Abstract

In this study, we propose a new concept for touch sensors based on the measurement of current generated by electrostatic induction. The proposed sensor can detect the timing of contact between two objects under perfect noncontact condition. When a human body comes in contact with an object, electrostatic charge is generated in the human body due to the tribological interaction. We assume that the human body is a good conductor. As a result, an instantaneous change is observed in the electric potential of the human body. Therefore, contact can be detected by detecting the change in the electric potential of the human body. We have developed an effective technique for measuring the change in the electric potential of a human body using a noncontact electrode. Such indirect measurement is made possible by the measurement of the instantaneous current flowing through the electrode instead of the measurement of the voltage of the electrode by the conventional capacitively coupled method. This new technique requires the measurement of the electrostatic induction current generated due to changes in the electric potential of the human body.

1 Introduction

Touch and tactile sensors are indispensable in various applications not only on earth but also in space. Several touch and tactile sensors have been investigated for small and high-performance. The conventional touch and tactile sensors include pressure-sensitive conductive rubber sensors [1-5], strain gage sensors [6,7], acoustic sensors [8], piezoelectric sensors [9], and capacitor sensors [10]. These sensors are used to detect contact between the sensor and an object. However, if we can develop a method to detect contact in the absence of any direct interaction between the sensor and the object, the method will find wide application in space.

In this study, we propose a new concept for touch sensors based on the measurement of current generated by electrostatic induction. The proposed sensor can detect the timing of contact between two objects under perfect noncontact condition. When a human body comes in contact with an object, electrostatic charge is generated in the human body due to the tribological interaction. We assume that the human body is a good conductor. As a result, an instantaneous change is observed in the electric potential of the human body. Therefore, contact can be detected by detecting the change in the electric potential of the human body. We have developed an effective technique for measuring the change in the electric potential of a human body using a noncontact electrode. Such indirect measurement is made possible by the measurement of the instantaneous current flowing through the electrode instead of the measurement of the voltage of the electrode by the conventional capacitively coupled method. This new technique requires the measurement of the electrostatic induction current generated due to changes in the electric potential of the human body.

2 Principle

In general, triboelectricity between two different materials has transiently generated physical and chemical complex phenomena, such as surface forces, light emission, fractoemission, and plasma generation. Many investigators have attempted to understand the mechanism of triboelectricity [11-17]; however, the phenomenon is not yet fully understood. When a dielectric material comes in contact with another material, an electric charge is generated in both materials. The polarity and strength of the charges generated differ according to the materials, surface roughness, temperature, strain, and other properties.

A schematic of the principle for detecting the electrostatic induction current generated by the changes in the electric potential of a subject’s body due to the tribological interaction is shown in Fig. 1. An instantaneous charge is generated on the surface of the contact region of the subject’s body due to the triboelectricity between the subject’s body and the wall. Therefore, the electric potential $U_H$ of the subject’s body can be expressed as follows:

$$ U_H = \frac{Q_T}{C_O} , $$

where $Q_T$ is the instantaneous charge due to the triboelectricity and $C_O$ is the capacitance of the subject’s body relative to neighboring objects. The induced charge $Q$ of the measurement electrode can be expressed as follows:
\[ Q = C(U_\Pi - V), \quad (2) \]

where \( C \) represents the capacitance between the subject’s body and the measurement electrode and \( V \) is the potential of the measurement electrode. When the subject’s body comes in contact with a wall, we can express the induced current \( I \) flowing through the measurement electrode as follows:

\[ I = \frac{dQ}{dt} = \frac{C}{C_0} \frac{dQ_T}{dt}. \quad (3) \]

Under perfect noncontact conditions, it is possible to measure the electrostatic induction current generated from triboelectricity between the subject’s body and the wall. Therefore, contact can be detected by detecting the change in the electric potential of the human body. Moreover, we can estimate the instantaneous electric charge \( Q_T \) from triboelectricity by the integration of the measured induced current \( I \) as follows:

\[ Q_T = \frac{C_0}{C} \int I dt. \quad (4) \]

Therefore, we can obtain the estimated triboelectricity between the subject’s body and the wall under noncontact and in situ conditions.

3 Experimental System

3.1 Contact Detection by Standoff System

A schematic of the measurement system for detecting the electrostatic induction current generated by the changes in the electric potential of a subject’s body is shown in Fig. 1. The electrostatic induction current flowing through an electrode placed tens of millimeters from the subject’s body is converted into voltage using an I-V converter with a conversion ratio of 10 V/pA and comprising an operational amplifier. In addition, induction currents generated by commercial power sources manifest in the form of noise. Therefore, a filtering system with a cutoff frequency of 20 Hz is used. Therefore, this measurement system is unaffected by the noise from other electronic device such as mobile phone or microwave oven. The analog signals are subsequently converted into digital signals using an analog-to-digital (A/D) converter. Data are acquired at a sampling frequency of 100 Hz and stored on a personal computer. The measurement electrode is square in shape with a side length of 10 cm.

The static electric field due to charged material surrounding the electrode has affected the absolute value of the capacitance \( C \) which formed between the subject’s body and a given measurement electrode. However, static electric field has little effect on the measurement, because the instantaneous electrostatic induction current arises from the changes of the capacitance \( C \) according to the subject’s motion. In fact, the generated transient current can be detected only the contact between the subject’s body and the wall.

![Figure 1. Schematic of measurement system for detecting contact between subject’s hand and wall](image1)

![Figure 2. Photograph of contact detection equipment by standoff system](image2)

It was observed that the intensity of the electrostatic induction current was inversely proportional to the distance between the subject and the electrode. However, the intensity of the electrostatic induction current was not dependent on the angle between the electrode and the subject facing it. Available sensing range of this system is about 3 m. The photograph of the standoff contact detection system is shown in Fig. 2.
3.2 Contact Detection by Portable Detection System

We also propose another concept for detecting contact conditions between subject’s body and wall material as shown in Fig. 3. A schematic of the measurement system for detecting the electrostatic induction current generated by the changes in the electric potential of a subject’s body in a space station is shown in Fig. 2. The proposed portable contact sensor attached to subject’s body can detect the contact conditions. A schematic of the portable measurement system is similar to Fig. 1, except for using a wireless transmitter. The sensor provides the subject information about the surrounding frictional conditions allowing it to interact with its environment.

Figure 3. Schematic of measurement system for detecting contact between human body and object in space station

The analog signals are subsequently converted into digital signals using an analog-to-digital (A/D) converter. Data are acquired at a sampling frequency of 20 Hz and stored on a personal computer using ZigBee as a wireless transmitter. The measurement electrode is square in shape with a side length of 2 cm. The photograph of the prototype portable contact detection sensor is shown in Fig. 4.

4 Results and Discussions

4.1 Contact Detection by Standoff System

The upper panel of Fig. 5 shows that the electrostatic induction current from triboelectricity is mainly generated on the contact between the subject’s finger and the wall of wood. A detection electrode was placed 2 m away from the center of subject. The contact period between the subject’s finger and the wall is about 2 s. Therefore, a periodic signal with a period of 2 s was observed in the waveform of the electrostatic induction current. It is believed that the origin of periodicity is the periodic friction from the contact of the subject’s finger.

Figure 5. Typical waveform of electrostatic induction current (upper panel) and of the estimated charge (lower panel) generated due to contact between subject’s hand and wall

When friction between the human skin and wood occurs, the human skin becomes positively charged according to the triboelectric series. The estimated capacitance $C_0$ of the subject’s relative to the ground is about 7 pF by geometrical arrangement in experiment. In
addition, the estimated capacitance $C$ between the subject’s body and the measurement electrode is about 0.044 pF. Therefore, we can obtain the instantaneous charge $Q_T$ from triboelectricity due to contact between the subject’s finger and the wall of wood by using the estimated capacitance values of $C$ and $C_0$ and an integral value of the measured electrostatic induction current, as predicted by Eq. (4). We can detect the subtle contacts in triboelectricity from the rotating equipment under noncontact and in situ conditions.

The lower panel of Fig. 5 shows the results of the instantaneous electric charge $Q_T$ from triboelectricity, which is mainly generated on the contact between the subject’s finger and the wall of wood. Therefore, we can obtain the instantaneous charge $Q_T$ from the contact under perfect noncontact and in situ conditions by detecting an electrostatic induction current that flows through an electrode placed at a distance of 2 m from the subject’s body.

4.2 Foot Contact Detection Due to Walking by Standoff System

The human body is electrically charged during walking [18-23]. In the case of a subject walking, we assume that there are two highly resistive layers between the feet of the subject and the floor, as shown in Fig. 6. One layer is the sole of the subject’s footwear. The other is the surface of the floor. The capacitance $C_f$ of the feet relative to the ground may be calculated as the sum of the capacitance $C_s$ of the sole and the capacitance $C_f$ of the surface of the floor. In addition, $C_o$ is the capacitance of the rest of the subject’s body relative to nearby objects on the floor. Therefore, the potential $U_B$ of the human body when it is performing walking motion can be expressed as follows [21].

$$U_B = Q_B \frac{\varepsilon_o S + x C_B}{C_B \varepsilon_o S},$$

where

$$C_B = C_o + C_s = C_o + \frac{C_s C_f}{C_s + C_f}.$$  

$Q_B$ is the instantaneous charge of the human body during walking motion, $\varepsilon_o$ is the permittivity of the air gap between the sole and the floor, and $S$ is the effective sole area at a height $x$ above the floor. The induced charge $Q$ of the measurement electrode placed at a certain distance from the subject can be expressed as follows:

$$Q = C(U_B - V),$$

where $C$ is the capacitance between the human body and measurement electrode, and $V$ is the potential of the measurement electrode.

When the subject is performing waking motion, an instantaneous charge is generated on the surface of the contact region of the subject’s body due to the triboelectricity between the sole of the subject’s footwear and the surface of the floor. From the above two equations, the induced current $I$ flowing through the measurement electrode can be expressed as follows [22]:

$$I = \frac{dQ}{dt} = C \frac{dU_B}{dt} = C Q_B \left( -\frac{x}{\varepsilon_o S^2} \frac{dS}{dt} + \frac{1}{\varepsilon_o S} \frac{dx}{dt} \right)$$

We assume that the human body is a good conductor. The first term in Eq. (8) represents the current induced due to the motion of the foot before it is lifted off the floor. The second term represents the current induced due to the motion of the foot and leg after the foot is lifted off the floor. The second term is approximately proportional to the velocity of the foot. Therefore, in the case of walking motion near the measurement electrode, it is possible to measure the current generated under perfect noncontact conditions.

Figure 6. Schematic of system for measuring electrostatic induction current generated by human walking motion

By increasing the sensitivity of the touch sensor, we can detect the timing of contact between the subject’s body and the floor or wall by placing the electrode 3 m from the subject’s body, as shown in Fig. 6. In this measurement system, capacitance is generated between the subject’s body and electrode. The typical waveforms of the electrostatic induction current flowing through the electrode due to stepping motion are shown in Fig. 7. The figure shows changes in the electric potential of the subject’s foot due to contact with the floor during the stepping motion. The waveforms show peaks corresponding to the time when the subject’s foot comes in contact with the floor and when the subject’s foot is...
off the floor.

Fig. 7 shows waveforms of the current generated by the human motion of walking. Cadence components are observed in the resulting waveform for each case. These components indicate the presence of a gait cycle in the walking motion. The gait cycle consists of a combination of alternating swing and stance phases of the left and right feet.

For example, the waveform contains cadence components of both the feet during bipedal stepping; this reveals that the toe of the left foot is lifted off the floor and the heel of the right foot comes into contact with the floor simultaneously. When the toe of the right foot is lifted off the floor, the effective sole area $S$ decreases and the distance $x$ between the right foot and the floor increases continuously. As a result of the walking motion, the current $I$ flowing through the measurement electrode increases, as predicted by the first term on the right-hand side of Eq. (8). In rapid succession, $I$ decreases, as predicted by the second term on the right-hand side of Eq. (8). Furthermore, in the second half of the swing phase, a rapid decrease in $x$ induces a decrease in $I$, as predicted by the second term on the right-hand side of Eq. (8). In rapid succession, $I$ decreases due to the increase in the effective sole area $S$ from the heel contact, as predicted by the first term on the right-hand side of Eq. (8). Therefore, Eq. (8) effectively explains the behavior of the waveform of the electrostatic induction current $I$ flowing through the measurement electrode.

Therefore, we can detect the timing of not only contact but also noncontact using the proposed technique. The proposed technique shows good measurement reproducibility. Furthermore, we propose an occurrence model for the electrostatic induction current generated by contact and noncontact. This model effectively describes the behavior of the electrostatic induction current flowing through the electrode.

4.3 Contact Detection between Human Body and Wall by Portable System

Fig. 8 shows that the electrostatic induction current from triboelectricity is mainly generated on the contact between the subject’s finger and the wall of wood by using the portable contact sensor. The contact period between the subject’s finger and the wall is about 2 s. Therefore, a periodic signal with a period of 2 s was observed in the waveform of the electrostatic induction current. Therefore, we can detect the subtle contact event under noncontact and in situ conditions. We have developed an effective technique for contact detection by measuring the change in the electric potential. Such indirect measurement is made possible by the measurement of the instantaneous current flowing through the electrode instead of the conventional touch and tactile sensors. The proposed technique would be suitable for manufacturing process in the assembly of large equipments because this technique has the ability to detect subtle contact events in alignment. Furthermore, the proposed technique would be applicable for not only contact sensing in space vehicle but also docking control with space station because this technique has the ability to detect subtle contact event between objects.

5 Conclusions

In this study, we propose a new concept for touch sensors based on the measurement of current generated by electrostatic induction. The proposed sensor can detect the timing of contact between two objects under perfect noncontact condition. When a human body comes in contact with an object, electrostatic charge is generated in the human body due to the tribological interaction. As a result, an instantaneous change is observed in the electric potential of the human body.
Therefore, contact can be detected by detecting the change in the electric potential of the human body. We have developed an effective technique for measuring the change in the electric potential of a human body using a noncontact electrode. Such indirect measurement is made possible by the measurement of the instantaneous current flowing through the electrode instead of the measurement of the voltage of the electrode by the conventional touch and tactile sensors. This new technique requires the measurement of the electrostatic induction current generated due to changes in the electric potential of the human body.

References