Journal of Electrostatics 77 (2015) 101–109

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

A non-contact technique using electrostatics to sense three-dimensional hand motion for human computer interaction

Kai Tang, Xi Chen*, Wei Zheng, Qingwei Han, Pengfei Li

State Key Lab of Mechatronics Engineering and Control, Beijing Institute of Technology, Beijing 100081, PR China

A R T I C L E I N F O

Article history:
Received 17 July 2014
Received in revised form
19 July 2015
Accepted 21 July 2015
Available online 11 August 2015

Keywords:
Electrostatic detection
Hand motion
Human–computer interaction

A B S T R A C T

This paper proposes a technique for three dimensional non-contact sensing of hand motion through electrostatic field. In order to determine hand direction and speed in three-dimensions, the technique exploits the geometrical relationship among six spherical electrodes organized in two planes, and the induced current on the electrode due to hand movement. This system consists of an electrode array, current-sensing circuits, a digital signal processing module with virtual instrument technology, and LabVIEW for visualization. The experimental results demonstrate that by analyzing the currents induced in the electrodes, the angle and speed of hand motion can be inferred with high precision, and the system's effectiveness enable for accurate recognition of hand motion and human–computer interaction.

1. Introduction

In recent years, a hotspot in Human–computer Interaction (HCI) research has been to facilitate user input. More natural and comfortable HCI methods are the goal of several research efforts. Traditional methods in gesture recognition are primarily based on visual sense [1,2], wearable devices or a combination of the two [3–6]. Advantages of using visual sensing include passive detection, non-contact and freedom of movement. However, recognition using visual sensing also presents drawbacks such as blind spots, complex algorithms and sensitivity to environment. To address these limitations, HCI researchers adapted wearable devices with electromyography (EMG) sensors, which are placed on the user's skin [7–10].

Based on this idea, a method using electrostatic detection to monitor three dimensional hand motion is proposed, which has the advantages of non-contact as well as passive detection. As a human body in motion becomes electrostatically charged through contact and friction charging [11], the resultant change of an electrostatic field enables an indirect measurement of body movement. Researchers measured electrostatic signals during walking with a measuring device on the body [12,13] and used a non-contact method to measure the human body's electrostatic signal [14–17], particularly the electrostatic signal generated from walking [18,19]. With the detection of the current on the electrode generated with the capacitance change between the hand and electrodes, the 8 orientations in a plane can be recognized with a four electrode array and neural network [20,21]. The induced current in a plate electrode varies with the relative position of the charge source [22]. Consequently, monitoring the direction and speed of hand motion using a plate electrode is difficult. So, in order to achieve accurate recognition of hand motion in three-dimensions, a detection methodology using a six spherical electrode array arranged in two planes is put forward.

2. Theory

The electric field in the immediate vicinity of the hand of a charged human body varies as the hand moves. If grounded conductors are immersed in this electric field, charges induced on the conductors will vary with hand motion resulting in induced currents. Especially, it is detected in the research that the induced currents are generated by the change rate of the electric field which is solely affected by the movement of the charge source. The still human body, (Compare to the fast moving hand, the rest parts of the body can be regard as being immobile), to the contrary, causes a minimal or background disturbance in the electric field. Hence, the detection circuit will responds only to the moving hand. Taking advantage of the correlation between the induced current and the electric field change, as a result of hand motion, the trajectory of hand motion can be detected through analysis of the induced current on the electrode.

* Corresponding author.
E-mail address: chenxi@bit.edu.cn (X. Chen).

http://dx.doi.org/10.1016/j.elstat.2015.07.006
0304-3886/

We use spherical electrodes because they are symmetric [23]. The charge induced in a spherical electrode varies only with the distance of the charged source from the electrode. Specifically, there is no angular variation.

A quantitative analysis of the charge induced on the spherical electrode is given. Fig. 1 (a) shows the position relationship between the hand, with a charge Q, moving along a trajectory, and spherical electrode placed on the origin. The distance from the center of charge to the center of spherical electrode O is r. In Fig. 1 (b), an abstraction of Fig. 1 (a), R_0 is the radius of spherical electrode. The boundary condition is the electric potential on the surface of the spherical electrode $U_{R_0} = 0$. According to the uniqueness theorem, the space electric field and the induced charge distribution on the conductor surface are certain, so the method of images is employed to analyze the induced charge distribution on the spherical electrode.

Based on the above boundary condition of the electrode and the symmetry of induced charge distribution, the assumption is made that charge Q' is on line OQ, and the value and position of Q' are [24]:

$$Q' = -\frac{R_0}{r}Q, \quad d = \frac{R_0^2}{r} \tag{1}$$

Where d is the distance from Q' to O.

Within the spherical coordinates, the potential of any point P outside the spherical can be expressed as:

$$\begin{aligned} U &= \frac{1}{4\pi\varepsilon_0}\left(\frac{Q}{a} + \frac{Q'}{a'}\right) \\ &= \frac{1}{4\pi\varepsilon_0}\left(\frac{Q}{\sqrt{r^2 + R^2 - 2rR\cos\theta}} - \frac{\frac{R_0 Q}{r}}{\sqrt{d^2 + R^2 - 2dR\cos\theta}}\right) \end{aligned} \tag{2}$$

Where a, a', and R are the distances from P to Q, Q', and O, respectively, and θ is the angle between OP and OQ.

The electric field distribution is symmetrical about OQ, and has no relationship with azimuth angle φ. The three components of electric field strength can be expressed as [24]:

$$\begin{cases} E_R = -\dfrac{\partial U}{\partial R} = -\dfrac{Q}{4\pi\varepsilon_0}\left[\dfrac{-R + r\cos\theta}{\left(r^2 + R^2 - 2rR\cos\theta\right)^{3/2}} + \dfrac{R_0(R - d\cos\theta)}{r\left(d^2 + R^2 - 2dR\cos\theta\right)^{3/2}}\right] \\ E_\theta = -\dfrac{1}{R}\dfrac{\partial U}{\partial\theta} = -\dfrac{Q}{4\pi\varepsilon_0 R}\left[\dfrac{-rR\sin\theta}{\left(r^2 + R^2 - 2rR\cos\theta\right)^{3/2}} + \dfrac{R_0 dR\sin\theta}{r\left(d^2 + R^2 - 2dR\cos\theta\right)^{3/2}}\right] \\ E_\varphi = -\dfrac{1}{R\sin\theta}\dfrac{\partial U}{\partial\varphi} = 0 \end{cases} \tag{3}$$

The total electric field strength E is calculated as $E = E_R + E_\theta$.

Taking $R = R_0$ and Equation (1) into Equation (3), the electric field strength of spherical outer surface can be expressed as:

$$\begin{cases} E_{R|R=R_0} = -\dfrac{Q}{4\pi\varepsilon_0}\dfrac{r^2 - R_0^2}{R_0\left(r^2 + R_0^2 - 2rR_0\cos\theta\right)^{3/2}} \\ E_{\theta|R=R_0} = -\dfrac{Q}{4\pi\varepsilon_0 R_0}\dfrac{-rR_0\sin\theta + rR_0\sin\theta}{\left(r^2 + R_0^2 - 2rR_0\cos\theta\right)^{3/2}} = 0 \end{cases} \tag{4}$$

Total electric field strength $E_{|R=R_0} = E_{R|R=R_0}$. That is to say, the electric field strength of outer surface points to the center of sphere along the radius direction and perpendicular to the spherical surface.

The induced charge surface density can then be expressed as:

$$\begin{aligned} \sigma &= -\varepsilon_0\frac{dU}{dn}\bigg|_{R=R_0} = -\varepsilon_0\frac{\partial U}{\partial R}\bigg|_{R=R_0} \\ &= -\frac{Q}{4\pi}\frac{r^2 - R_0^2}{R_0\left(r^2 + R_0^2 - 2rR_0\cos\theta\right)^{3/2}} \end{aligned} \tag{5}$$

The induced charge on the spherical surface is:

$$\begin{aligned} Q_E &= \int \sigma dS = \int -\frac{Q}{4\pi}\frac{r^2 - R_0^2}{R_0\left(r^2 + R_0^2 - 2rR_0\cos\theta\right)^{3/2}}2\pi\rho dl \\ &= -\frac{R_0}{r}Q \end{aligned} \tag{6}$$

Where $\rho = R_0\sin\theta$, $dl = R_0 d\theta$, $0 \le \theta \le \pi$, the induced charge on the spherical surface is equal to the image charge, which is consistent with the conclusion in Ref. [25].

The induced current on spherical electrode can be expressed as:

$$i = \frac{dQ_E}{dt} = \frac{d\left[-\frac{R_0}{r}Q\right]}{dt} = \frac{QR_0}{r^2}\frac{dr}{dt} \tag{7}$$

In Equation (7), when $dr/dt = 0$, the moment when hand motion is tangent to sphere with radius r, $i = 0$. Since the induced current i represents the change rate of electric field E, when i is 0 the change rate of electric field is 0, which is an extreme of the induced electric charge on the electrode.

Fig. 2 shows the oscillogram is obtained when the hand moves in front of the electrode from the left-to-right and back again. As Fig. 2 shows, the oscillogram demonstrates a positive trend when hand approaches the electrode and a negative trend when the hand moves away from the electrode. The Zero Crossing Point (ZCP) is defined when the sensor output waveform changes from positive-to-negative or from negative-to-positive.

In other words, the ZCP appears when the hand is closest to the spherical electrode. Therefore, we can identify the time when the hand is closest to the electrode.

The calculations above demonstrate that the positional relationship between the hand and electrode can be obtained through analysis of the induced electrostatic signal generated on the electrode during hand motion. The different induced waveforms generated on the different spherical electrodes arranged in space are used to obtain position parameters of hand motion. More