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Wireless Control of Robotic Artificial Hand Using Myoelectric Signal Based on Wideband Human Body Communication

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ABSTRACT A Myoelectric hand is a robotic artificial hand controlled by myoelectric signals and driven by motors. The myoelectric signals are detected on the arm and sent to the motor controller by wire for driving the artificial hand. However, from the point of view of convenience, wireless connection between the myoelectric signal detector and the motor controller is strongly desired. In this paper, we developed a human body communication-based wireless transmitter and receiver for transmitting the myoelectric signals from the arm to the motor controller of the myoelectric hand. The transmitter and the receiver employed a wideband impulse radio system at about 10–50-MHz extremely weak radio power band and were implemented on a field programmable gate array, respectively. The feasibility of the wireless myoelectric hand was confirmed by a wireless transmission experiment of myoelectric signals and an operation experiment of the myoelectric hand. The wireless transmission experiment achieved a correlation coefficient as high as 0.999 between the transmitted and received myoelectric signals, and the operation experiment demonstrated a normal movement of the myoelectric hand controlled by the wireless myoelectric signals. This result should be the first realization example of wireless control of a robotic artificial hand based on human body communication technology.

INDEX TERMS Biomedical application, human body communication, impulse radio transceiver, wireless control, wireless myoelectric hand.

I. INTRODUCTION

In recent years, wireless technology is being widely used in various healthcare and medical applications [1], [2]. Myoelectric hand is an artificial one used to replace a hand amputated due to an accident or illness. Fig. 1 shows the structure of a myoelectric hand. It consists of a detector for acquiring three kinds of myoelectric or electromyogram (EMG) signals and a controller for driving the motors to operate the artificial hand based on the detected myoelectric signals [3]. As shown in Fig. 1, the myoelectric signals need to be detected at the upper part of forearm, and then sent to the motor controller of artificial hand. Between the upper part of forearm and the artificial hand, there is a transmission route consisting of two parts. The first part is the forearm, and the second part is a socket to the artificial hand. Usually, the wires are used to connect between the detector and the artificial hand. They are along the arm surface but available inside the socket. Wireless link between the myoelectric signal detector and the motor controller of artificial hand is highly expected in reducing the patient's burden and increasing the convenience. In view of the structure of artificial hand, we have two choices for the wireless link. One choice is using wireless communications for both parts of the transmission route; the second choice is doing so only for the first part. In this study, in place of the usual link of wire between

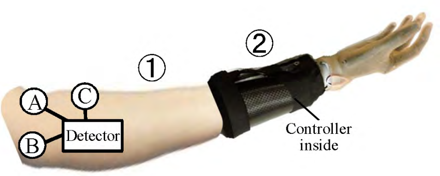

FIGURE 1. Outline of myoelectric artificial hand. The myoelectric signals are detected at three locations of the upper part of forearm.

the myoelectric signal detector and the motor controller of artificial hand, we focus the wireless transmission on the first part of the transmission route, i.e., the forearm part, in view of that the wires can be embedded inside the socket in the second part of the transmission route.

Since the myoelectric hand is an appliance supporting the user's life, malfunction and control delay due to various noises should be avoided [4]. So a wireless myoelectric hand requires a communication method with high reliability and low time delay. Moreover, it also requires low power consumption since it works with battery. Based on these considerations, we attempt to adopt a wideband human body communication (HBC) technology to realize the wireless myoelectric hand. HBC was first introduced in [5] for short-range communications. It uses the human body as a transmission route to transmit data, and usually operates in the range of dozens of kHz to dozens of MHz with a narrow band modulation [6], [7], because at these frequencies the propagation loss along the human body is smaller than that through air. In the myoelectric hand, by using the arm as the transmission route, we can remove the wires on the arm surface. One feature of HBC is its very low propagation loss because the human tissue looks like a conductor at low frequencies. Another feature of HBC is that it does not need an antenna for radiating electromagnetic wave. In place of an antenna, HBC employs a pair of electrodes for adding a signal to be transmitted to the human body and then transmit the signal along the body medium. It is available to use the electrodes for detecting the myoelectric signals as the HBC transmitting electrodes by a time division algorithm [8]. This feature can largely reduce the complexity of transmitter. Moreover, we adopt an impulse radio (IR) modulation system for the wireless transmission of myoelectric signals. The IR system is a wideband technology so that a high anti-interference performance can be expected. Since it directly uses short pulses to transmit data, a carrier signal generating circuit is not required, which contributes to high-speed data transmission, low time delay and low power consumption [9]. For effective realization of the IR-based HBC technology in the wireless myoelectric hand, we employ an extremely weak radio power band at 10 - 50 MHz because of its small signal attenuation along the human arm.

This paper is organized as follows. Chapter 2 describes the specifications of communication part of the wireless myoelectric hand. Chapters 3 and 4 describe the design and realization of the transmitter and receiver, respectively. Chapter 5 describes the experimental result of the wireless transmission of myoelectric signals, and Chapter 6 describes the experimental result of movement of the developed wireless myoelectric hand. Chapter 7 concludes this study.

II. BASIC DESIGN

Fig. 2 shows the block diagram and view of the wireless myoelectric hand to be developed. The myoelectric signals are detected by three pairs of electrodes on the arm, and are then differentially amplified and sent to a transmitter (Tx).

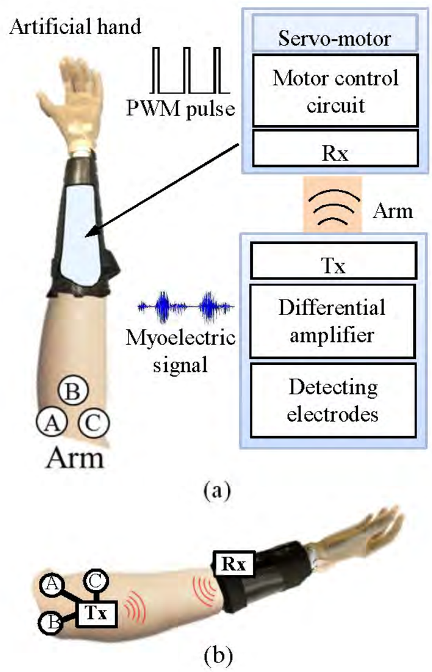

FIGURE 2. (a) Block diagram of wireless myoelectric hand. (b) View of wireless myoelectric hand.

The modulated myoelectric signals are sent to a control board consisting of a receiver (Rx) and a motor controller. The controller analyzes the demodulated myoelectric signals and produces the corresponding pulse width modulation (PWM) signals for driving the servo-motors to operate the artificial hand.

Based on that the myoelectric signals are usually in the frequency band below several hundred hertz and have a level in the order of micro-voltages, we designed the transmitter and receiver for the wireless myoelectric hand.

A. FREQUENCY COMPONENT OF MYOELECTRIC SIGNAL

Fig. 3 shows an example of time waveform and normalized amplitude of frequency spectrum of a myoelectric signal detected from the flexor digitorum superficialis muscle, which is one kind of myoelectric signals used to operate the myoelectric hand. As can be seen from Fig. 3, the signal's largest amplitude is found at approximately 200 Hz, and the signal bandwidth can be considered to be 600 Hz. So a sampling rate of 2 kHz is reasonable for analog to digital conversion. In addition, 12-bit quantization is usually used to convert the analog myoelectric signal to digital data for wireless transmission. This suggests that a data rate of 24 kbps is required at least. Since the myoelectric hand is usually controlled by three myoelectric signals at the same time, the actual data rate should be 72 kbps at least.

B. FREQUENCY BAND OF WIRELESS TRANSMISSION

In a wireless myoelectric hand, the communication distance is short from the myoelectric signal detector to the

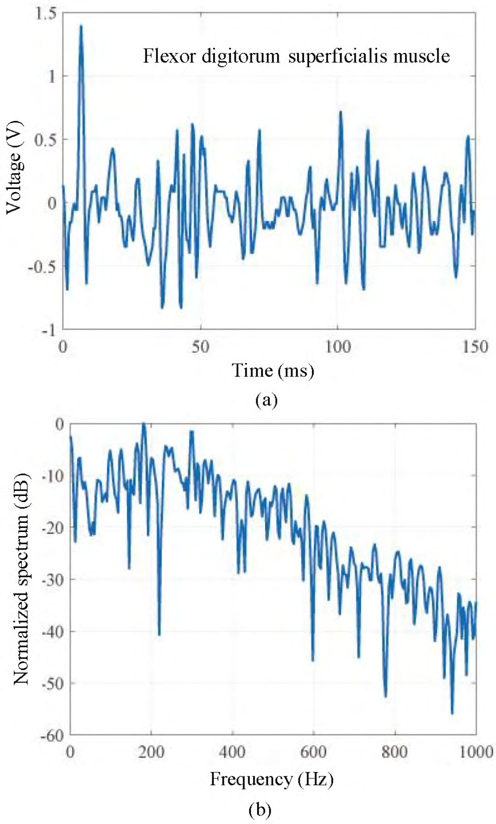

FIGURE 3. Example of myoelectric signal detected at the flexor digitorum superficialis muscle location. This signal is usually used to perform bending of the palm. (a) Amplified time waveform. (b) Normalized amplitude of frequency spectrum.

TABLE 1. Usable frequency bands.

Name	Frequency band	Propagation loss
HBC	10 - 50 MHz	Small
WMTS	608 - 614 MHz	⇓
ISM	2.4 GHz, 900MHz	⇓
UWB	3.1 - 10.6 GHz	Large

HBC: Human body communication
WMTS: Wireless medical telemetry service
UWB: Ultra wideband

motor controller. Table 1 gives usable frequency bands for short-range communications and compares their propagation losses. Since the frequencies of myoelectric signals are usually below several hundred hertz, a high data rate of wireless transmission is not necessary. As shown in Fig. 2(b), the wireless transmission of myoelectric signals is actually along the human arm, because the detector of myoelectric signals is set on the arm surface. This suggests that HBC technology is a feasible choice for realizing the wireless transmission, because compared to WMTS, ISM and UWB signals, the HBC band signal not only provides a very low propagation loss but also does not need an antenna for radiating electromagnetic wave [6], [7]. That is, the human arm itself acts as a transmission route, and the sensing electrodes act for both detecting the myoelectric signals and applying the transmit signals to the arm [8]. Therefore, we decided to employ the HBC technology with a frequency band of 10 - 50 MHz. This frequency band falls in the extremely weak radio band defined in Japan [10]. In the extremely weak radio band, no license is needed as long as the radiated electric field intensity is below 500 μV/m at a distance of three meters from the transmitter. Such a wide band can provide communication with very short time delay and high anti-interference ability. Its low power density is also helpful to reduce electromagnetic absorption in the human body.

C. MODULATION SCHEME

To effectively use the frequency band from 10 to 50 MHz, a wideband transmission system is desirable. The IR system employs very short pulses in terms of time for modulation, and does not need to generate a carrier signal. These features contribute to low power consumption and high-speed data transmission. The modulation methods usually used in an IR system are on-off keying (OOK) or pulse position modulation (PPM). Multiple PPM (MPPM) has higher immunity to noises because it uses multiple pulse positions [11] and does not need a threshold for bit decision. In view of the high reliability required for a myoelectric hand, we decided to adopt IR-MPPM for transmitting the myoelectric signal in the wireless myoelectric hand.

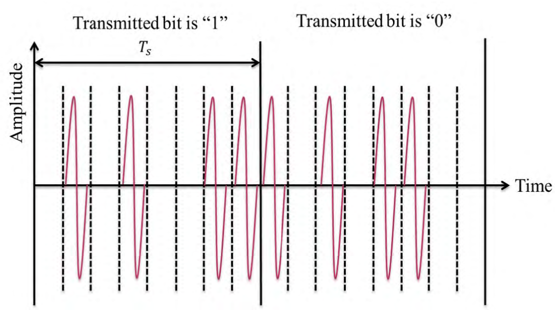

FIGURE 4. Example of IR-MPPM time waveform. In this case eight pulses are used to represent one information bit. Information bit "1" is represented by a sequence of chips "01010011" and "0" is represented by a sequence of chips "10101100", where chip '0' denotes no pulse transmitted and chip "1" denotes one pulse transmitted.

Fig. 4 shows an example of IR-MPPM time waveform to be transmitted in the transmitter. Each bit consists of 8 chips, and each chip corresponds to one pulse. IR-MPPM represents the bit information by the position of multiple pulses in one bit. For example in Fig. 4, information bit "1" is represented by the sequence of "01010011", and information bit "0" is represented by the sequence of "10101100". The data rate can be changed by adjusting the number of pulses in each bit. To ensure a small time delay of operation in the myoelectric hand and keep sufficient anti-interference ability, we adopted eight chips for representing one bit. This yields a data rate of 1.25 Mbps, which satisfies the requirement described in subsection A.

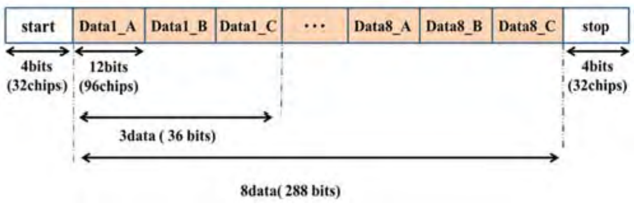

FIGURE 5. Packet structure.

D. PACKET STRUCTURE

Fig. 5 shows the structure of packet to be transmitted. One packet is composed of 296 bits, where four bits as start bits, four bits as stop bits, and 288 bits as information bits.

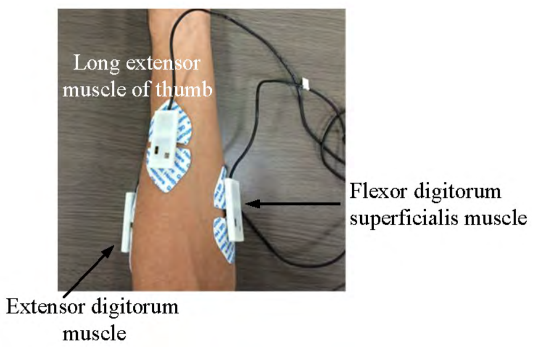

FIGURE 6. Detection of three myoelectric signals used to control myoelectric hand.

Since the myoelectric hand is controlled by using the myoelectric signal detected at three different locations on the arm as shown in Fig. 6, three input ports are required for the analog-to-digital converters (ADCs). The ADCs quantize each sampling data to 12 bits, so that 36 bits corresponding to the three input ports are accumulated in the memory each time. The packet will be generated when 288 bits (that is, 8 sampling data) are accumulated in the memory. In addition to the information bits, we set up four bits as the start bits for indicating the beginning of a packet, and four bits as the stop bits for indicating the end of the packet. Unlike the information bits, the start bits and stop bits are represented by a unique pulse train of 32 chips corresponding to four bits, respectively.

The packet was designed to have a transmission rate of 2 kHz for avoiding it directly fall into the frequency band of myoelectric signals (<600 Hz) to cause interference. A low pass filter (LPF) with −3 dB cut-off frequency of 500 Hz was further inserted in the detection circuit to eliminate mixing of packet transmission rate component into myoelectric signals. This is especially important to HBC in which the electrodes are used for not only detecting the myoelectric signals but also transmitting the IR signals. An inappropriate packet transmission rate may directly interfere the myoelectric signal detection.

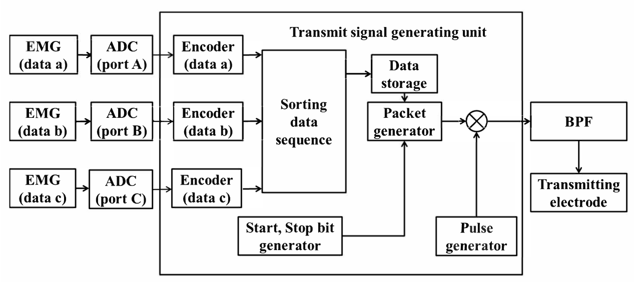

FIGURE 7. Block diagram of transmitter.

TABLE 2. Specifications of FPGA board for transmitter.

Model name	COSMOZ125
Clock frequency	∼ 100 MHz
Port number of ADC	8 ports
Quantization bit of ADC	12 bits
Sampling rate of ADC	∼ 100 MHz
Mounted operating system	Linux

III. DESIGN OF TRANSMITTER

Based on the basic design described in the above section, we developed the transmitter and receiver for wireless myoelectric hand. Fig. 7 shows the block diagram of the transmitter. We designed the transmitter with Verilog-HDL and implemented the design in a field programmable gate array (FPGA) board. The specifications of the FPGA board used for the transmitter are summarized in Table 2. In Fig. 7, firstly, the ADCs mounted on the FPGA board acquire the myoelectric signals from the three ports with a reasonable sampling rate and 12-bit quantization. Each digital bit is input into an encoder respectively where each bit is represented by 8 chips according to Fig. 4. The encoded data are then sorted and accumulated in the data storage module. In the data storage module, the sampling rate of myoelectric signals is fixed at 2 kHz. Once the digitized data of eight sampled myoelectric signals are accumulated in the storage module, the start bits and stop bits will be added to the data and finally, one packet is generated. Each chip in the generated packet is OOK modulated by a multiplier and a pulse generator, so that the chip is "1" when the pulse exists, and the chip is "0" when the pulse is absent. This modulation scheme is the so-called IR-MPPM. The output pulses are then filtered to make its signal components being approximately between 10 and 50 MHz by a 9-stage Butterworth-type analog band pass filter (BPF) formed of inductors and capacitors. Fig. 8 shows the actual pulse waveform for representing one chip and its frequency spectrum, which was produced by the pulse generator made from an analog transistor circuit with digital input. As can be seen, the produced pulse has a width of around 100 ns, and its −10 dB bandwidth is from 8 to 55 MHz, i.e., most of the signal components fall in 10 - 50 MHz band.

Such wideband IR-MPPM signals are transmitted through a pair of transmitting electrodes on the arm surface to the receiver in the myoelectric hand at a data rate of 1.25 Mbps.

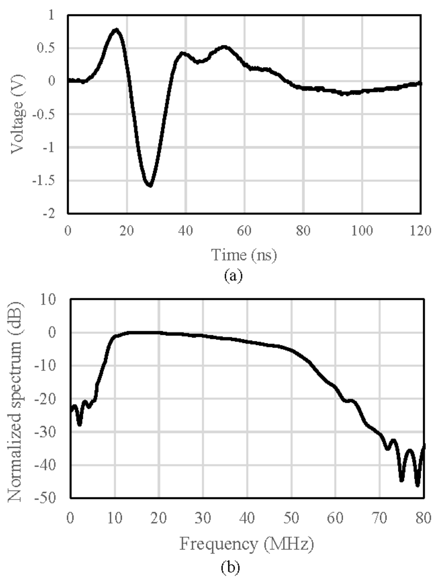

FIGURE 8. Pulse to be transmitted. (a) Time waveform with a width of around 100 ns, which is used to represent one chip. (b) Amplitude of frequency spectrum. The −10 dB bandwidth is from 8 to 55 MHz, and most of the signal components fall in 10 - 50 MHz band.

TABLE 3. Specifications of the transmitter.

Major frequency band	10 - 50 MHz
Sampling rate of myoelectric signal	2 kHz
Data rate	1.25 Mbps
Modulation	IR-MPPM
Packet length	296 bits
Output power	-10 dBm

The transmitter repeats these steps sequentially to transmit the myoelectric signals to the motor controller for operating the artificial hand. Table 3 summarizes the specifications of the transmitter.

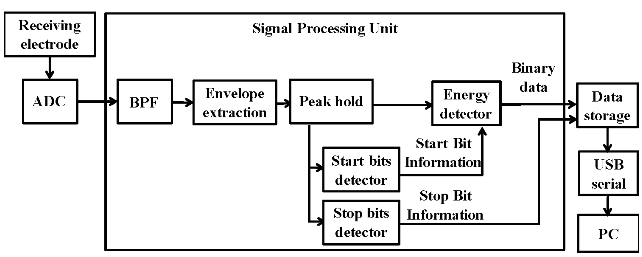

FIGURE 9. Block diagram of receiver.

IV. DESIGN OF RECEIVER

Fig. 9 shows the block diagram of the receiver. We implemented the design of Fig. 9 also in an FPGA board (Xilinx, Virtex-6). The receiving electrodes are set on the surface of forearm end connecting to the socket of artificial hand. Firstly, the received pulse signal is digitized with a quantization level of 10 bits in the ADC mounted on the FPGA board. Next, the signal components from 10 MHz to 50 MHz

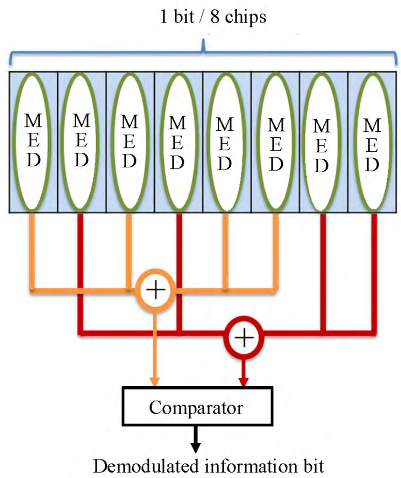

FIGURE 10. Block diagram of energy detector. MED means detection of the maximum value of the envelop in each chip.

TABLE 4. Specification of the FPGA-implemented receiver.

Demodulation method	Energy detection
Sampling rate of ADC	312.5 MHz
Quantization bit of ADC	10 bits
Clock frequency of FPGA	156.25 MHz

are extracted from the digitized signal by a digital BPF. The envelope of the signal passed through the BPF is extracted in the envelope extraction module consisting of a full-wave rectifier circuit and a LPF. Then the peak hold module detects the maximum value of the envelope within each chip (pulse) duration and records it. After that, the recorded data are sent to the start bit detector, stop bit detector and energy detector. The start bit detector has 32 registers corresponding to 32 chips, and the maximum value in each chip is stored in each register. When a data sequence corresponding to the start bits is detected, the start bit detector sends a sign to the energy detector, and the energy detector begins to carry out the energy detection and obtain the information bits of "1" or "0". Fig. 10 shows the block diagram of energy detection. At first the maximum envelop value in each chip is detected. Then their sum for the 1st, 3rd, 5th and 6th chips and the sum for the 2nd, 4th, 7th and 8th chips are calculated respectively. Referring to Fig. 4, the former corresponds to information bit "0" and the latter corresponds to information bit "1". By comparing their magnitudes with a comparator we can determine the information bit is "0" or "1" where a threshold is not necessary. The demodulated information bits are temporarily stored in the data storage module. When the stop bit detector detects the stop bits by the same operation as the start bit detector and send a sign to the data storage module, the demodulated information bits are sent either to the motor controller or to the PC via USB interface. The specifications of the receiver implemented on the FPGA board are summarized in Table 4.

TABLE 5. Recipe for making the bio-equivalent phantom.

Glycerin	300.0 g
Deionized water	417.9 g
Sodium benzoate	2.1 g
Agar	21.6 g

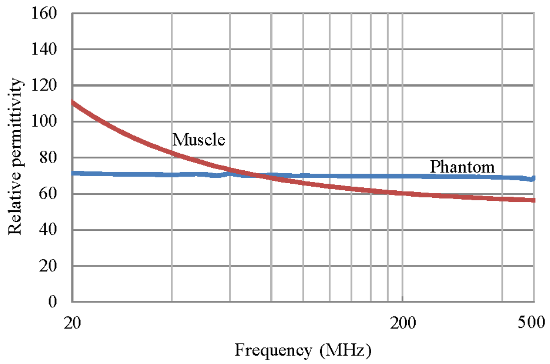

FIGURE 11. Relative permittivity of bio-equivalent arm phantom.

V. EXPERIMENTAL VALIDATION OF WIRELESS TRANSMISSION

A. BIO-EQUIVALENT ARM PHANTOM

We first validated the performance of the developed transmitter and receiver by using an arm-shaped bio-equivalent gel phantom with a length of 30 cm. The bio-equivalent gel phantom is composed of glycerin, deionized water, sodium benzoate and agar [12], which simulates the dielectric properties (permittivity and conductivity) of human arm at the frequency band used for myoelectric signal transmission. Table 5 gives the recipe for making the bio-equivalent gel phantom, and Fig. 11 shows the relative permittivity of the gel phantom measured using an open-ended coaxial type dielectric probe (SPEAG, DAK-12). Also shown in the figure is muscle's average relative permittivity [13]. Although the two curves do not fit well in a wide frequency range, the difference at the frequency of 30 MHz does not exceed 10%. The same result was also obtained for conductivity.

B. PSEUDO MYOELECTRIC SIGNAL GENERATOR

Since a bio-equivalent gel phantom cannot provide myoelectric signals used for operating the myoelectric hand, we employed a pseudo myoelectric signal generator [14], as shown in Fig. 12, to produce pseudo myoelectric signals instead of real signals in the validation experiment of wireless transmission. The pseudo myoelectric signal generator outputs three channel myoelectric signals from a PC, which are added to the three pairs of detecting electrodes of the myoelectric hand, respectively, for operating the artificial hand. The repeatable pseudo myoelectric signals are convenient in investigating communication performance.

C. VALIDATION RESULTS OF WIRELESS TRANSMISSION

Fig. 13 shows the block diagram and view of validation experiment of wireless transmission, and Table 6 summaries the detailed parameters in the validation experiment. We first conducted a test experiment to verify the accuracy of operation of the transmitter and receiver with three sine signals. The three sine signals with different amplitudes (0, 180 mV and 360 mV) at 300 Hz were input to the transmitter from the pseudo signal generator. They were then modulated by the developed transmitter and added on the transmitting electrode. The modulated signals were transmitted through the bio-equivalent arm phantom, and received by the receiving electrodes. The received signals were amplified by 40 dB, and then attenuated by a programmable attenuator to an adequate voltage level not exceeding the input limit voltage of the ADC in the receiver. After the demodulation, the demodulated signals were sent to the PC via USB interface for evaluation of communication performance. From Fig. 14, it can be seen that the received three sine signals agree well with the transmitted ones, which suggests that both the transmitter and the receiver

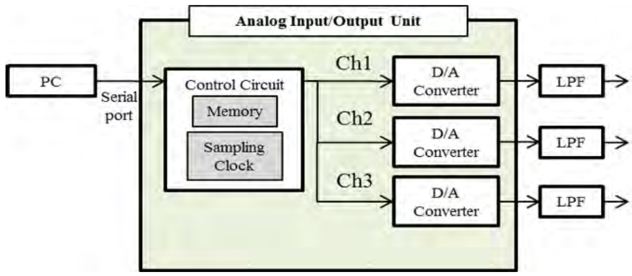

FIGURE 12. Pseudo myoelectric signal generator.

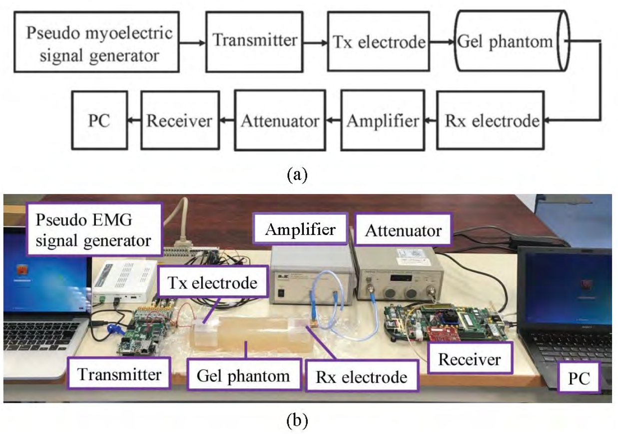

FIGURE 13. (a) Block diagram of validation experiment. (b) View of experiment. The gel phantom corresponding to the first part of the transmission route in Fig 1.

TABLE 6. Detailed parameters in the validation experiment.

Pseudo signal generator	Sampling frequency Quantization level Output channel number Output voltage level	2 kHz 12 bits 4 -5 V ~ +5 V
Gel phantom	Dielectric property Length	Similar to muscle 30 cm
Transceiver	Electrode type Amplifier Variable attenuator	Silver/silver chloride 40 dB 0 - 20 dB

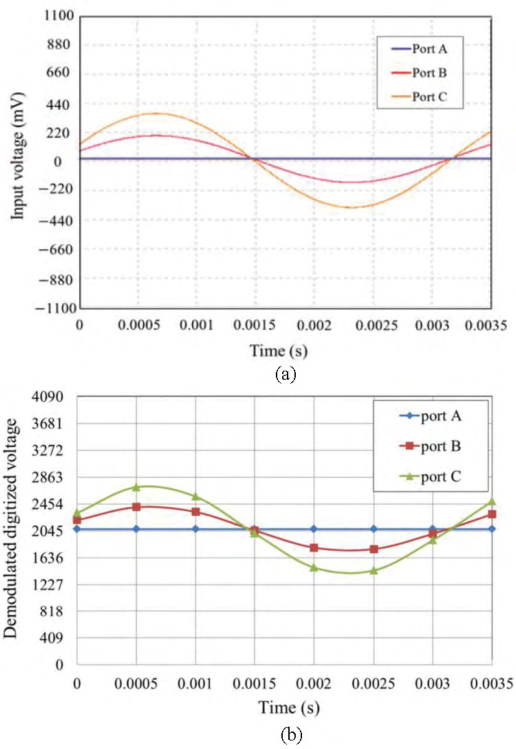

FIGURE 14. Validation experiment result for sine signals. (a) Input to the transmitter of three port sine signals. (b) Demodulated three port sine signals.

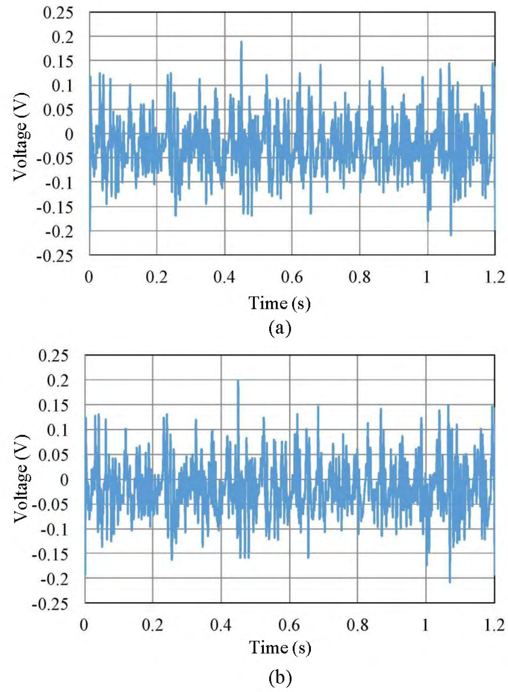

FIGURE 15. Validation experiment result for a myoelectric signal transmission. The myoelectric signal was detected at the flexor digitorum superficialis muscle location of arm, and used to perform bending of the palm. (a) Myoelectric signal to be transmitted. (b) Demodulated myoelectric signal.

work well at a communication distance of 30 cm along the human arm with a data rate of 1.25 Mbps.

Then we conducted the validation experiment by using the pseudo myoelectric signals. The pseudo myoelectric signals were generated by the pseudo signal generator, and were modulated by the developed transmitter and added on the transmitting electrodes. The modulated signals were transmitted through the bio-equivalent arm phantom, and demodulated by the receiver. The demodulated pseudo myoelectric signals were also sent to a PC via USB interface for performance evaluation. Fig. 15 shows the time waveforms of a myoelectric signal to be transmitted and the demodulated one. To check the degree of agreement between the two signals, we calculated their correlation coefficient and obtained a correlation as high as 0.999. This result suggests that the developed transmitter and receiver can provide a wireless transmission of myoelectric signals with high accuracy.

VI. OPERATING EXPERIMENT OF WIRELESS MYOELECTRIC HAND

After the validation of wireless transmission, we set up the myoelectric hand instead of the PC in the same experimental environment as in Fig. 13 to operate the myoelectric hand using the wireless myoelectric signals. Fig. 16 shows the view of operating experiment of the wireless myoelectric hand. In the experiment, we employed the myoelectric signals for two kinds of movements from the pseudo myoelectric signal generator. One movement was to keep the artificial hand grasping for five seconds, and the other movement was to keep the hand opening for five seconds. The two movements were repeated five times. We verified whether the myoelectric hand operated according to the signals output from the pseudo myoelectric signal generator. Table 7 summarizes the experimental result for the five times movements of the wireless myoelectric hand. The symbol ''ok'' means successful operation of the wireless myoelectric hand. All the five times experiments showed that the myoelectric hand was operated according to the signal outputs.

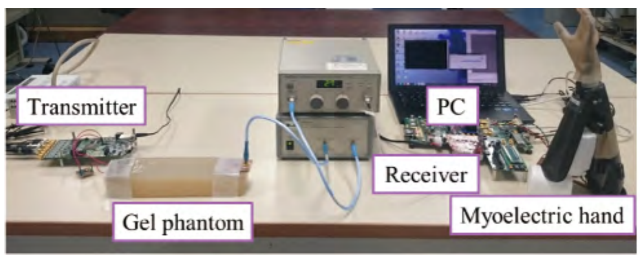

FIGURE 16. View of experiment to operate the wireless myoelectric hand. The gel phantom corresponding to the first part of the transmission route 1 in Fig. 1.

TABLE 7. Experimental result of wireless myoelectric hand operation.

	1st	2nd	3rd	4th	5th
Keep hand grasping	ok	ok	ok	ok	ok
Keep hand opening	ok	ok	ok	ok	ok

Moreover, we also investigated the effect when changing the communication distance along the bio-equivalent arm phantom. Since the detector locations are basically on the upper arm and the signals need to be transmitted to the artificial hand, the communication distance is quite limited, in the order of several tens centimeters. We changed the distance between the transmitting and receiving electrodes up to 40 cm, and no communication error was observed. In addition, even if the receiving electrodes were set on the surface of the thermoplastic socket, the communication was still established at spacing up to 4 cm from the forearm end to the receiving electrodes due to a near-field electromagnetic coupling, and a normal movement of the artificial hand was kept. When the socket was covered with aluminum foil, this distance was further extended up to 10 cm. This means that if the socket is made of conductive material, the HBC technology can be easily applied to the entire route in Fig. 1.

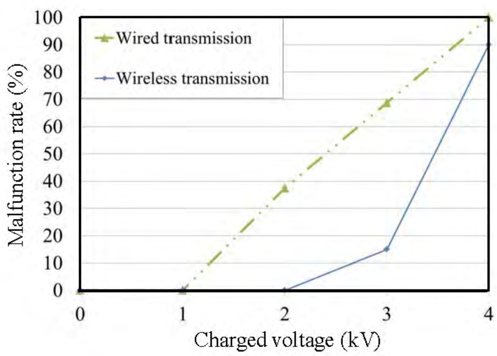

FIGURE 17. Malfunction rate of myoelectric artificial hand in an IEC 61000-4-2 defined indirect ESD test environment.

In addition, to demonstrate the anti-interference performance of the wideband IR-based HBC technology in wireless myoelectric hand, we measured the malfunction rate of the myoelectric hand under an indirect electrostatic discharge (ESD) test environment. The indirect ESD test follows IEC 61000-4-2 standard [15]. The test setup consists of an ESD gun and a vertical or horizontal coupling plane. The ESD gun was first charged to a high voltage and then was discharged through the vertical coupling plane. The wireless myoelectric hand to be tested was placed at a distance of 0.1 m from the vertical coupling plane. The discharge produced an impulse noise and may make the artificial hand malfunction. Fig. 17 shows the measured malfunction rate of the wireless myoelectric hand as a function of ESD charging voltage. Also shown in the figure is the malfunction rate when the myoelectric signals were sent to the controller of artificial hand by wire. As seen from Fig. 17, the malfunction rate decreases significantly in the case of wireless transmission compared with the case of wired transmission. As a reason, in the case of wired transmission, malfunction occurred due to the influence of the ESD noise superimposed on the wire which transmits the control signal. In the case of wireless transmission, however, we employed a wideband IR-MPPM scheme where multiple pulses were transmitted to represent one information bit. Moreover, the energy detection in the receiver just compares the total energy values of a plurality of pulses corresponding information "0" and "1" without using a threshold. This makes difficult for bit error to occur even when an impulse ESD noise with a very short duration in the order of tens ns is superimposed, and as a result the malfunction rate is reduced. So the developed transmitter and receiver work well, and it is feasible to realize a wireless myoelectric hand with the wideband IR-based HBC technology.

A demonstration video for the wireless myoelectric hand controlled by an actual person is possible in the Graphical Abstract. A slight time delay may be observed between the actual hand movement and the robotic hand movement. This is not due to the wireless transmission of myoelectric signals because the transmission of one packet only requires 0.24 ms in view of the data rate of 1.25 Mbps. In fact, even in the wire case, such a delay can still be observed. The reason of the slight time delay is that we have to acquire the myoelectric signals for a certain period of time in order to analyze the type of hand movement. By analyzing the myoelectric signals at a certain period of time, we determine the type of hand movement and produce the corresponding PWM signal for driving the motors and moving the hand. These processes produce the slight time delay between the actual hand movement and the robotic hand movement.

VII. CONCLUSION

In this study, we have developed a prototype wireless myoelectric hand. Since the major transmission route of myoelectric signals from the signal detector to the motor controller is along the human arm, we have adopted the HBC technology in view of its low propagation loss on the human body. The HBC-based transmitter has employed the extremely weak radio power band of 10-50 MHz with IR-MPPM. The wideband IR system provides high-speed transmission and anti-interference feature. It also contributes to low power consumption. All of these are essential in designing a myoelectric hand. Based on these considerations, we have designed the transmitter and receiver and implemented them on an FPGA board respectively, although they do not have a sufficiently small size. The FPGA implementation of the prototype transmitter and receiver is to make it easy to adjust and optimize the modulation/demodulation scheme and the transmitter/receiver structure. It is straightforward and not difficult to make the FPGA implementation into integrate circuits (ICs) with a practical size by the current IC technology.

To validate the feasibility of the wireless myoelectric hand, we have conducted some experiments to confirm the wireless transmission performance of myoelectric signals and the operating performance of the artificial hand, by using a pseudo myoelectric signal generator and a bio-equivalent arm phantom. For the wireless transmission performance, we have confirmed a correlation coefficient as high as 0.999 between the transmitted and received myoelectric signals. For the operating performance of the wireless myoelectric hand, we have verified whether the wireless myoelectric hand operates according to the signal outputs from the pseudo myoelectric signal generator, which designates two kinds of movement of hand. In all the cases, the myoelectric hand has been found to operate properly based on the wireless myoelectric signals. Therefore, the developed wireless myoelectric hand based on HBC technology is sufficiently feasible.

Although this study only demonstrated the usefulness of wireless link for using myoelectric signal to control artificial hand, this technique is also possible to be applied to control an artificial arm or leg based on the myoelectric signals. Moreover, since human movement is actually controlled by the brain, it may become possible in the future to detect the brain signals and send them to the artificial hand, arm or leg to control its movement. In that cases, the wires should be quite long and many wires may be required, so that a wireless technology is absolutely necessary. In addition, from the point of view of electromagnetic compatibility, the wire between the bio-sensor and the artificial hand, arm or leg can act as an antenna for receiving electromagnetic noises or interferences. However, the IR-based wideband HBC provides higher immunity to them as shown in Fig. 17.

The future subject is to miniaturize the transmitter and receiver by IC technology, and implement them into the myoelectric hand.

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