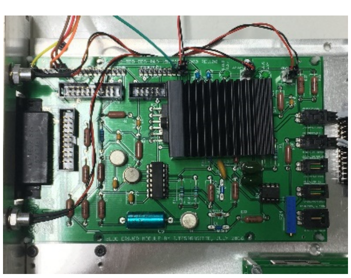

Figure 2: In-house PWM drive PCB.

FPGA and Analog-to-Digital Converter (ADC)

In this prototype development, FPGA evaluation and development board is intended to be our choice for test and implementation, fast information processing, and customization of digital controller and its peripherals. The Digilent's Zedboard [3] featuring a Zynq XC7Z020 is chosen for the design. In order to sample the position data from multiple potentiometer feedback signals, a multi-channel ADC is needed. For the choice of a multi-channel bipolar simultaneous sampling ADC evaluation board, the Analog Devices' EVAL-AD7606SDZ [4] and its FMC adapter board are selected to be used with the Zedboard. The ADC board is a fully featured evaluation kit for the AD7606 which has 8 channels with a resolution of 16 bits each. Figure 3 shows how the controller board and the ADC board are connected.

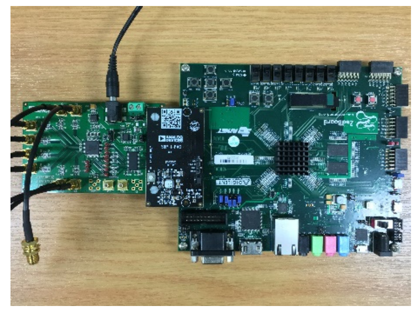

Figure 3: Zedboard and 8-channel ADC.

In the Programmable Logic (PL) part of the Zedboard, two custom IP blocks are designed using VHDL [5]. The IPs are synthesized and mapped using the Xilinx's Vivado Design Suite 2014.4 development tools in order to provide signal interface with the ADC and the collimator jaws. The algorithm in the ADC driver block, AD7606 Interface IP, is generated with a finite state machine (FSM) for proper operation. It is designed so that all interface signals meet technical timing requirements. Figure 4 shows the final design of the AD7606 Interface IP.

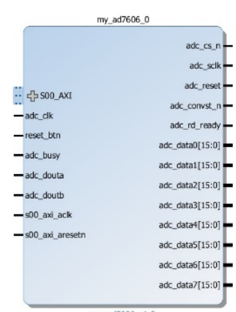

Figure 4: AD7606 Interface IP.

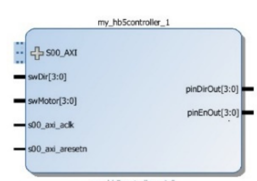

Figure 5: PWM Controller IP.

The second custom IP is implemented as a PWM controller. The inputs of the PWM logic block are designed to receive data (in BCD form) as a percentage of the duty cycle for each collimator jaw. All four duty cycle values are sent from the Processing System (PS) part of the Zedboard simultaneously using Advanced eXtensible Interface

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(AXI) bus protocol. The other inputs of the IP are motor direction and motor enable signals to each of the collimator jaws to enable motor rotation. This IP block is shown in Figure 5.

Feedback and System Integration

Typical dc motor position control is implemented in this motion control system. The feedback control diagram of each collimator jaw is shown in Figure 6. In this project, the PID algorithm is applied to each of the collimator jaw closed-loop control to simplify the controller realization.

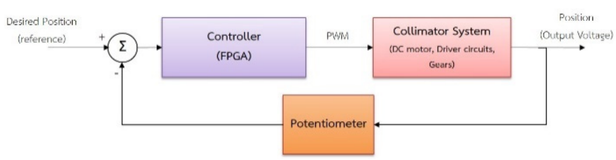

Figure 6: Feedback control loop of each collimator jaw.

The standard PID controller is described, in parallel form with its Laplace transform, by

$$\frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d s \qquad (1)$$

where K_p is the proportional gain, K_i is the integral gain, K_d is the derivative gain, $E(s)$, the error or the difference between reference and the plant output, is the controller input, and $U(s)$ is the controller output.

For digital implementation in the Zedboard, the PID controller is realized by using bilinear or trapezoid transformation method [6]. The Z-transform of Eq. (1) is described by

$$\frac{U(z)}{E(z)} = \frac{K_1 + K_2 z^{-1} + K_3 z^{-2}}{1 - z^{-2}} \qquad (2)$$

where

$$K_1 = K_p + \frac{K_i}{2} + 2K_d$$
$$K_2 = K_i - 4K_d \qquad (3)$$
$$K_3 = -K_p + \frac{K_i}{2} + 2K_d$$

which can be converted back to difference equation as

$$u[k] = u[k-2] + K_1 e[k] + K_2 e[k-1] + K_3 e[k-2] \qquad (4)$$

For the software part of the system, Eq. (4) is implemented in the PS part using Xilinx SDK 2014.4. To further simplify the controller structure, PI controller is chosen ($K_d = 0$). The raw position data sampled by the ADC are further converted to appropriate unit, and provided to the closed-loop control for error calculation. To set the desired collimator position to the control loop, user can determine each set point value via LabVIEW user interface, which is sent to the PS part through UART via PC. The detailed block diagram of the control system is illustrated in Figure 7. The signal interface between the PL part and the ADC through FMC connector and that between the PL part and all four collimator jaws through PMOD connector are also shown.

Figure 8 shows the LabVIEW GUI that is used in the system test. Initially, without the field size calibration at the machine isocenter, the position of the collimator jaw is read in millivolts. The set points can be assigned to each of the collimator jaws and the output values from the ADC are also displayed. Furthermore, the status of the collimator control system and serial communication via RS-232 is also shown.

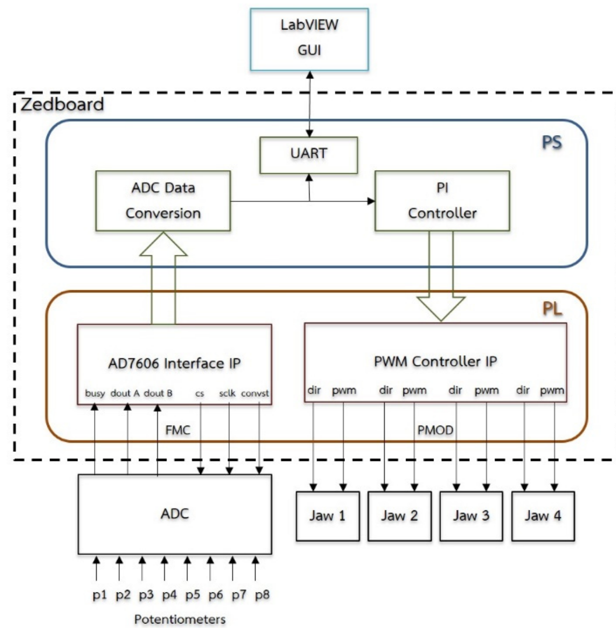

Figure 7: Block diagram of the control system and interface between hardware.

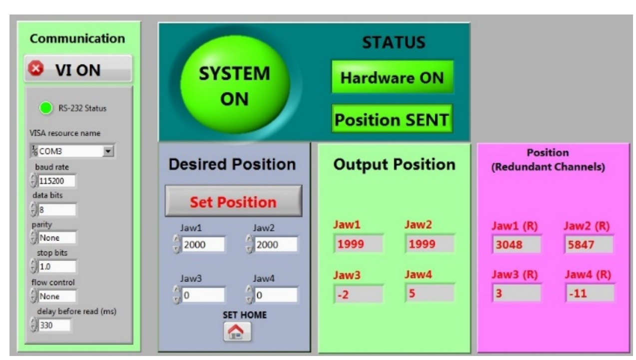

Figure 8: LabVIEW GUI.

RESULT AND DISCUSSION

Interface between the ADC board and FPGA was first carefully tested in order to achieve timing requirements and acquire correct collimator position values. Figure 9 shows the oscilloscope capture of the interface signals between FPGA and ADC. As previously shown in the block diagram in Figure 7, the signals from FPGA to ADC are chip select (cs), serial clock (sclk), and conversion start (convst), and the signals from ADC to FPGA are busy and digital data in serial form (dout A and dout B). The result

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shows that we receive correct information from all eight 16-bit channels with a 20 MHz sclk. The same result is also obtained from using higher sclk frequency up to 30 MHz.

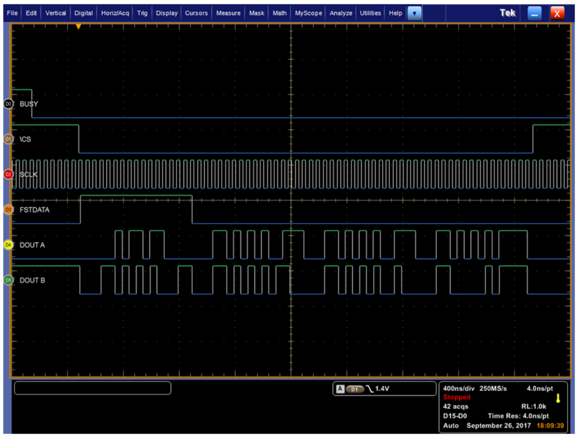

Figure 9: Interface signals between FPGA and ADC.

Implementation of the PI controller in the control loops was observed after an optimized tuning for the different values of controller gains K_p and K_i for each of the collimator jaws. Different position arrangements were tested. The result of the step response, with the best tuned controller gains, is shown in Figure 10. Waveform charts display the output of the collimator position values in the Main Control System Software. The expected result of the overall system response is obtained and very satisfactory.

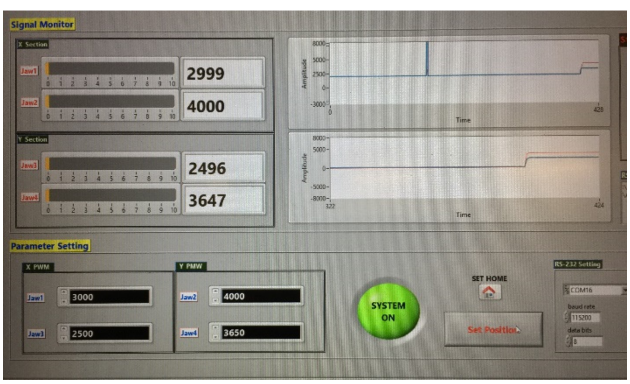

Figure 10: Main Control System Software of the machine.

The serial communication between PC and Zedboard works well. All parameter settings can be performed and position values can be displayed satisfactorily. One task that could improve the system performance is the implementation of Ethernet communication in the PL fabric of the Zedboard. In this way, the main processor would not have been busy with the serial communication while processing the feedback control algorithm. This is aimed to be done in the next phase of this project.

CONCLUSION

The motion control system of the secondary collimator is developed in order to produce different field size and arrangement of the collimator jaws in the medical linac treatment head. Reverse engineering approach has been employed via the donated machine. A number of new hardware and software have been developed. Many in-house electronic PCBs have been fabricated and controller evaluation boards have been selected. Tests and calculation have been conducted in order to successfully generate and control the desired movement of the collimator jaws. The digital logic blocks and custom IPs generated using VHDL to interface with a multi-channel simultaneous-sampling ADC and collimator jaws hardware allow concurrent operation and control of multiple dc motors. This substantially reduces the processing time compared to that utilized by other classical electronic controllers.

The digital PID controller algorithm is successfully implemented in the Zedboard's Processing System for multiple motor control loops. The resulting collimator position values are correctly displayed by the LabVIEW GUI via RS-232. Similarly, the position set points can be input through the GUI and sent to the controller for calculation. The overall characteristics of the control system and hardware implementation are found to be very satisfactory.

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