The Motion System Based on Electrostatic Field Sensors

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Introduction

The use of electrostatic field sensors (EFSs) as an interface illustrates development of a new paradigm in human-computer interaction. This is because the EFSs by their nature „communicate“ directly with the human body and its properties as physical matter. Electromagnetic tracking systems use special devices carried by people to measure the strength of the electromagnetic field at the position of the participant and thus calculate his location in space. Vision interfaces analyze an image, treating it as a set of abstract pixels, where the only information is of colors or shapes which virtually have no direct relation with the human body.

In contrast, the EFSs react directly on the physical condition and properties of the human body such as capacitance and conductance, thus metaphorically exemplifying the attempt to explore new ways of reading human bodies with computer systems, starting with their physical properties.

The goal of this work is to connect the EFSs to a computer system as a simple movement and gesture interface to serve as gestural noncontact device for virtual environments.

Underlying ideas

The operation of this interface is based on the same underlying principles as they were used in the musical instrument called Theremin which was invented by the Russian scientist Lev Termen (Leon Theremin) in the early 1920's. Figure 1 shows the design of a classic Theremin.

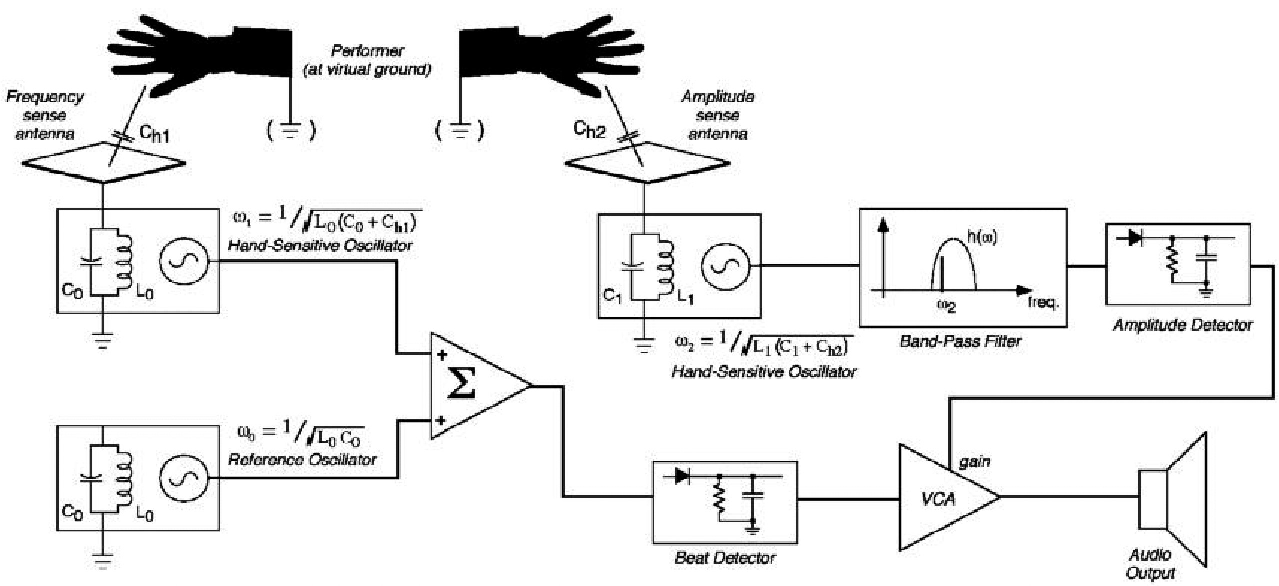

Figure 1. Design of the classic Theremin (the picture from [2]).

The main parts of the device are two LC oscillators with very close own frequencies. One of them has fixed capacitance and inductance, the second has an external antenna connected to its capacitor. By moving a hand into the vicinity of the antenna the user actually adds the capacitance C_{h_1} to the oscillator. Since the user's hand is grounded through his/her body the capacitor C_{h_1} is connected in parallel with the capacitor

C_0. As the user varies the distance of his/her hand from the antenna, the capacitive coupling and the resulting frequency ω_1 is changed according to the formula $\frac{1}{\sqrt{L_0(C_0 + C_{h_1})}}$. Because the capacitance C_0 is usually very small (typically below a picofarad), this oscillator must be run well above audio frequencies (typically 100 kHz to 1MHz) to attain significant coupling and dynamic range. The radio-frequency wavelength is approximately 3 km at 100 kHz, therefore most Theremins and devices based on their principles of operation should be analyzed as a slowly varying electrostatics problem with negligible radiation effects. The hand dependent frequency ω_1 is then down-shifted to audio band by mixing the ω_1 signal with a fixed frequency reference ω_0 and detecting the new frequency beats at $\omega_1 - \omega_0$. Theremins usually use a second proximity-variable oscillator/antenna ω_2 to control the amplitude of the audio signal. The ω_2 signal is applied to a steep bandpass filter, than the amplitude of its output is detected to determine the gain of a voltage controlled amplifier (VCA) in the audio path. As a hand moves near this volume-controlled antenna, ω_2 moves into tune with the band pass filter, changing the audio level through the VCA. So one can play music controlling the pitch and the volume of the sound simply moving the hands near the pitch and volume antennas and not touching anything.

The general idea of the Theremin and EFSs, affecting the parameters of the oscillator via user's body motion, can be used in a variety of applications for proximity sensing. In such applications a set of antennas is used to provide more data about space characteristics of matter induced the change of oscillator's characteristics.

In particular, MIT Media laboratory built a set of sensors used for different modes of navigation in the 3D world with free user's hand. Details can be found in [1, 2, 3].

Setup: electrostatic field sensors desktop interface

In our present implementation we use two specially designed EFSs with two spherical antennas connected to each EFS (Figure 2).

Figure 2. Setup of the system of EFSs for navigation in virtual environments.

The EFS circuits have been designed by Martin Nawsrath at KHM-Academy of Media Arts (Köln, Germany). In his device the output can be provided in two forms: usual audio output and digital output that delivers the values of the shift of the base frequency of the audio signal from its „neutral“ value at each time of sampling. The basic frequency of the EFS's oscillator when the user's hand is out of the area of the EFS's antenna sensitivity is assumed under the „neutral“ value. The digital output of each device is connected to the serial input of the computer. If this installation is used for navigation in virtual environments, the position of user's viewpoint is updated in accordance with the data arriving at the serial inputs of the computer (Figure 2).

The digital output of each EFS is provided by a microprocessor which performs the Fourier transform of the audio signal. It also sets the pitch to zero when it have not changed during a predefined time (10 s in our application).

Before describing the actual operation of our system and the mapping of data from the EFSs to parameters of the user's viewpoint in the virtual environment, we introduce the physical principles of our implementation.

Physical principles of our implementation

When the user's hand is in the area of sensitivity of the antennas, the equivalent electric scheme presented in the Figure 3 below can be used for describing the physical properties of our application.

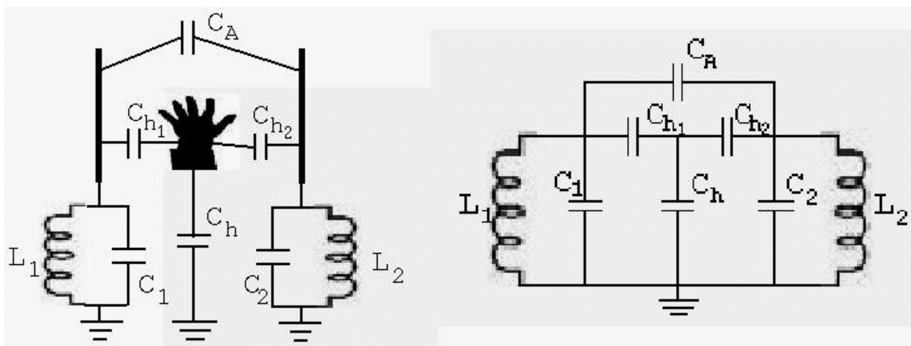

Figure 3. The equivalent electrical scheme in our application.

The capacitances C_{h_1} and C_{h_2} between the hand and each of the antennas and the capacitance C_A between the antennas depend on the current position of the hand. The capacitance C_h is dominated by the capacitance between the surface of the shoes of the user and the ambient room ground. It is typically much larger than capacitances C_{h_1} and C_{h_2}. Capacitances C_{h_1}, C_{h_2} and C_A are always much smaller than C_1 or C_2. One can show using those assumptions that oscillations with two frequencies are presented in the electrical circuit of the Figure 3:

$$\omega_1 = \frac{1}{\sqrt{L_1 C_1}} \left(1 - \frac{C_A + C_{h_1}}{2C_1} \right) \quad (1)$$

$$\omega_2 = \frac{1}{\sqrt{L_2 C_2}} \left(1 - \frac{C_A + C_{h_2}}{2C_2} \right) \quad (2)$$

Note, that native frequencies $\frac{1}{\sqrt{L_1 C_1}}$ and $\frac{1}{\sqrt{L_2 C_2}}$ of each EFS must differ to a certain amount to allow for following their shift by the microprocessor when the environment near antennas is being changed. Otherwise the microprocessor might mix the frequencies and follow the shift of the second frequency. To avoid this we use EFSs where the native frequencies (655 kHz for the first EFS and 455 kHz for the second one) differ to a significant value.

C_A, C_{h_1} and C_{h_2} are abstract quantities that do not have real physical sense. One can show that these quantities are easily expressed through capacitance coefficients [4]:

$$C_{11} = C_{h_1} + C_A, \quad C_{22} = C_{h_2} + C_A$$

So, equations (1, 2) can be rewritten in the following form:

$$\omega_1 = \frac{1}{\sqrt{L_1 C_1}}\left(1 - \frac{C_{11}}{2C_1}\right)$$

$$\omega_2 = \frac{1}{\sqrt{L_2 C_2}}\left(1 - \frac{C_{22}}{2C_2}\right)$$

Capacitance coefficients C_{11} and C_{22} have simple physical sense. Each of them is equal to the charge on the corresponding antenna provided the antenna is under unit potential and the other conductors in the system are being grounded.

The problem can be stated now as follows. Given the shifts from „neutral“ frequency for each sensor and, as a consequence, quantities C_{11} and C_{22}, the hand position must be derived from these quantities.

It is known that capacitance coefficients are quite easy calculated for the system of many conducting spheres. For our system this would be the case if we use spherical antennas and treat user's hand as a conducting sphere.

Thus, for example, C_{22} can be calculated in the following way (see Figure 4).

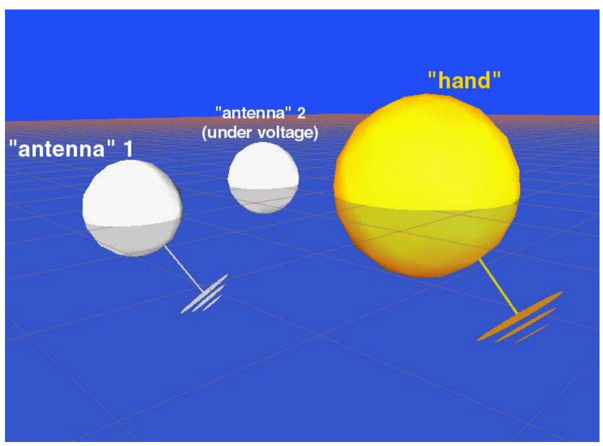

Figure 4. Physical model of our system.

We put a point charge $q = a$ in the center of the antenna 2, where a is the radius of the sphere's antenna; that would raise the potential at this conductor to unit in the absence of the other conductors.

It is known from electrostatics that for the system of a point charge and a grounded sphere with radius a and located on the distance x from the charge, the field outside the sphere can be calculated as superposition of the given point charge and an imaginary charge $q' = -\frac{a}{x}q$ located inside sphere on the distance $x' = \frac{a^2}{x}$ from the center of the sphere as shown in the Figure 5.

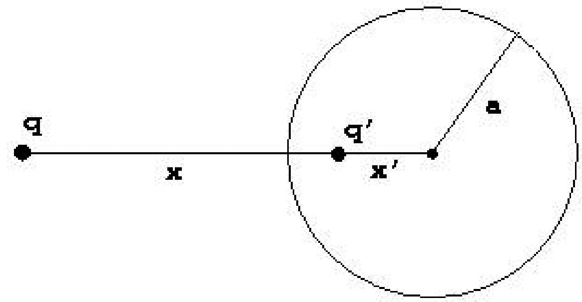

Figure 5. Electrostatic image of a point charge in a conducting grounded sphere.

Thus, we need to put additional charge in the other spheres on Figure 4 to compensate for the change of potential due to the charge in the center of the antenna 2. Then, for each sphere we need to compensate for the change of potential due to recently introduced charges in the other spheres. This procedure converges to finite solution and gives the resulting charge in the antenna 2 which is equal to the capacitance coefficient C_{22}.

Understanding the physical principals of our implementation we are now describing the actual operation of the system.

Operation of the system

We can calculate analytically capacitance coefficients for any position of the sphere representing user's hand and approximate the function $C_{ii} = F(x, y)$ with as large number of points as desirable and store these data in the file.

During operation each EFS provides the shift of the frequency from its „neutral“ value. For that value an isoline is calculated from the analytical data. The position of the user's hand is calculated as intersection of the isolines as shown on the Figure 6.

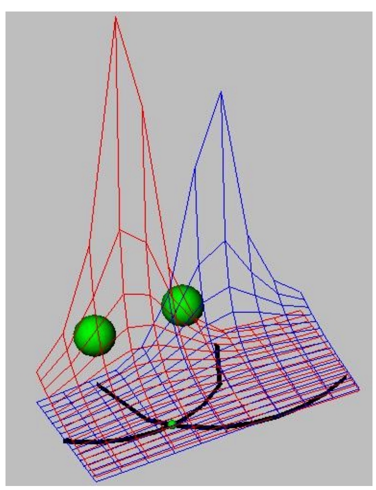

Figure 6. Operation of the system.

Mapping of data and applications

We implemented two commonly used modes of navigation: the „examine“ and „walk“ modes.

In the „walk“ mode the y coordinate serves for determining the speed of the motion in the virtual environment. The speed depends linearly on the y and is maximal if $y = 0$.

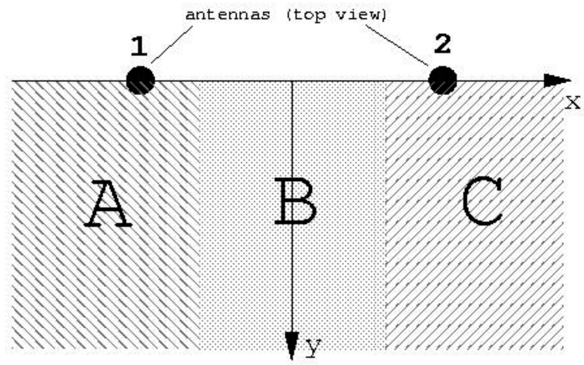

Figure 7. Mapping of data from the EFSs.

If the user's hand is located in on of the areas A or C (Figure 7), the user's viewpoint begins to turn with an angular velocity, increasing linearly with the distance from the current hand's location to the border with the area B. The radius of the turn is determined in accordance to the formula $\vec{v} = [\vec{\omega}, \vec{r}]$.

We use SGI's Inventor API for mapping the data from the EFSs to the parameters of the user's viewpoint in the virtual environment and for rendering the scene stored in the Inventor file format.

Numerous tests with different people show that they immediately recognize the relation between the position of the hand and the change of viewpoint parameters in the virtual environment.

Conclusion

The principles of the EFSs are based on detecting the change of alternate electrical current parameters induced by the movement of the user's hand/body in the vicinity of several electrodes/antennas, which constitute the complex electrical circuit.

The EFSs in our framework permit the navigation in a 2D virtual space with simple and immediately understandable hand gestures through well-known „walk“ and „examine“ metaphors of navigation without the need for wearing or holding any device.

The effect of electrostatic field sensing does not depend on the object's surface texture, light conditions or other factors that put limits on video tracking. EFSs can provide up to 1kHz update rate. There is an economy of data: only three channels are required to locate a hand in the 3D space. In addition, EFSs are very cheap (several dollars per a channel of data). All these factors make electrostatic field sensing a very promising area for the use in navigation and interaction in virtual environments.

References

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[3] Smith, J. et al, „Electric Field Sensing For Graphical Interfaces“, Special Issue on Input Devices, IEEE Computer Graphics and Applications, May 98

[4] Smythe, W., „Static and Dynamic Electricity“, Third Edition, McGraw-Hill Book Company, 1968