FPGA-Based Tactile Sensory Feedback System with Optical Fiber Data Communication Link for Prosthetic Applications

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Abstract — **Tactile sensory feedback systems could enable the prosthetic system to convey touch information to the amputee. Employing sensor arrays with a high number of sensors gives high-resolution tactile information but imposes challenges on the embedded electronics in processing and transmitting a large number of tactile data to the prosthetic user. This work proposes the design of a FPGA-based approach for tactile sensory feedback systems that employs an optical fiber data communication link for prosthetic applications. The system consists of an interface electronics to manage the data acquisition from the tactile sensor array, a digital coding unit, an optical fiber-based communication link, a digital decoding unit and a further interface electronics to communicate with external apparatus. The data acquisition process followed by a UWB-based optical modulation allows for the transmission of pulsed coded tactile data through the optical fiber to a final user by means of, for example, an electrotactile stimulator combined with flexible electrodes. The transmitter and receiver systems have been implemented on two different FPGA boards with the optical communication channel connecting the two boards. The designed system functionality was demonstrated by employing an experimental setup where sequence of sensor data, emulating an array of 32 sensors sampled at 2kHz, were employed to verify the correctness of the data transmission at 100Mbps data rate through the optical fiber. Experimental results validated the functionality of the proposed design and demonstrated that the optical communication link highly improves the robustness to electromagnetic disturbances, the transmission data rate as well as the power consumption.**

Keywords — **Sensory Feedback Systems, Optical Fiber Links, Prosthetic Applications.**

I. Introduction

Tactile sensory feedback systems are crucial for prosthetic limb to restore the sense of touch. The restoration process requires a sensing system based on tactile sensors to interact with the environment. The system provides (i.e. for prostheses or robots) features of the touched objects such as shape, texture, size, etc. When mechanical stresses are applied to the sensor surface, corresponding signals are generated. At this time, a read-out circuitry acquires these signals by an analog-to-digital converter and then pass the digitized samples to a processing unit. The processing unit runs a statistical learning algorithm on the data to extract meaningful information about the touch and, on this basis, provides the electrotactile stimulations understandable by the user through a stimulator.

The specifications of each block of the system are influenced by the requirements of the specific application. Employing a large number of tactile sensors of fast response is significant for obtaining human-like touch sensing capability [1]. However, this places constraints on the choice of the electronic circuits interfacing the sensors. The interface electronics should handle multiple sensor signals by using analog-to-digital converters that provide simultaneous conversions. Then, the interface electronics must process and digitize the data within a defined application bandwidth (e.g., up to 1 kHz). Moreover, transferring large amount of data to the processing unit requires a suitable data transmission paradigm. In this respect, the key issue is what type of transmission channel is required in the case of targeting high-data rate, large bandwidth with low power consumption.

Current research efforts in tactile sensing systems mainly focus on developing different types of electronic skin together with the related acquisition interface electronics [2]–[8]. For robotics applications, the proposed approach in [2] was that one to scan POSFET sensor arrays and recover the contact forces having frequency contents up to 1KHz. Moreover, the authors defined the main parameters for the data acquisition system fixing the bit rate (BR) for 16 taxels equal to 1.6Mbps. Another robotic application based on integrating a large number of capacitive sensors in developing a skin was proposed in [3]. In this paper the authors interconnect 16 PCB through inter-integrated circuit (I2C) serial bus, where each PCB carries 12 taxels. The proposed method is limited by the low sampling rate of the AD7147 charge-to-voltage-converter and by the exploited standard communication buses (I2C and CAN) for data transfer. Author in [4] has introduced an electronic hardware capable of detecting normal contact and slip forces applied on the surface of robotic fingertip. Six A/D converters of a microcontroller-based board (C8051F311) receives the signals of polymer Polyvinylidene fluoride (PVDF) sensors. Thus, integrating multiple finger tips will make collecting large data a complex task as well the transmission bandwidth will be an issue to be considered. On the other hand, the common concern in [5]-[8] was developing an efficient interface electronics that handles PVDF sensors for the prosthetic application. The authors of [5] focused on defining the properties of the interface electronics according to the sensor force /charge dynamics by interfacing the PVDF sensors to the proposed charge amplifier circuit. Aiming a wearable system, the key approach in [6], [7] and [8] is to have an energy efficient and miniaturized read-out electronics with the capability of handling a large number of sensors. The design reported in [7] and [8] pre-processes the raw data locally by taking into consideration the limited transmission bandwidth offered by the Bluetooth and USB interface. Therefore, the aforementioned studies were proposed to develop an efficient electronic system unit connected to powerful sensors regardless the type and the capacity of the transmission channel. This justifies the lack of studies that deal with the effect of implementing an efficient communication link on the behaviour of the tactile sensing system.

In this regard, the present work takes the advantage of a wide-bandwidth and high-efficient optical communication link integrated in the sensory system. In particular, this paper presents a novel architecture based on the use of an optical fiber communication link for data transmission in the tactile sensory feedback systems for prosthetic applications. The proposed solution, implemented on FPGA boards, is capable of acquiring data coming from a sensor array and transmit them through the optical communication channel to a prosthetic user through an electrotactile stimulation after coding the data by a UWB-inspired pulsed modulation technique [9,10]. This provides high data rate transmission, low power consumption, high electromagnetic compatibility and signal integrity so reducing interferences and disturbances. Moreover, the proposed approach paves the way toward the employment of large number of tactile sensors without any concern about the transmission bandwidth of the acquired data.

II. System Architecture: Design and Implementation

Fig. 1 shows the design architecture of the tactile sensory feedback system. The proposed solution consists of a transmitter, a receiver and a data communication link. The transmitter module is implemented on an FPGA board (Spartan 6 - SP601 by Xilinx) and includes the ADC INTERFACE block that allows to control an external data acquisition module composed of an analog-to-digital converter (i.e., DDC232) with an offset circuit to sample bipolar signals of sensors array. The acquired sensor data are stored in a shared global data buffer, arranged in a suitable data package and then managed by the PULSED DIGITAL CODING block. Referring to Fig. 2, this block generates always a "*synchronism pulse*" in correspondence to the rising edge of the clock signal *CLOCK_M1* and a "*data pulse*" on the falling edge of the same clock signal only if the bit to be coded from the serial data is equal to "1" [9,10]. Thus, after coding the serial data package into a digital pulsed signal, the optical communication link based on an optical fiber, allows to transmit the coded data to the receiver module. The latter, also implemented on an FPGA board (Virtex 6 - ML605 by Xilinx), performs the recovery of the clock signal and of the data from the received pulsed voltage signal so re-generating the transmitted data package through the DIGITAL DECODING block. Moreover, after a suitable data processing performed by the UART INTERFACE block, the receiver can send the processed data to a PC and/or an oscilloscope for visualization as well as can control an external electrotactile stimulator by means of a direct connection through a USB port translating the tactile data into stimulator commands. Moreover, the receiver module has a shared global data buffer to store the decoded/recovered data. In the following sections, we will describe in more details each part of the complete system.

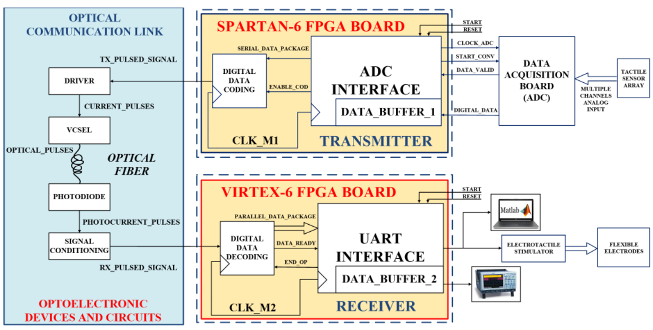

Fig. 1. Implementation block scheme of the overall system architecture from sensors to stimulation.

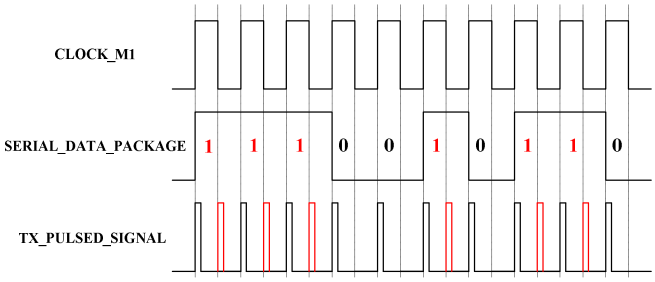

Fig. 2. Example of the timing diagram of the optical UWB-based pulsed data coding technique.

A. *The transmitter module*

The transmitter module works at a main clock frequency (i.e., *CLK_M1*) equal to 100MHz. After a *START SIGNAL* goes high to the ADC INTERFACE block, the transmitter is enabled to generate a proper clock signal to retrieve data from an external data acquisition module operating, for example, at 2kS/s conversion rate (e.g., a DDC232 20bit 32channels ADC by Texas Instruments). In particular, every time the transmitter toggles the signal *START_CONV*, the external ADC simultaneously scans and starts to convert the analog signals generated by the array of sensors. The converted signals are shifted out to the acquisition module (i.e., the ADC INTERFACE block) through a serial interface/protocol. Thus, when the acquisition and the conversion is accomplished, the *DATA_VALID* pin of the ADC goes low indicating that the data are ready and can be stored in the internal global data buffer including a header sequence. Then, the signal *ENABLE_COD* goes high enabling the digital coding block to perform the coding of the data stored in the buffer into a digital pulsed signal, preceded by a suitable train of "*synchronism pulses*". The "*synchronism pulses*" are generated to allow for the clock recovery process performed by the receiver module. The transmitter module generates a coded serial data package at each time the data transmission is required. In particular, in the upper part of Fig. 3, is shown the serial data package to be sent that consists of an orderly sequence of samples (each one corresponding to the related sensor of the input array) and a header used to detect the beginning of this package. Moreover, the serial data package includes at the beginning a series of "0" bits (that provide the "*synchronism pulses*") required for the receiver clock recovery process. The lower part of Fig. 3 reports the coding of the serial data package into a pulsed signal.

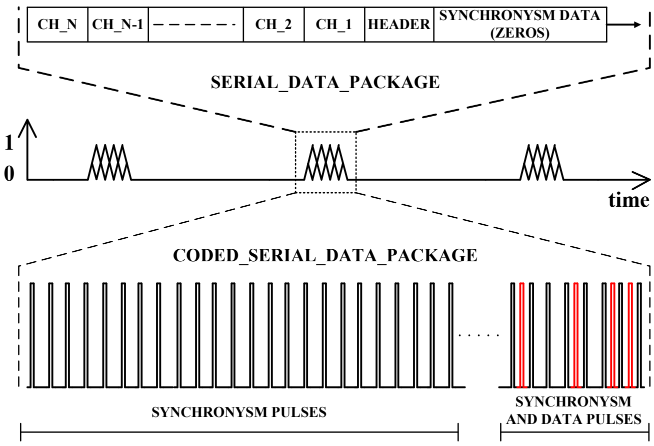

Fig. 3. The serial data package structure/composition.

B. *The optical data communication link*

The first block of the optical link is the driver circuit that converts the voltage digital pulses into current pulses to drive a Vertical Cavity Surface Emitting Laser VCSEL, OPV314AT by TT Electronics) emitting at λ=850nm with a response time lower than 100ps. In this way, the laser pulses are the optical replica of the current pulses. The VCSEL is coupled to one end of a 1m length 50/125µm multi-mode optical fiber while the other end is coupled to a high-speed Si-based photodiode (PD, DET025AFC/M by Thorlabs) with rise/fall times of about 150ps. This photodiode detects the laser pulses and generates their replica as photocurrent pulses. The PD is finally interfaced with a signal conditioning circuit, based on a transimpedance amplifier, that converts current pulses into voltage pulses to be decoded by the receiver module. In particular, it provides a suitable amplification of the pulsed signal to reach amplitudes matching with the logic threshold levels of the standard I/O LVCMOS25 considered and employed for the transmitter and the receiver module.

C. *The receiver module*

The receiver module works with a main clock signal *CLK_M2* equal to 200MHz. By using an internal PLL, the Digital Decoding block regenerates a 100MHz clock signal starting from the received "*synchronism pulses*" and uses this to properly recover the transmitted coded data. When the header sequence is recognized, the correct data are available into the bus "*PARALLEL_DATA*" and the control signal *DATA_READY* is set high. Thus, the data can be acquired and stored into the global data buffer and, then, processed and sent to a stimulator and/or to a PC monitor through a standard UART communication protocol implemented by the UART INTERFACE block (or simply evaluated by an oscilloscope). More in detail, the data are processed to provide proper control commands to the stimulator device together with the generation of stimulations corresponding to the touch detected by the input sensors. The control commands carry out the parameters related to the stimulations to be generated (e.g., stimulation pulse intensity, frequency and electrode channel position, etc.) that could change according to the type and the force intensity of the touch of the sensing elements (i.e., their physical stimulation). Finally, the control signal "*END_OP*" indicates that the data buffer is empty when switched to a high level and so another serial data package can be acquired, stored and processed.

III. Experimental Results

Fig. 4 shows the experimental set-up implemented to validate and test the proposed overall system. In particular, the test-bench includes two FPGA boards that implement the transmitter and the receiver modules and the optoelectronic devices and circuits of the optical fiber communication link.

In order to conduct preliminary tests of the designed architecture, a package of 512 bits, composed by a repeated [0,1] sequence, has been employed to verify the correctness of the data transmission. All the signals and reported figures have been evaluated and acquired through a 6GHz bandwidth digital oscilloscope LeCroy Master 8600A. In particular, Fig. 5 shows the sent serial data package and its corresponding pulsed coded signal. In the magnified sections of Fig. 5, are highlighted the HEADER and the begin of the serial data package, while in the lower part is shown the transmitted pulsed signal corresponding to the coded serial data package, probed at the end of the optical communication link (i.e., the voltage generated by the signal conditioning block).

In Fig. 6 is reported the measurements related to the receiver module. The receiver is able to perform the data and the clock recovery by regenerating the "*data_recovery*" and the "*clock_recovery*" signals starting from the received input pulsed signal. More in detail, the "*clock_recovery*" signal is generated starting from the "*synchronism pulses*" and can be considered stable and correct only when the "*stable_clock*" signal is set to a high value. Then, the detection of the package HEADER identifies the beginning of the 512 bit of the sent data composed by the repetition of a [0,1] bit sequence. Finally, the received "*data_pulses*" are correctly decoded and re-converted into a serial data package.

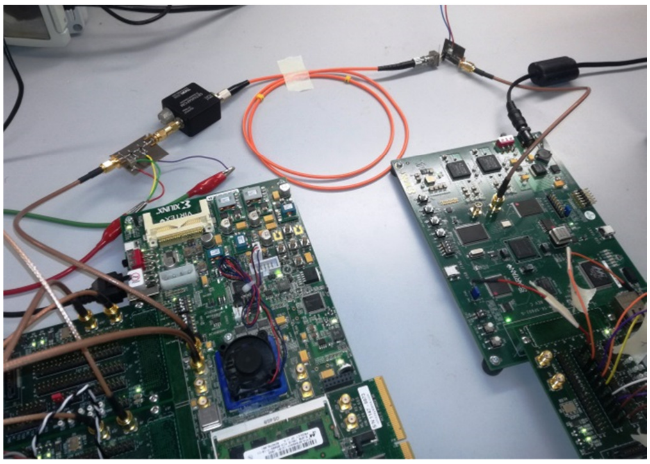

Fig. 4. Photo of the experimental set-up showing the two FPGA boards and the optical communication link composed by the optoelectronic devices and circuits together with the optical fiber.

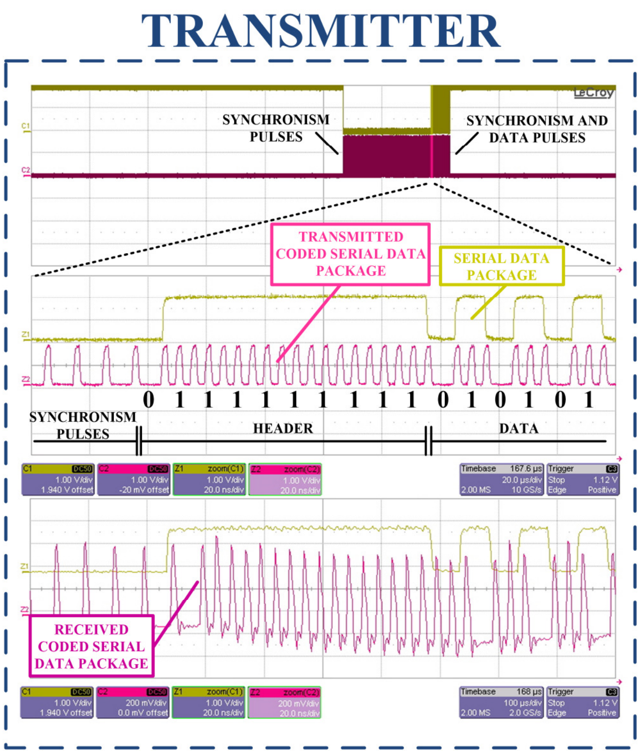

Fig. 5. Experimental measurement: main signals related to the transmitter module operating at 100Mbps and transmitting a repeated {0,1} bit serial sequence.

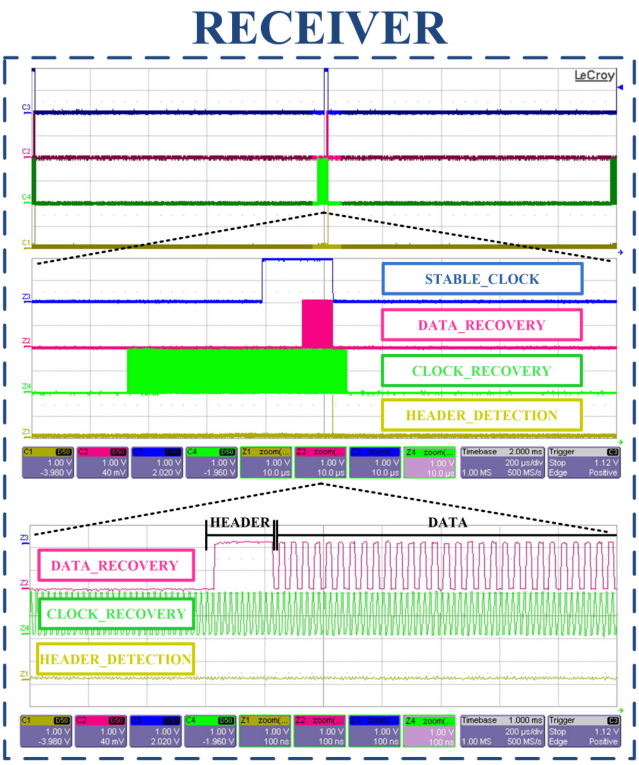

Fig. 6. Experimental measurement: main signals related to the receiver module operating at 100Mbps and receiving a repeated {0,1} bit serial sequence.

In order to evaluate the correct transmission of the serial data operated by the system, a package of 512 bit containing the samples of a ramp voltage signal has been assembled and periodically sent from the transmitter to the receiver. After the data decoding and processing was performed by the receiver module, the recovered data have been transmitted through a UART communication protocol, implemented on the receiver FPGA, to the PC. In particular, as shown in Fig. 7, Matlab environment has been used for the acquisition of the received and decoded data package and to plot the corresponding samples.

TABLE I. PROPOSED TACTILE SENSORY FEEDBACK SYSTEM: MAIN SPECIFICATIONS, PERFORMANCES AND CHARACTERISTICS.

Emulated number of tactile sensors	32
Sensor data sampling rate	2 kHz
Optical transmission data rate	100 Mbps
Optical link power consumption	5 mW
Transmission power efficiency	50 pJ/bit
FPGA LUTs for the Tx + Rx	1422 + 1323
FPGA FFs for the Tx + Rx	2230 + 2865

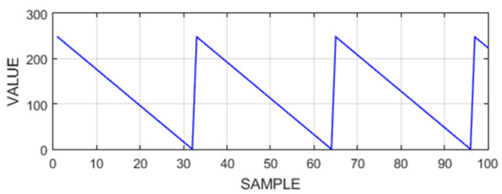

Fig. 7. Example of samples of a periodic ramp voltage signal transmitted to a PC through a UART communication protocol, implemented on the receiver FPGA, and plotted in Matlab environment.

IV. CONCLUSION

This paper reported on a tactile sensory feedback system based on an optical fiber communication link for the prosthetic application. The system blocks were implemented on FPGA-based boards, where one of these boards acquires the sampled data coming from a tactile sensor array by managing an analog-to-digital converter. Moreover, it performs a UWB-based pulsed data coding to be sent via an optical fiber communication link to a receiver realized by using the second FPGA board. The receiver handles the data-recovery process by decoding the received data to be finally processed. In addition, the receiver is capable to provide the control commands to properly manage an external electrotactile stimulator. The transmission performances have been evaluated by emulating the data coming from a sensor array sent to an external apparatus (i.e., PC and/or oscilloscope) that represents a possible stimulator. A summary of the main overall system specifications, performances and characteristics is reported in Table 1. The achieved results show the correct functionality of the proposed system and validate the improvements achieved in the transmission data rate and in the power consumption. These results enable the proposed solution to be suitably employed with tactile sensor arrays having a higher number of sensors, sampled at higher data sampling rates, that require the transmission of significant amount of data.

ACKNOWLEDGMENT

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