Optoelectronic Acquisition and Control Board for Musical Applications

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ABSTRACT

A modular and reconfigurable hardware platform for analog optoelectronic signal acquisition is presented. Its intended application is for fiber optic sensing in electronic musical interfaces, however the flexible design enables its use with a wide range of analog and digital sensors. Multiple gain and multiplexing stages as well as programmable analog and digital hardware blocks allow for the acquisition, processing, and communication of single-ended and differential signals. Along with a hub board, multiple acquisition boards can be connected to modularly extend the system's capabilities to suit the needs of the application. Fiber optic sensors and their application in DMIs are briefly discussed, as well as the use of the hardware platform with specific musical interfaces.

Keywords

fiber optic sensing, analog signal acquisition, musical interface, MRI-compatible

1. INTRODUCTION

The ability to acquire sensor data is paramount to direct measurement of musician gestures in digital musical instruments (DMI). While more and more sensor packages have digital outputs, there are many DMI applications where analog acquisition and signal processing is still required [19]. Sensing techniques vary depending on the nature of the environment and the phenomena being sensed. Optical sensing is advantageous in situations where electromagnetic interference (EMI) is of concern. Of specific challenge to the authors is the design of digital musical interfaces compatible with magnetic resonance imaging (MRI). Using functional MRI, neuroscientists are able to correlate musician gestures with neural activation to better understand the brain structures and pathways involved in musical motor learning [1, 8, 17, 2]. The MRI scanner uses high-intensity magnetic and radio-frequency fields which interfere with most electronics [7]. As well, electronics brought into the MRI room can interfere with the sensitive MRI acquisition hardware, distorting images or posing a potential threat to the safety of subjects and technicians. Development time in the MRI scanner is expensive thus an all-optical approach to sensing decreases costs and ensures MRI-compatibility, even in newer high-field scanners.

This paper details the design of an analog acquisition and control board designed specifically for optical sensing in DMIs. While optical sensing was the focus for this hardware platform, it is easily reconfigurable and reprogrammable to tackle most analog and mixed-signal needs. This platform can operate on its own or integrated as a node device into the hub-and-node framework presented in [9]. As well, this work is a complete redesign of the hardware presented in [8]. Whereas the previous revision consumed significant setup time with hand-tuned comparators reference signals, this platform uses analog-to-digital conversion (ADC) and can be auto-calibrated.

NIME'12, May 21 – 23, 2012, University of Michigan, Ann Arbor.

2. FIBER OPTIC SENSING TECHNIQUES

While optical sensing has been applied to DMIs [14, 11, 16], few interfaces have made use of the the possibilities that fiber optic sensors provide [6, 10, 8, 12]. Optical fibers make use of total-internal reflection of light in order to maintain signal strength over long cable runs without being susceptible to EMI. An example application of the use of fiber optic cables in musical instruments is the design of electromagnetically-actuated pipe organs where control signals need to travel long distances from the control panel to the pipes without being corrupted by EMI generated by electromechanical valves [5]. Outside of the musical realm, fiber optic sensing is commonly used for remote temperature measurement in dangerous locations, stress and strain within bridges and roads, and for *in vivo* medical imaging [15, 18].

The simplest types of sensors modulate light intensity, while more complex arrangements can be used to measure polarization, interferometric phase shifts, and wavelength modulation [20]. Example applications of simple intensity-based fiber optic sensing for for DMIs include the use of bend sensors to measure flexion and force, end-coupled reflective diaphragm for vibration sensing, and optical quadrature (or other photo-mask configurations) for position and velocity measurements, among many others [7].

3. ACQUISITION AND CONTROL BOARD

The purpose of the optoelectronic acquisition board is to interrogate fiber optic sensors, perform basic signal processing, digitize acquired signals, and communicate data to the hub. The hardware platform is comprised of several subsections including: power supply, analog front end, light-emitting diode (LED) drivers, the programmable system-on-chip (PSoC), and a USB-to-UART integrated circuit for communication. The board is based around a Cypress PSoC which consists of an 8-bit microcontroller with integrated

Table 1: Optoelectronic control board features.

Feature	Description
μC	8-bit microprocessor core, up to 24MHz clock, with analog and digital blocks
Amplifiers	8 off-chip opamps, 8 variable-gain instrumentation amplifiers, and up to 4 on-chip PGAs
Analog μC inputs	Externally-multiplexed onto 8 analog pins, internally multiplexed onto 4 analog buses
ADC	Many choices available, e.g. three simultaneous 8-bit conversions at 3kHz
Analog outputs	4 buffered outputs, available input from analog inputs or DAC
LEDs	Eight buffered digital outputs, PWM drive
Power supplies	5V USB and 3.3V (digital), 3.3V and 1.8V (analog)
Comm.	USB, I2C, SPI, and others
Optical sensing	Photodiodes and high-intensity LEDs coupled to POF ST connectors for remote optical sensing
Modularity	I2C for board-to-board communication on a hub and node bus
Reconfigurable	Run-time control of analog multiplexing and gain, on-chip analog and digital blocks configured through firmware

reconfigurable analog and digital blocks [3]. See Table 1 for a summary of the board's features.

3.1 Analog Front End and LED Drivers

The analog subsection is comprised of eight opamps and eight instrumentation amplifiers. The gains of the latter are electronically-programmable. The outputs from these 16 amplifiers are multiplexed down to eight channels which connect to analog input pins of the PSoC. For optoelectronic acquisition, straight tip (ST) fiber optic housings are employed to allow for quick and robust connection to ST-terminated plastic optical fiber (POF) cables. Eight ST housings with photodiodes are connected to the opamps wired as transimpedance amplifiers. Photodiodes provide a high bandwidth linear current proportional to light intensity. Six different pair-wise configurations are connected to instrumentation amplifiers. This allows for the multiplexing of eight single-ended and six differential measurements. The instrumentation amplifier gains are set by electronic potentiometers, controlled by the PSoC over a serial peripheral interface (SPI) bus.

Eight red (660 nm) LEDs in ST housing were selected to match the transmission spectrum of the POF [13]. MOSFET switches are used to drive the LEDs, controlled by the PSoC. The effective LED intensity can be controlled by modulating the duty cycle of a pulse-width-modulated signal of a sufficiently high frequency. At the far end of the emitting and receiving fibers, optical measurements can be made. Four emitter followers are wired to buffer analog outputs from the PSoC to drive LEDs or actuators. Four additional PSoC pins with special connection to specific analog blocks are also brought out to a header on the board.

It should be noted that the board was fabricated with space to install additional passive components on the analog front end in order to accommodate resistive or voltage-based sensors, as well as active filtering. Two of the instrumentation amplifiers are left uncommitted and can be used for strain gauges or bio-signal electrodes (e.g. electromyogram, electroencephalogram, galvanic skin response). Fig. 1 shows a sample configuration with three PWM-controlled LEDs coupled with fiber optic cable to four photodiodes, providing four single-ended measurements and three differential measurements.

3.2 Internal PSoC Hardware and Firmware

Internally, the PSoC has several reconfigurable analog and digital hardware blocks in addition to the 8-bit microprocessor core, all programmable through firmware. Thus, depending on the application, the board can be reconfigured to suit the developer's needs: one configuration might require one differential analog input to be bandpass-filtered and digitized with a 14-bit ADC at 10kHz in order to drive a single degree-of-freedom haptic interface using a digital-to-analog converter (DAC), while another configuration might require the programmable amplification and digitization of several slowly-varying analog signals that are then sent off-board for logging or further processing for an interactive multimedia installation. The system allows for both of these hardware configurations to exist simultaneously or toggled at run-time.

For the acquisition of single-ended and differential optoelectronic signals, a single internal hardware configuration was implemented with a programmable analog gain and multiplexing structure to allow for a flexible trade-off between the number of acquired signals and the acquisition speed. The higher-level settings including the selection and ordering of channel acquisition, data reporting selection and speed, LED intensity, internal and external gain stage settings, and calibration can be modified at run-time through commands sent to either the USB port or over I2C. Auxiliary PSoC pins are brought out to headers and reserved for additional digital communication (e.g. secondary SPI master and slave busses) and in-circuit serial programming.

3.2.1 PSoC Hardware Configuration

The application-specific internal hardware configuration enables the multiplexing of the eight analog inputs onto three programmable-gain amplifiers (PGA) before being synchronously digitized with a three-channel 8-bit ADC running at 3kHz. Six of the eight LEDs are PWM-controlled, allowing for variable intensity output. An SPI master block is used to control the electronic potentiometers which set the instrumentation amplifier gains. An I2C slave block is implemented to send acquisition data and receive commands from a hub board with an ARM-core microcontroller, while a UART block is connected to the external UART-to-USB chip to allow for an auxiliary communications channel. Nonvolatile memory (NVM) is used to store and load settings and calibration data. Additionally, a 16-bit counter block is used to control the timing of certain interrupt service routines (ISR).

3.2.2 Application Firmware

On boot-up, the system and all its hardware blocks and registers are initialized. If valid, settings from a prior configuration are loaded from NVM. The ADC acquisition ISR steps through the selected subset of possible input channels (referred to as an acquisition frame), setting respective multiplexer switches and gain settings before each three-channel parallel acquisition is initiated. Upon acquisition of an entire frame, the data is loaded into the I2C buffer to be read by the I2C master device. If enabled, data can be printed without polling to the USB port at a rate and in an order selectable at run-time. Otherwise data can be polled over I2C or USB.

An auto-calibration procedure is implemented which first maximizes the LED outputs so as not to saturate the photodiodes, then the dynamic range of the differential chan-

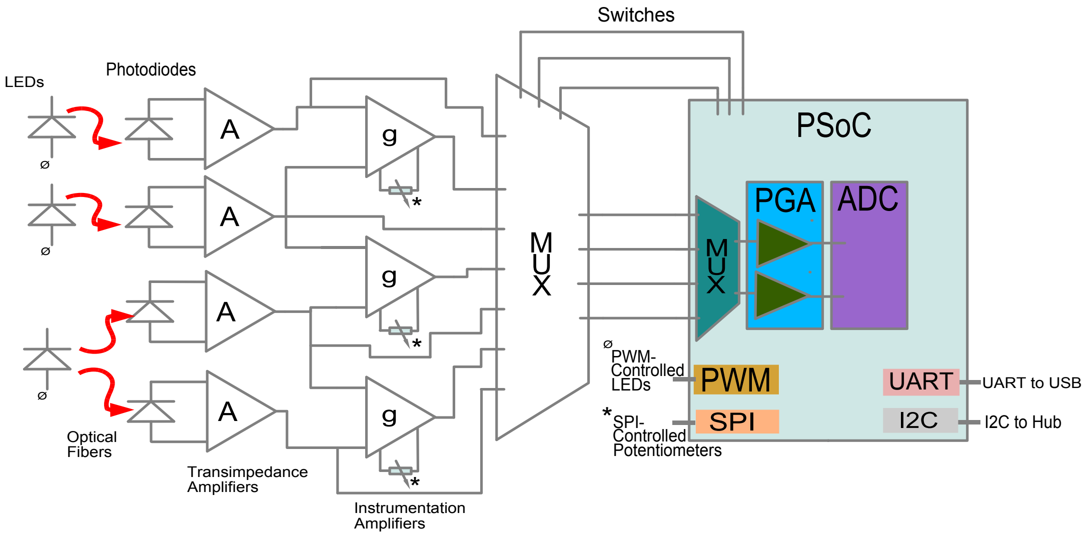

Figure 1: Analog front end, showing an example configuration utilizing four optical channels: three differential and four single-ended.

nels is maximized by setting the instrumentation amplifier gains, and finally the dynamic range of the input to the ADC is maximized by setting the PGA gains. In order to properly calibrate the analog signal chain, a run-time command is available to pair specific LEDs with their respective photodiode channels. Ambient light compensation is implemented by taking the difference between a signal captured with its respective LED on, versus with the LED off. As noted, calibration values and other settings including I2C address and LED-photodiode pairings can be saved to, and loaded from, NVM using commands sent over USB or I2C.

4. HUB BOARD

The purpose of the hub board is to collate acquired signals from multiple optoelectronic boards, centrally configure the nodes, provide higher-level signal processing, time-stamp incoming data from multiple sources, and act as a communication link between the interface and the host computer if required by the application. While the node boards are able to communicate directly with the host computer, this channel is reserved for manual configuration and debugging. The hub board is based on a 32-bit ARM Cortex M3 microcontroller. The I2C bus is used as the main communications link between it and the node boards, however SPI is suggested for higher-speed data transfer. The hub board is also used to run mapping and synthesis algorithms as discussed in [9]. Fig. 2 shows a prototype optoelectronic board with four efferent fibers and eight afferent fibers connected in a differential configuration, along with an I2C connection to a hub board and a USB connection to a laptop computer.

5. APPLICATION IN DMIs

The optoelectronic acquisition and control board has been used with three different interfaces for musical expression: the MRI-compatible piano keyboard presented in [8]; a second revision of the MRI-compatible keyboard, which makes use of differential photo-masks to more accurately measure key position and velocity; and the Ballagumi, a flexible silicone interface embedded with fiber optic bend and pressure sensors, shown in Fig. 3 and presented in [12]. For the Ballagumi, the optoelectronic boards are used to acquire bend and deformation signals from 32 optical fibers, which are then analyzed and mapped on the hub board or a PC to sound synthesis. The modular and reconfigurable optoelectronic boards, in consort with a hub board, enable a single hardware platform to be used with different physical interfaces and optical sensing techniques with little to no change in hardware or firmware, using run-time commands to reconfigure the platform to suit the needs of the specific application. To replace the photodiodes with resistive or voltage-based sensors, they simply need to be connected to the opamp inputs directly, rather than the transimpedance architecture inputs. In addition to LEDs for visual feedback, small actuators can be connected to the buffered analog outputs for haptic feedback, driven with an arbitrary control signal using the DAC or directly with an amplified input signal.

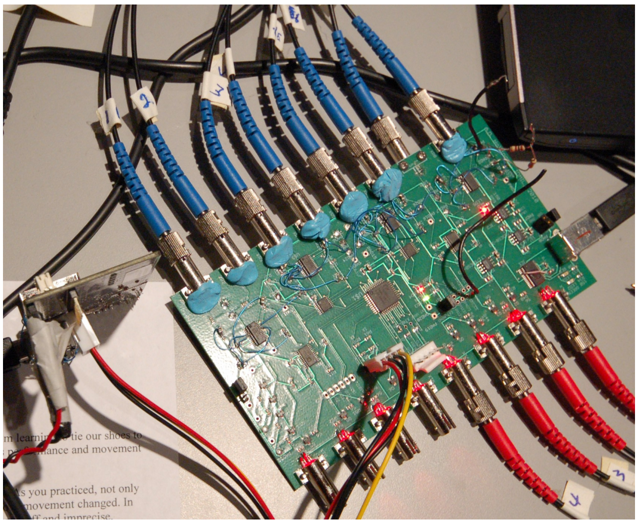

Figure 2: Optoelectronic acquisition and control board with fiber optic connectors.

6. CURRENT AND FUTURE WORK

A second generation optoelectronic acquisition and control board has been designed. Fabrication is in progress and thereafter application development and testing will com-

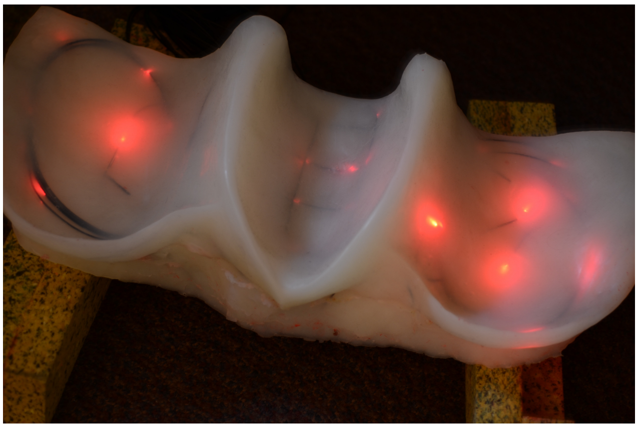

Figure 3: The Ballagumi: an optically-sensed flexible musical instrument.

mence. The main goals of the updated design are to decrease the form factor, improve the analog signal integrity, and increase the acquisition rate and data throughput. The board is based on the recently-released PSoC 5 which features a 32-bit ARM Cortex M3 core running at 80MHz with integrated USB device support, analog and digital blocks, and in-system debugging capabilities [4]. In addition to the PSoC 5, the newly designed board features adjustable high-capacity constant-current LED drivers to allow for more precise setting of LED light intensity; a micro-SD card slot for additional non-volatile storage; an electronically-controlled adjustable voltage reference; a more numerous array and flexible mapping of analog and digital pins; as well as uncommitted electronically-controlled potentiometers for interfacing with analog sensors and active filters.

7. ACKNOWLEDGMENTS

Many thanks to the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant and Canadian Foundation for Innovation (CFI) for funding this research. Thanks as well to Sunstone Circuits for their academic sponsorship discount.

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