LETTER

IEICE Electronics Express, Vol.9, No.23, 1799-1806

Detection of human arm approaching direction based on electrostatic coupling in human body communication

Keigo Kagimoto, Daisuke Anzai, and Jianqing Wang[a)]

Graduate School of Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya, 466–8555 Japan

a) *wang@nitech.ac.jp*

Abstract: A human body can be considered as a communication channel in which the electrical signal propagates through the body based on an electrostatic coupling mechanism when the frequency is sufficiently low. Since the human body approximately acts as a conductor in this case, we can detect the existence of the human body by measuring the corresponding electric filed variation in a close proximity of the human body. In this study, we aim to detect the approaching direction of a human arm based on this electrostatic coupling mechanism in human body communication for application to a user-machine interface. We first provide an appropriate explanation of this detection system based on the electrostatic coupling mechanism, and then conduct not only a computer simulation but also an experiment to validate the feasibility of the proposed detection system.

Keywords: user-machine interface, human body communication, approaching direction detection, electrostatic coupling

Classification: Microwave and millimeter wave devices, circuits, and systems

DOI: 10.1587/elex.9.1799
Received November 05, 2012
Accepted November 09, 2012
Published December 06, 2012

References

[1] T. G. Zimmerman, "Personal Area Networks (PAN): Near-Field Intra-Body Communication," M. S. Thesis, MIT Media Laboratory, Sept. 1995.

[2] M. Shinagawa, M. Fukumoto, K. Ochiai, and H. Kyuragi, "A near-field-sensing transceiver for intrabody communication based on the electro-optic effect," *IEEE Trans. Instrum. Meas.*, vol. 53, no. 6, pp. 1533–1538, Dec. 2004.

[3] K. Doi and T. Nishimura, "High-reliability communication technology using human body as transmission medium," *Panasonic Electric Works Technical Report*, vol. 53, no. 3, pp. 72–76, Aug. 2005.

[4] F. Abe and M. Nishigaki, "A proposal of information convey to electronic triage tag using intra-body communication," *2009 Symposium on Cryptography and Information Security*, no. 4E2-1, p. 353, Jan. 2009.

[5] K. Fujii, K. Ito, and S. Tajima, "A study on the calculation model for signal distribution of wearable devices using human body as a transmission channel," *IEICE Trans. Commun.*, vol. J87-B, no. 9, pp. 1383–1390, Sept. 2004.

[6] J. Wang, Y. Nishikawa, and T. Shibata, "Analysis of on-body transmission

IEICE Electronics Express, Vol.9, No.23, 1799-1806

mechanism and characteristic based on an electromagnetic field approach," *IEEE Trans. Microw. Theory Tech.*, vol. 57, no. 10, pp. 2464–2470, Oct. 2009.
[7] H. Baldus, S. Corroy, A. Fazzi, K. Klabunde, and T. Schenk, "Human-centric connectivity enabled by body-coupled communications," *IEEE Commun. Mag.*, pp. 172–178, June 2009.
[8] K. Fujii, M. Takahashi, K. Ito, and N. Inagaki, "A Study on the electric field distribution around human body with wearable devices focused on the earth ground," *Proc. ISAP*, pp. 410–413, 2007.
[9] N. Haga, K. Saito, M. Takahashi, and K. Ito, "Proper derivation of equivalent-circuit expressions of intra-body communication channels using quasi-static field," *IEICE Trans. Commun.*, vol. E95-B, no. 1, pp. 51–59, Jan. 2012.

1 Introduction

Human body communication (HBC) is a promising candidate to be used in user-machine interface [1, 2, 3, 4]. When a human wearing a HBC transmitter touches a receiver, the communication channel will be established between the transmitter and the receiver through the human body so that the signal from the transmitter propagates along the human body. The propagation characteristic depends on signal frequency. There may be three propagation mechanisms [5, 6, 7]: the surface propagation of the $1/d$ term, the reactive induction of the $1/d^2$ term, and the electrostatic coupling of the $1/d^3$ term, where d is the distance between the transmitter and the receiver. These three terms don't depend on the actual propagation distance but the distance normalized to the wavelength. That is to say, at a specified distance d, the contribution from the three different mechanisms depends on the frequency. At low frequencies, the wavelength is large and the normalized distance is consequently small. So the electrostatic coupling term is dominative. It is possible in this case to assume the environment as a reference to detect the variation of electrical potential of the human body or electric field around the human body.

In this study, we propose a system to detect the human arm approaching detection. Such a system can provide useful means in user identification. The basic idea is based on the electrostatic coupling mechanism in HBC. We first describe the system model and explain the basic principle. Then, we conduct a computer simulation to demonstrate the feasibility of such a detection system by using a finite difference time domain (FDTD) numerical method. Finally, we show an experimental validation for the simulation results.

2 System model and principle

The system model to detect the approaching direction of a human arm is shown in Fig. 1. Tx is a transmitter electrode, and Rx1, Rx2 and Rx3 are voltage sensors with the same electrode structure as Tx. All the electrodes consist of a pair of square metal electrodes (20 mm × 20 mm with a spacing of 10 mm). At the transmitter electrode, which is placed on the center of a

DOI: 10.1587/elex.9.1799
Received November 05, 2012
Accepted November 09, 2012
Published December 06, 2012

IEICE Electronics Express, Vol.9, No.23, 1799-1806

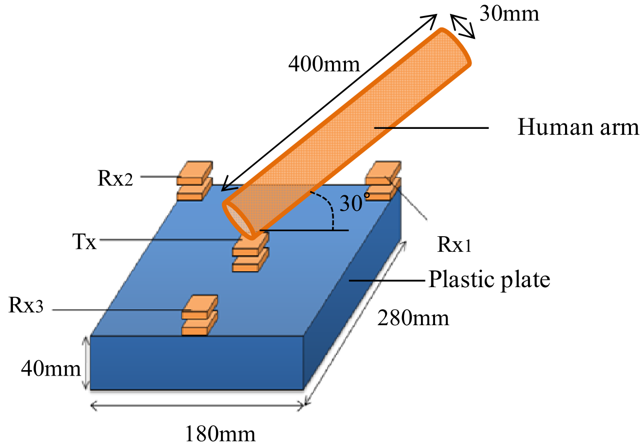

Fig. 1. System model to detect the approaching direction of a human arm.

plastic plate (180 mm × 280 mm × 40 mm) surface, a voltage source is applied to generate an electric field in its close proximity. When the human arm approaches from some direction to touch the transmitter electrode, a signal will propagates along the arm. If the frequency is below a few tens of MHz, the human body approximately acts as a conductor so that its electrical potential changes with the transmitted signal. Then the three sensors can detect the varying electrical potential of the body with respect to the environment or the electric field in their close proximity. With an appropriate arrangement for the three voltage sensors, we can determine the arm approaching direction based on the magnitude relationship of the voltages detected at the three sensors.

The principle of the detection system can be explained based on the electrostatic coupling mechanism as shown in Fig. 2, in which we only consider the transmitter Tx and the voltage sensor Rx3. First, V_{in} is the voltage source in the transmitter electrode with a frequency of 10 MHz, and R_{in} is the internal resistance of the voltage source. Next, there are two routes for the signal from the transmitter Tx to the voltage sensor Rx3. One route is air, and the other route is the human body. The lower route in Fig. 2 is a capacitive coupling between the upper parts of the transmitter electrode and the sensor electrode, which is denoted by C_2. The upper route is approximated by a parallel circuit of the capacitance C_H and the resistance R_H to express the human arm, as well as a capacitance C_1 approximating the coupling between the human arm and Rx3. It should be

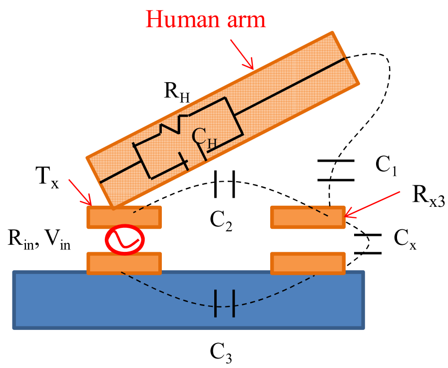

Fig. 2. Electrostatic coupling expression between a human arm and the detection system.

DOI: 10.1587/elex.9.1799
Received November 05, 2012
Accepted November 09, 2012
Published December 06, 2012

ELectronics EXpress
IEICE Electronics Express, Vol.9, No.23, 1799-1806

noted that C_1 varies with the approaching direction of the human arm. In addition, C_x is the capacitance between the two plates of Rx3 electrode. C_3 is the capacitance between the lower parts of the transmitter electrode and the sensor electrode. It should also be noted that there is an additional capacitive coupling between the human body and the earth ground [1]. However, it is insensitive to the distance between them, and furthermore, if the transmitter and the voltage sensor are close to each other, the capacitance between them should be dominant to the signal propagation. Therefore, in this paper, we ignore the capacitance between the human body and the earth ground. It has been numerically confirmed that the effect of the earth ground is insignificant to the received voltage at the human arm [8].

With these electrostatic coupling considerations, the sensor voltage at C_x can be obtained as a function of the approaching direction of the human arm for each C_1. Table I shows the parameters for explaining the basic principle of the detection system when the human arm model approaches the Tx in an inclination angle of 30 degrees with respect to the horizontal plane. The human arm model was assumed as a muscle tissue. R_h and C_h are calculated from $R_H = l/\sigma S$ and $C_H = \varepsilon S/l$, respectively, where l is the length of arm, S is the cross-section of the arm, σ is the conductivity of the arm, and ε is the permittivity of the arm. Moreover, C_1, C_2 and C_3 are approximately determined from $\varepsilon_0 S_e/d$, respectively, where S_e is the equivalent cross-section and d is the distance between the two metal plates or between the arm and the metal plate of the transmitter/sensor electrodes. Although a numerical electromagnetic field analysis technique, as used in [9], can give the parameter values in a higher accuracy, it is sufficient to use these simple approximations for our objective of explaining the basic principle.

Table I. Parameters in the electrostatic coupling model.

Parameter	Value	Parameter	**Value**
V_{in}	1.0 V, 10.0 MHz	C_1(270°)	0.017700 pF
R_{in}	50.0 Ω	C_1(315°,225°)	0.000925 pF
C_H	17.8 pF	C_1(0°,180°)	0.000765 pF
R_H	124.0 Ω	C_1(45°,135°)	0.000667 pF
C_2,C_3	0.003210 pF	C_1(90°)	0.000636 pF
C_x	0.354 pF		

Fig. 3 shows the sensor voltage at C_x, which was calculated from the electrostatic coupling model in Fig. 1. As can be seen, the sensor voltage is the largest when the human arm is just over the sensor. This is because when the human touch the transmitter, the signal from Tx propagates along the arm so that the electric potential of the arm varies and the electric field around the arm becomes larger than that in the absence of the arm. This feature results in a larger voltage at the sensor when the arm is just over the sensor. As the arm separates from the sensor, the detected voltage will decrease. In such a way, we can know whether the arm approaches from the sensor direction.

DOI: 10.1587/elex.9.1799
Received November 05, 2012
Accepted November 09, 2012
Published December 06, 2012

IEICE Electronics Express, Vol.9, No.23, 1799-1806

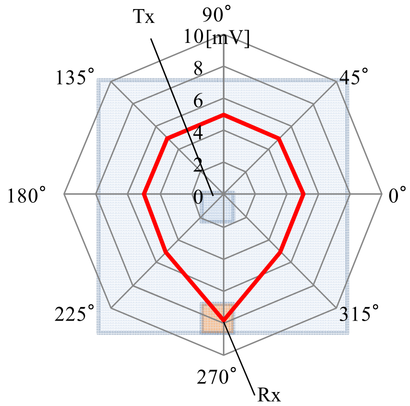

Fig. 3. Sensor voltage at Rx3 calculated from the electrostatic coupling model.

3 Simulation

To examine the feasibility of the detection system, we conducted a simulation for the system model in Fig. 1 by using the FDTD method. The system model was composed of 5-mm voxel cells. The plastic plate was assumed to have a relative permittivity of 4 and a conductivity of zero. The human arm was assumed as muscle with a conductivity of 0.64 S/m and a relative permittivity of 160. We calculated the voltages at the three sensors when the human arm approached to the transmitter from 0 degree to 360 degrees, in an inclination angle of 30 degrees with respect to the horizontal plane. Fig. 4 shows an example of FDTD-simulated electric field distribution when the human arm is touching the transmitter Tx in a specific direction. The electric field distribution shows that, when the human arm is approaching to Tx, the electric field will be increased in the close proximity of the human arm. Consequently, the voltage detected at the sensor closest to the human arm is the largest.

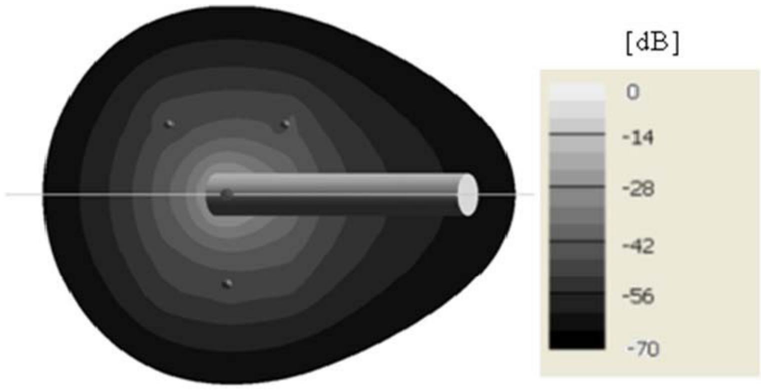

Fig. 4. Electric field distribution when the human arm approaches to the transmitter electrode.

Fig. 5 shows the FDTD-simulated voltages at the three sensors Rx1, Rx2 and Rx3 as a function of approaching direction from 0 degree to 360 degrees. As can be seen in (a), when the human arm is absent, the detected voltages at all of the sensors are less than 2 mV and are almost at the same level. However, when the human arm is approaching to the transmitter

DOI: 10.1587/elex.9.1799
Received November 05, 2012
Accepted November 09, 2012
Published December 06, 2012

IEICE Electronics Express, Vol.9, No.23, 1799-1806

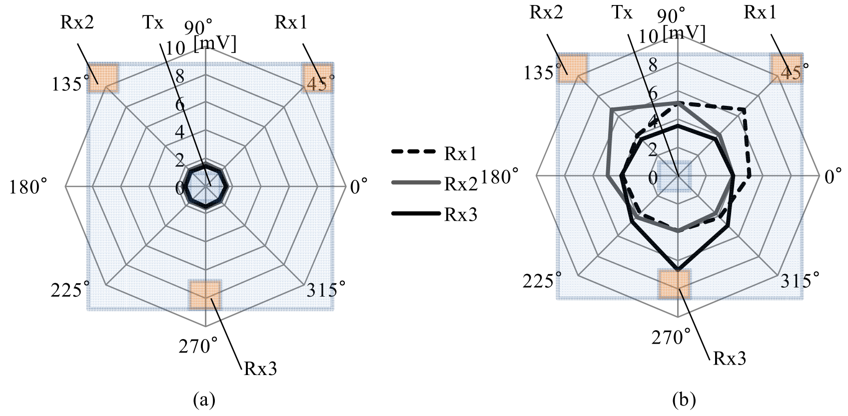

Fig. 5. FDTD-simulated voltages at the three sensors. (a) in the absence of the human arm, (b) in the presence of the human arm.

from an angle between 0 degree and 360 degrees with a 45 degree interval, the detected smallest voltages at Rx1, Rx2 and Rx3 are about twice larger and the detected largest voltages are about three times larger than that in the absence of the human arm. Moreover, the largest voltage is always detected when the sensor is closest to the approaching human arm. As opposed to this, as the human arm separates from the sensors, the detected voltages decrease. When the human arm has an approaching direction in the opposite of the sensor, the detected voltage is at the smallest level. Therefore, the approaching direction of the human arm can be determined by comparing the magnitudes of the voltages at the three sensors as long as they are placed at appropriate locations.

4 Experimental verification

We further conducted an experimental verification for the FDTD-simulated results described in the previous section. Fig. 6 shows the experimental setup of our prototype detection system. The transmitter electrode was constituted of a differential pair of rectangle metal plates with a similar size to the simulated one. The transmitting signal was

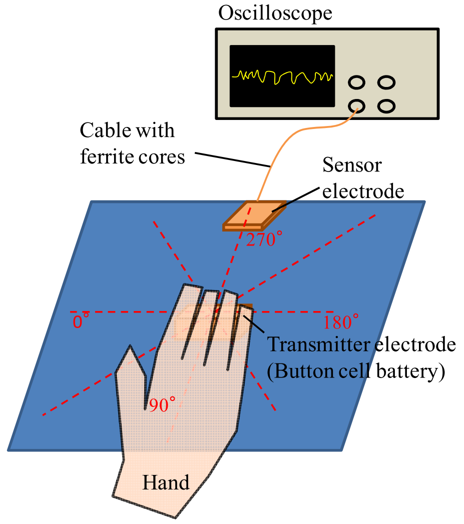

Fig. 6. Experimental setup of the prototype detection system.

DOI: 10.1587/elex.9.1799
Received November 05, 2012
Accepted November 09, 2012
Published December 06, 2012

ELectronics EXpress
IEICE Electronics Express, Vol.9, No.23, 1799-1806

generated by applying a 10 MHz sine signal at the transmitter electrode. In order to remove any possible influence from the earth ground through power lines, the transmitter was operated by a button cell battery. On the other hand, the sensor electrode also consisted of two rectangle metal plates with a spacing of 0.3 mm. The arrangement of the transmitter electrode and the voltage sensor was referred to the FDTD simulation model in previous section. The distance between the transmitter and the sensor was fixed at 110 mm.

As shown in Fig. 6, the peak to peak voltage at the sensor was directly detected by an oscilloscope. The voltages detected at the sensor were obtained when the human arm touched the transmitter from an approaching direction between 0 degree and 360 degrees. During the measurement, the human arm was always touching the transmitter electrode but changed the approaching direction with an interval of 45 degrees. Ferrite cores were used to cover the entire cable between the sensor electrode and the oscilloscope for preventing possible leakage of electromagnetic radiation from it.

Fig. 7 shows measured results by using the prototype detection system, where only one voltage sensor was set at the approaching direction of 270 degrees. The measured results show that the detected voltage at the sensor is the largest when the human arm is just over the sensor electrode, i.e., in the approaching direction of 270 degrees or the sensor direction. Additionally, the farther the approaching direction of the human arm detached from the sensor, the more the detected voltage decreases. The detected voltage is always at the largest level when the approaching direction of the human arm is identical to the sensor, and the smallest level when the approaching direction of the human arm is opposite to the sensor. This tendency of the experimental results fits well with the FDTD-simulated results, although there are some discrepancies in detected voltage levels probably due to the difference between the highly simplified human arm model and the actual human body. In total, however, the experiment reasonably validates the feasibility of the detection system.

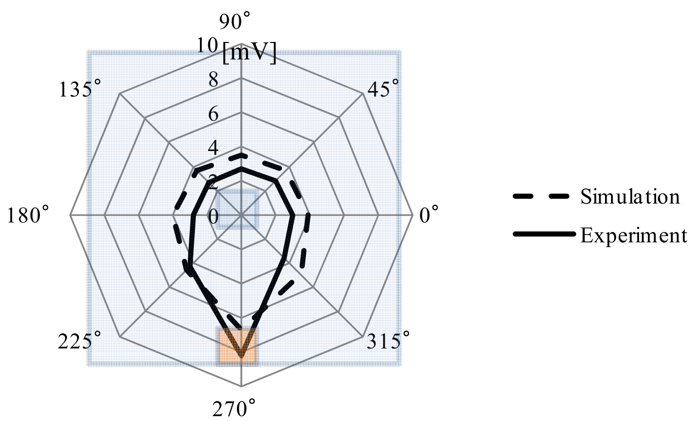

Fig. 7. Measured sensor voltage with the prototype detection system.

DOI: 10.1587/elex.9.1799
Received November 05, 2012
Accepted November 09, 2012
Published December 06, 2012

5 Conclusion

As a user-machine interface application scenario, we have proposed a system based on electrostatic coupling in HBC to detect a human arm approaching direction. At first, we have explained the basic principle of the detection system. Then we have demonstrated the appropriate sensor arrangement in the detection system and the feasibility of the approaching direction detection of the human arm by using three voltage sensors. Finally we have experimentally validated the simulation results by using a prototype detection system.

A future subject is to apply and optimize the detection system in actual user-machine interface scenarios.

DOI: 10.1587/elex.9.1799
Received November 05, 2012
Accepted November 09, 2012
Published December 06, 2012