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INVITED PAPER

Wide Band Human Body Communication Technology for Wearable and Implantable Robot Control

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SUMMARY This paper reviews our developed wide band human body communication technology for wearable and implantable robot control. The wearable and implantable robots are assumed to be controlled by myoelectric signals and operate according to the operator’s will. The signal transmission for wearable robot control was shown to be mainly realized by electrostatic coupling, and the signal transmission for implantable robot control was shown to be mainly determined by the lossy frequency-dependent dielectric properties of human body. Based on these basic observations on signal transmission mechanisms, we developed a 10-50 MHz band impulse radio transceiver based on human body communication technology, and applied it for wireless control of a robotic hand using myoelectric signals in the first time. In addition, we also examined its applicability to implantable robot control, and evaluated the communication performance of implant signal transmission using a living swine. These experimental results showed that the proposed technology is well suited for detection and transmission of biological signals for wearable and implantable robot control.

key words: Body area communication, human body communication, impulse radio, wireless robot control, weak radio power band.

1. Introduction

As an aging society progresses, expectations are increasing for various wearable and implantable robots that can be worn on or embedded in the human body and help people according to their will. When a person tries to move a part of the body, a command from the brain is sent to the muscle through nerves as a myoelectric signal of several tens of millivolts. Even if a person loses his arm or leg in an accident, when he tries to move them, the same myoelectric signal will be generated in his muscle by his brain commands. By detecting the myoelectric signal with an electrode sensor attached to the surface of the skin and analyzing its frequency, amplitude, etc., what action the person is going to take can be understood. Then a control signal can be generated based on the analysis result and used to drive a wearable or implantable robot\(^{[1]-[6]}\). A wearable or implantable robot can be skillfully moved like a human. It can even do more advanced tasks than can be done with human hands and fingers.

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Fig. 1 Conceptual diagram of wearable robot control.

Fig. 2 Conceptual diagram of implantable robot control.

Moreover, given that the myoelectric signals are generated by brain commands, it should be also possible to generate the control signals based on brain waves to drive the robot.

A myoelectric signal controlled robot mainly consists of a sensor unit which detects the myoelectric signals, a controller unit which analyzes the signal and generates a pulse width modulation (PWM) signal necessary for motor control, and a motor drive unit to drive the robot\(^{[2][7]}\). For a wearable robot, a number of wires are used for signal connection between each units, and are stretched around the human body. These wires not only cause inconvenience during use, but also from the electromagnetic compatibility (EMC) perspective, the wires themselves often act as antennas, which is one
of the causes of erroneous control due to electromagnetic interference [7]-[10]. Wireless control based on myoelectric signals is therefore expected. In addition, for implantable robots, wireless control is essential because the robot is embedded inside the human body so that wire connection is impossible. Figs. 1 and 2 show the conceptual diagrams of wireless wearable robot and implantable robot controlled using myoelectric signals, respectively. A transmitter (Tx) is integrated into the sensor unit and a receiver (Rx) is integrated into the controller unit for wireless control. How to achieve the wireless communication for both wearable and implantable robot control is the topic of this paper.

This paper introduces a 10-50 MHz band human body communication (HBC) technology suitable to the wearable and implantable robot control using myoelectric signals. Chapter 2 explains why this frequency band is chosen and what is the transmission mechanism in this frequency band. Chapter 3 describes the basic design and performance of the developed 10-50 MHz band HBC-based impulse radio (IR) transceiver for this purpose, and Chapter 4 shows some experimental results to demonstrate the validity of this technology. Chapter 5 concludes this paper and gives future prospects.

2. Frequency Band and Transmission Mechanism

As shown in Figs. 1 and 2, a myoelectric sensor unit and a wireless communication module are essential for the wearable and implantable robot control. The most popular method to detect myoelectric signals are to use a pair of electrodes that touch the surface of human skin and acquire the myoelectric voltage potential. Fig. 3 shows the block diagram of myoelectric sensor with a wireless communication module for a wearable robotic hand. The myoelectric signals detected by multiple pairs of electrodes are differentially amplified and sent to a transmitter (Tx). The myoelectric signals modulated in the Tx are transmitted to a receiver (Rx) for demodulation and then sent to a motor controller. The motor controller analyzes the demodulated myoelectric signals and produces the corresponding PWM signals for driving the servo-motors to operate the robotic hand. From this block diagram, it is clear that a short-range wireless communication scheme is required. In addition, since a myoelectric signal is usually in the frequency band below several hundred hertz, a data rate of tens of Mbps/s is sufficient even when multiple pairs of electrodes, or multiple channels, are used.

Possible frequency bands to such a short-range wireless communication are shown in Table 1 [11]-[13]. However, most of them are not specialized for a wireless transmission through the human body, except for the HBC band for on-body signal transmission. Also, except for UWB [14][15], a narrow band modulation scheme is usually adopted. To choose an appropriate frequency band for our purpose, let us consider the basic transmission mechanism and path loss in various frequency bands [16].

2.1 On-Body Transmission

The human body is a lossy dielectric medium. The wireless control of wearable robot needs on-body signal transmission. To derive the transmission mechanism from a theoretical approach, we simplify the human body to be a semi-ininitely large lossy dielectric medium with relative permittivity $\varepsilon$ and conductivity $\sigma$. When a vertical dipole is placed on the surface of the semi-ininitely large lossy dielectric medium as shown in Fig. 4, the z-directed electric field on the medium surface is given as [17]

$$E_z = 2 \left( G_s \frac{jk_0}{r} - \frac{1}{r^2} - \frac{j}{k_0r^3} \right) e^{-jkr}$$

(1)

where

$$G_s = (1 - u^2 + u^4)F$$

(2)
\[ F = 1 + j \sqrt{\pi \omega e^{-\omega}} \text{erfc}(\sqrt{-\omega}) \quad (3) \]

\[ w = \frac{1}{2} k_0 r a^2 (1 - a^2) \quad (4) \]

where \( u = k_0/k \), and \( k_0 \) and \( k \) are the wave numbers of free space and dielectric medium, respectively. In Eq. (1), the first term proportional to the inverse of the surface distance, that is, the \( 1/r \) term, can be approximately regarded as a wave propagating along the medium surface. Strictly speaking, a surface wave is a signal that propagates along a boundary of two kinds of different media without radiation to the outside. In this sense the first term is not a strict surface wave because it also radiates towards the outside of the boundary. However, in view of the fact that this field component decreases with an increase in the surface distance \( r \), we here refer to it as a “surface propagation component”.

In addition, the other two terms \((1/r^2 \text{ and } 1/r^3 \text{ terms})\) in Eq. (1) correspond to the induction and electrostatic field components of the dipole, respectively. The transmission mechanism of on-body communication can be therefore divided into three parts: the surface propagation of the \( 1/r \) term, the reactive induction of the \( 1/r^2 \) term, and the electrostatic coupling of the \( 1/r^3 \) term. Which term is dominant is not dependent on the actual propagation distance \( r \) but the distance normalized to the wavelength.

In order to distinguish the size of contribution from each term to the electric field component at \( r \), the percentages of the surface propagation component, the induction field component, and the electrostatic field component, that is, the three components in Eq. (1), were calculated using muscle’s \( \varepsilon_r \) and \( \sigma \). Fig. 5 shows the percentage of contribution as a function of frequency when \( r = 1 \text{ m} \). From Fig. 5, the three field components are found to be equal at 50 MHz. At frequencies below 50 MHz, the electrostatic field component is predominant and electrostatic coupling is the main on-body transmission mechanism. On the other hand, when the frequency exceeds 50 MHz, the surface propagation term becomes dominant. In particular, at frequencies larger than 100 MHz, the surface propagation component is larger than the sum of the other two components and acts as the main on-body transmission mechanism.

Based on the above observations, the on-body transmission mechanism in each frequency band can be summarized as [16]

- In the HBC band, almost 80% of the received electric field is contributed by the electrostatic field term. The signal transmission is thus realized mainly by electrostatic coupling;
- In the 400 MHz or 900 MHz band, more than 80% of the electric field is contributed by the surface propagation term, which serves as the main on-body transmission mechanism;
- In the 2.4 GHz band or UWB, more than 95% of the electric field is contributed by the surface propagation term. It completely dominates the on-body transmission.

Moreover, from the point of view of path loss, the HBC band is generally desirable because the path loss increases with frequency. Therefore, if we use this frequency band for wireless control of wearable robot, we should design the transceiver based on the transmission mechanism of electrostatic coupling. HBC uses the human body itself as a transmission route [18]-[21]. In place of an antenna, it 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. This feature is very suitable for wearable robot control based on myoelectric signals because the transmitting electrodes can be also used for myoelectric signal detection.

2.2 In-Body Transmission

An implantable robot is assumed to perform remote treatment such as excision of an affected part and injection of a drug into the human body. Its movement
may be based on the myoelectric signals of the robot operator, as shown in Fig. 2. In this case the wireless control must be established between the surface and the inside of the human body.

Let us consider a semi-ininitely large lossy dielectric medium again with muscle’s \( \varepsilon_r \) and \( \sigma \). We assume a \( z \)-directed plane wave of frequency \( f \) incident perpendicularly to it. The electric field strength in the lossy dielectric medium can be described as a function of the propagation distance \( d \) [16]

\[
E_z = E_{z0} e^{-jkd} = E_{z0} e^{-\kappa''d} e^{-j\kappa'd}
\]

(5)

where \( E_{z0} \) is the electric field at the boundary of air and lossy dielectric medium, and the wavenumber

\[
k = k' - jk'' = 2\pi f \sqrt{\mu_0 \varepsilon_0 \left( \varepsilon_r - j\frac{\sigma}{2\pi f \varepsilon_0} \right)}
\]

(6)

where \( \varepsilon_0 \) and \( \mu_0 \) are the permittivity and permeability of free space, respectively. It can be seen that the electric field strength attenuates exponentially with \( k'' \) inside the human body. The corresponding path loss was calculated from \( e^{\kappa''d} \) at two typical depth of 5 cm and 10 cm, and was shown in Fig. 6. Compared to the 400 MHz band, 2.4 GHz band and UWB, the path loss at the 10-50 MHz HBC band is much smaller, which can thus provide a significant improvement on the communication performance. This result suggests that the HBC is also appropriate for wireless control of implantable robot. However, unlike on-body transmission in a wearable robot case, the signal must penetrate the human body. The transmission mechanism is therefore based on electromagnetic wave propagation in lossy dielectric media. In addition, the HBC band falls in the weak radio power band in Japan [22]. According to the Japanese radio law, for license-free use of this frequency band, the radiated electric field strength should be smaller than 500 \( \mu \)V/m at a distance of three meters. This requirement is easy to meet in practice because HBC does not radiate much towards outside the human body.

3. Transceiver Design

As an application example of wearable robot control, we show a transceiver design for transmitting myoelectric signal along the human arm, as shown in Fig. 3, in which the myoelectric signals are used to control a robotic hand.

3.1 Packet Structure

Myoelectric signals are usually in the frequency range below 600 Hz. A sampling rate of 2 kHz is therefore suitable for analog to digital conversion (ADC). Assuming 12-bit quantization, a data rate of at least 24 kbps is required. Usually, a robot hand is controlled simultaneously by at least three myoelectric signals, so a data rate of 72 kbps or higher is required. Fig. 7 shows the structure of packet to be transmitted. One packet is composed of 44 bits, where four bits as start bits, four bits as stop bits, and 36 bits as information bits detected by three pairs of electrodes. The generation frequency of packets is important from the point of view of intra EMC. Since the electrodes are used for not only detecting the myoelectric signals but also transmitting the modulated signals, this frequency component may be added into the myoelectric signals. To avoid this frequency component falling into the myoelectric signal frequency range (below 600 Hz) to cause unnecessary interference, a packet generation frequency of above 1 kHz is desirable, which makes possible to remove it from the myoelectric signals by a low pass filter (LPF). The packets were therefore designed to have a generation frequency of 2 kHz in our transceiver. An inappropriate packet generation frequency will directly interfere the myoelectric signal detection.

3.2 Transmitter

A wide band transmission system is desirable for effective use of the 10-50 MHz frequency band. IR systems are modulated with very short pulses and do not need to generate a carrier signal. This feature contributes to
low power consumption and high-speed data transmission. The modulation methods commonly used in IR systems are on-off keying (OOK) or pulse position modulation (PPM). Multiple PPM (MPPM) uses multiple pulse positions for modulation and does not require a threshold to determine bits for demodulation, making it less susceptible to noise [23]. We therefore adopted IR-MPPM for transmitting the myoelectric signal for robot hand control. In the IR-MPPM, bit information is represented by the position of multiple pulses within one bit. In our transmitter, information bit “1” is represented by a chip sequence of “01010011”, and information bit “0” is represented by a chip sequence of “10101100”. That is to say, each bit is configured with eight chips. If the chip is “1”, one pulse is transmitted. If the chip is “0”, nothing is transmitted. The data rate is determined by how many chips used for configuring one bit. When one bit is configured with eight chips, the data rate is 1.25 Mbp/s, which fully meets the requirement described in the previous subsection.

Fig. 8 shows the block diagram of the transmitter [24]. Most of it was implemented in a field programmable gate array (FPGA) (Xilinx, Spartan-6). Firstly, the ADCs mounted on the FPGA board acquire the myoelectric signals from three ports with a sampling rate of 2 kHz and 12-bit quantization. Each digital bit is input into an encoder respectively where each bit is represented by eight chips as described above. The encoded data are then sorted and accumulated in the data storage module. Once the digitized data of three sampled myoelectric signals are accumulated in the storage module, the start bits and stop bits are added to the data and finally, one packet is generated as described in Fig. 7. Then IR-MPPM is performed by multiplying each chip of the generated packet by a pulse from the pulse generator made from an analog transistor circuit. The output pulses are filtered to make its signal components being approximately between 10 and 50 MHz by a 9-stage Butterworth-type analog band pass filter (BPF). Fig. 9 shows the actual time waveform of pulse train and the frequency spectrum of one pulse. 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. The transmitter repeats these steps sequentially and sends the myoelectric signals through the human body to the motor controller for operating the robot hand. Table 2 summarizes the specifications of the transmitter.

3.3 Receiver

Fig. 10 shows the block diagram of the receiver [24], which was also mainly implemented in an FPGA board (Xilinx, Spartan-6). The receiving electrodes are set on the surface of forearm end connecting to the socket of robotic hand. Firstly, the signal components from 10 to 50 MHz are extracted by a BPF, and then are digitized with a sampling frequency of 200 MHz and quantization level of 10 bits in the ADC mounted on the FPGA board. Next, 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. 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 perform the energy detection and obtain the information bits of “1” or “0”. For energy detection, the sum of energy of the 1st, 3rd, 5th and 6th chips and the sum of energy of the 2nd, 4th, 7th and 8th chips are calculated respectively. 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 required. 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 digital-analogue-converted (DAC) and sent to the motor controller for driving the robotic hand.

Fig. 11(a) shows the developed transceiver consisting of both transmitter and receiver parts, whose total size is 66 mm × 51 mm. A small version of transmitter is shown in Fig. 11(b), which employs a small-size FPGA (Lattice, iCE40) so that the total size is 22.8 mm × 17.8 mm. This size is possible to be used for implantable robot control.

4. Verification Results

4.1 On-Body Transmission

The performance of the developed transceiver was first verified using a 30 cm long arm-shaped bio-equivalent gel phantom. The bio-equivalent gel phantom was composed of glycerin, deionized water, sodium benzoate and agar, simulating the dielectric properties of human arm in the HBC frequency band [25][26]. Fig. 12 shows the block diagram of the experiment of wireless on-body transmission. Since the bio-equivalent gel phantom cannot provide myoelectric signals used for operating the robot hand, three pseudo myoelectric signals were generated by an arbitrary signal generator and added to the detecting electrodes on the phantom surface, respectively. Then the three detected myoelectric signals were modulated and the IR pulse outputs were applied to one of the three electrodes for transmitting along the arm-shaped gel phantom. The receiver with a receiving electrode was arranged on the other side of the arm-shaped gel phantom, and demodulated the received myoelectric signals. Fig. 13 shows the time waveforms of one of myoelectric signal to be transmitted and the demodulated one. To confirm the degree of agreement between the transmitted and received signals, their correlation coefficient was calculated, and as a result, a high correlation coefficient of 0.999 was obtained. This result shows that the developed transceiver can provide wireless on-body transmission of myoelectric signals with high accuracy.

4.2 Wearable Robotic Hand Control

Fig. 14 shows the scene of a verification experiment which uses an operator’s myoelectric signal to control a wearable robotic hand placed near the operator’s hand. In actual usage, the robotic hand should be attached to the operator’s hand, but here it was placed on the table for convenience. The myoelectric signals were detected from the operator’s arm, and then were sent to a transmitting electrode on the bio-equivalent gel phan-
The receiving electrode at the other end of the gel phantom was connected to the robot hand. So, the gel phantom was a placement of the operator’s arm, which simulated the transmission of the myoelectric signals through the operator’s arm. In the experiment, the operator performed two kinds of actions of hand. One action was to keep the hand grasping for five seconds, and the other action was to keep the hand opening for five seconds. The two actions were performed by five operators, respectively, and each operator repeated ten times. The robotic hand was checked to see whether it followed the operator’s action in real time. If it failed, it was counted as a malfunction. Fig. 15 shows the malfunction rate of the wearable robotic hand in a wide band impulse noise environment. The impulse noise was generated by an electrostatic discharge (ESD) test setup based on IEC 61000-4-2 [27]. The horizontal axis is the ESD discharging voltage at which the ESD events occurred at a distance of 10 cm from the robot hand, and the vertical axis is the malfunction rate obtained from 100 times of actions. The results showed that no malfunction occurred until an ESD discharging voltage of 3 kV. So the developed 10-50 MHz HBC-based transceiver can work well even in a strong impulse noise environment for wearable robot control. This is attributed to the wide band IR-MPPM scheme where multiple pulses are used 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 noise is superimposed, and therefore the malfunction rate is reduced.

4.3 In-Body Transmission

In implantable robot control, it is important to ensure signal transmission performance between the inside of the body and the surface of the body. We therefore conducted an in vivo implant communication experiment using a living swine [28]. Approval from the Norwegian Animal Research Authority was obtained prior to the living animal experiment at Oslo University Hospital, Norway. Fig. 16 shows the block diagram of the in vivo experiment of implant communication. The IR transmitter with a helical invert-F antenna of 2.6 cm × 1.6 cm [28][29] was inserted into the abdomen of the swine at two depths of 4.5 cm and 9 cm, respectively, as shown in Fig. 16(b). The same type of helical invert-F antenna connected to the receiver was placed on the surface of the swine’s abdomen and moved to take seven different positions. The communication distances between the implant transmitter and the on-body receiving antenna were measured using an electromagnetic tracking system (NDI, Aurora). The major tissue types along these distances were small intestine, fat, muscle and skin.

Fig. 17 shows the bit error rate (BER) perfor-
Fig. 16 (a) Block diagram of in vivo experiment of implant communication with a living swine. (b) The transmitter inserted into the abdomen of the swine at two depths of 4.5 cm and 9 cm, respectively.

Fig. 17 Measured BERs for different data rates at various communication distances.

5. Conclusion

Wearable and implantable robots are increasingly controlled by myoelectric signals and operate according to the operator’s will. In this paper, we have analyzed the mechanism of on-body and in-body signal transmission, and have introduced our developed HBC-based transceiver for wireless robot control using myoelectric signals. The transceiver employs a wide band IR scheme in the 10-50 MHz band and is implemented in a FPGA. Its usefulness for wireless control has been confirmed for a myoelectric signal controlled robotic hand, and the experimental results show normal movement of the robotic hand even in a strong impulse noise environment. This result should be the first realization of wireless control of robot based on HBC technology. Moreover, the performance of implant signal transmission using a living swine has also been verified for examining the feasibility of implantable robot control, and an acceptable BER level of $10^{-3}$ in the physical layer can be achieved up to a communication distance of 26 cm at a data rate of 2.5 Mbps, and 15 cm at a data rate of 10 Mbps. This experimental result shows the highest data rate reported so far for the communication distance to the deep part of a living body. Therefore, the 10-50 MHz HBC-based IR technology is particularly well suited for detection and transmission of biological signals in the human body, and is a good candidate for wearable and implantable robot control using myoelectric signals.

Moreover, considering that myoelectric signals are generated by brain commands, it will be possible to control the robot by directly measuring the brain waves of the operator and transmitting them wirelessly to the motor controller, which is our future challenge.

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