Capacitive Sensing Device in a Postural Control System

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Abstract: This paper presents a theremin used as a sensing device which provides a DC voltage output proportional to distance between the device and a human body in standing position. This device consists of a pair of Butler's oscillators, a heterodyning mixer, a low-pass 4th order Butterworth filter and a frequency-to-voltage converter. Output signal may be sent to another device such as an actuator or a measurement module, depending on the application type. Three sets of measurements for various types of sensing electrodes have been taken, and a third degree polynomial function has been fitted using a least square method.

Key-Words: human posture identification, proximity sensing**,** theremin, Butler's oscillator, posturography, least square method, curve fitting

1 Introduction

Theremin is an electronic musical instrument invented in 1919 by a Russian physicist named Lev Termen (his name was later changed to Leon Theremin) [1]. This instrument is very distinctive not only by the sound it produces but also by the fact that it is played without a direct physical contact between the performer and the instrument itself. One of many commercial realizations of this instrument is presented on Figure 1.

Fig. 1. A commercial realization of the theremin

This interaction between the performer and the instrument is based on variations of their mutual capacitance. These variations are used to control the resonant frequency of an oscillator, by adding the mutual capacitance to the main capacitance in the tuned circuit of an oscillator. Thus, the overall capacitance in the tuned circuit depends on the relative position of a human body in respect to the electrode mounted on the instrument's chassis. This electrode is known as an antenna, although it does not transmit nor receive any electromagnetic fields [2].

Theremin incorporates two antennas, which are displaced on two sides of the instrument, so that playing may be natural for man. The first antenna is provided for changing the tone of the sound on manner that approach of hand means higher pitch of the sound. Another antenna is being used for regulation of sound intensity, so that approach of one's hand to the antenna means lower intensity level [3].

External capacitance contribution ranges up to a couple dozens of picofarads. In order to achieve optimal resonant frequency deviations, the main capacitance defining the oscillator's nominal resonant frequency must be chosen carefully.

Non-human objects in the instrument's vicinity are also influencing the total capacitance in the oscillator, though on a minor level. In order to cancel these influences a variable capacitor is added to the tuned circuit. This capacitor is used as a calibration capacitor and must be properly adjusted if the instrument has been moved to a new environment, or if the objects in instrument's vicinity have been moved since the last calibration.

Human ability to maintain an upright stance and perform locomotion is guided by somatosensory, vestibular and visual information used in a complex regulatory feedback system, the postural control. In order to maintain balance in an upright stance, one must continuously perform minor corrective movements of the body to adjust the posture. One of the earliest attempts to assess postural control was made by Romberg (1853) who designed a simple clinical test, which is still used today. Some assessment methods of the postural control performance are based on direct measurements of body segment movements in 3D-space, using 3D measuring systems. Other assessment methods use an indirect approach, analyzing the properties of the forces and torques, evoked by the body movements towards the support surface by the feet, during different posturography trial conditions [4].

The subject of this paper is to explore the possibility of using the theremin as a sensing device in human postural control. For this reason a proximity sensor will be constructed based on the same operating principle used in theremin. The following section covers this operation principle. The electronic scheme is presented in section 3. The measured output voltage vs. body-to-electrode distance is shown in section 4. Section 5 covers the least square method used to fit a 3rd degree polynomial fuction fitted in one set of measurements.

2 Principle of operation

The fact that the theremin is being played without a direct physical contact between a person and the device resulted in an idea to create a human body proximity sensor which would operate on the same principle as the theremin does. For this purpose the electronic circuit used in the sensor will be derived from the block-diagram used in vast majority of theremin circuits, presented on Figure 2.

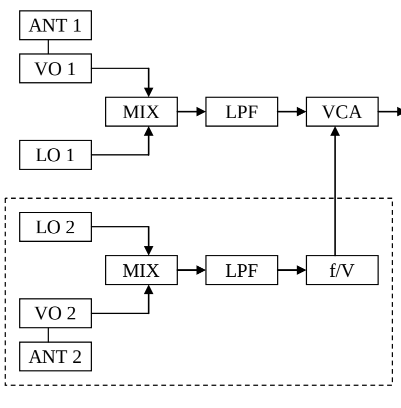

Fig. 2. Block-diagram of Theremin's instrument (proximity sensor - dashed line)

Signals from two tuned oscillators, variable oscillator VO 1 and local oscillator LO 1, are being sent to the mixer followed by a low-pass filter LPF. Variable oscillator 1 is connected to the antenna ANT 1 which influences its frequency, while local oscillator 1 has fixed frequency of 400-kHz. Signals on different frequencies, which are combination of input frequencies, exist at the output of the mixer MIX, but only signal on the frequency of input frequencies difference may pass through the filter due to its limit frequency of 4-kHz. Frequency of this signal is proportional to the distance between the antenna and the player's hand. Voltage controlled low-frequency amplifier VCA amplifies this signal and sends it to the power amplifier PA and finally to the loudspeaker SPKR. Completely the same situation is in the second part of the device with the oscillators LO2 and VO2. Signal from this filter goes to the frequency to voltage converter, so that its output DC level is proportional to the distance between the second player's hand and the antenna ANT 2. This signal additionally controls gain of voltage controlled amplifier so that effect of manual touchless volume control is obtained.

In order to construct a proximity sensor, the volume control part of Theremin's instrument will be used, which is presented in dashed part of Figure 1. According to this, the final electronic scheme will incorporate two oscillators, where the first oscillator's resonant frequency is controlled by changing the distance between a human body and the electrode, while other oscillator's resonant frequency is controlled by changing the value of variable capacitor used for calibration. Signals from two oscillators are being sent to a mixer followed by a low-pass filter. Converting the output signal's frequency to voltage yields an output DC voltage signal proportional to human body – electrode distance. Thus, this device will behave as a proximity sensor which might be used in a human motion detection system or in a variety of other applications. Later in this paper a novel assessment method for human postural measurements will be explored as one of possible applications. It is expected that the electrode shape will influence the sensitivity of the device, so three types of electrode shapes will be used and measured results will be compared in section 4. In order to define a functional relation between the output voltage and body-to-electrode distance, a polynomial function will be fitted using a least square method in section 5.

3 Electronic scheme

Following the presented principle of operation it is possible to realize schematic on a variety of different manners. Since the most important parts of the device are oscillators, special attention was paid to their realization. Butler's oscillator is applied due to the possibility of connecting the external electrode or a variable capacitor in parallel with the main capacitor in the tuned circuit, Figure 3. Variations of this additional capacitance in the oscillator will result in variations of the resonant frequency.

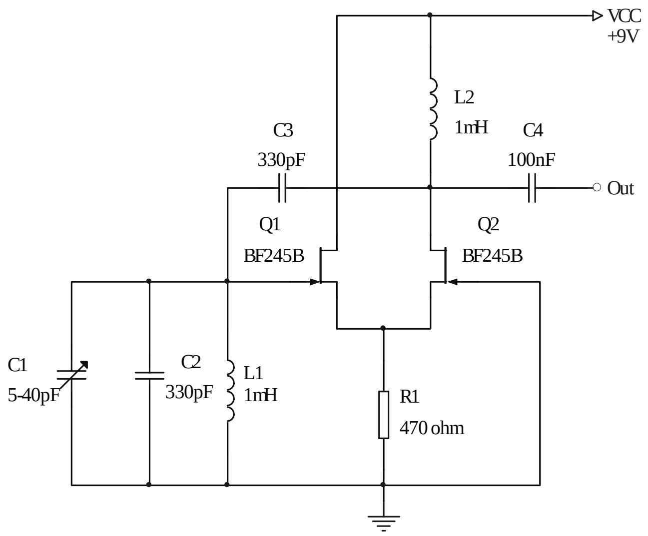

Fig. 3. Butler's oscillator schematic

Device uses two unipolar transistors, first one in a source follower configuration, while the second one is connected as common gate amplifier [5]. The positive voltage parallel feedback is obtained by capacitor C_3. This type of feedback amplifier may be characterized with amplification in form of transfer resistance

(1) $$R_M = \frac{U_{out}}{I_{in}}$$

and with β-factor as

(2) $$\beta = \frac{I_f}{U_{out}}$$

where U_{out} is voltage on the output of the *A*-branch, I_{in} is current on its input, I_f is current on the output of the β-branch and U_{out} is voltage on its input, which is output of the *A*-branch. Oscillation condition

(3) $$1 + \beta R_M = 0$$

yields

(4) $$\omega^3 L_1 C_2 r_d (C_1 + C_2) + \omega^2 L_1 (C_1 - g_m r_d C_2) + \omega C_2 r_d + 1 = 0$$

r_d stands for dynamic resistance of FET and g_m for its forward transconductance. Equation 4. has been obtained applying a linear model of unipolar transistor. Due to the fact that oscillator operates in large signal region some discrepancies of calculated and measured results will exist, so that values of elements have to be corrected experimentally or applying some computer simulation. The wave-shape of U_{out} is presented on Figure 4.

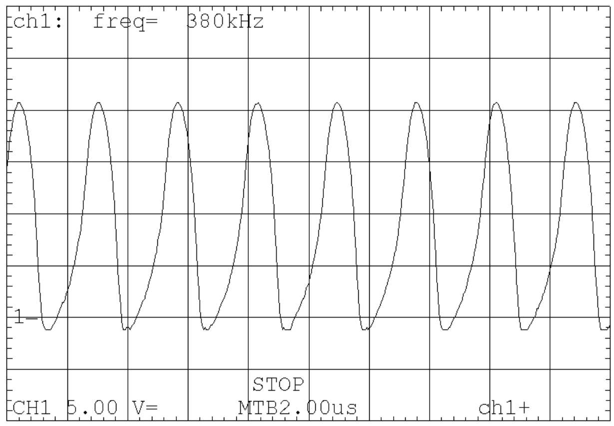

Fig. 4. Oscillator's output waveform

The mixer is followed by a low-pass Butterworth filter with 4-kHz limiting frequency and 80dB/decade slope. The low-pass filter is followed by a frequency to voltage converter, which gives a DC voltage proportional to frequency of filter's output signal. This frequency is equal to the difference in frequency of the two oscillators. Depending on the setting of the variable capacitor during the calibration procedure this frequency may increase or decrease while the human body approaches the electrode. Thus, this DC level is also proportional to the human body – electrode distance.

4 Measurements

Once the device has been realized and tested for functionality, certain measurements have been taken in order to observe the output voltage vs. body-to-electrode distance and to determine which type of electrode shape provides the best results. For this reason, three types of electrode shapes have been used: a copper rod, a copper plate and an insulated copper wire forming a spiral, as presented on Figure 5.

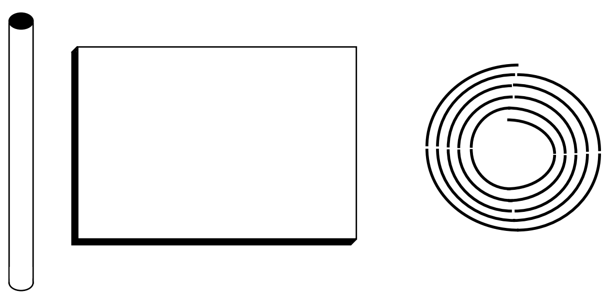

Fig. 5. Rod, plate and spiral-shaped electrode

The three measurements, one for each electrode, have been taken in the following manner. The variable capacitor in the local oscillator is set so that output voltage has a minimum value when a human body is away from the device and rises while the hand approaches the electrode. Once the device is calibrated in this manner, the hand is positioned as close as possible to the electrode without touching it. Then the output voltage is measured and the hand is moved 1cm away from the electrode for the next measurement. This step is repeated until there is no significant output voltage drop while increasing the distance, as shown in Figure 6. Measured values for all three types of electrodes are presented in Figure 7.

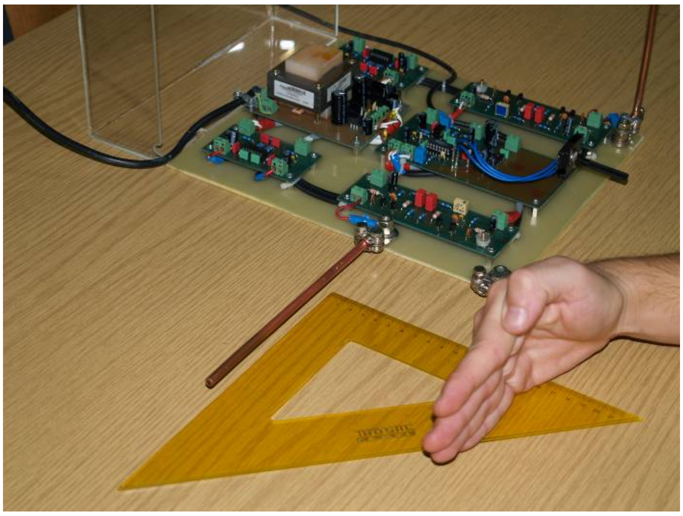

Fig. 6. Measurement method

The capacitance between the electrode and the human body depends on both the distance between them and their overlapping area. This explains the lower output voltage level and sensitivity range when using the rod-shaped electrode. Hence, in order to achieve greater sensitivity, plate-shaped electrodes should be used.

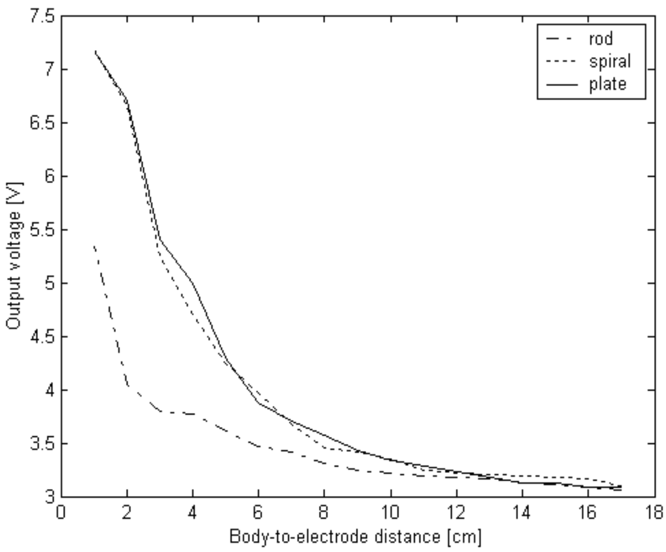

Fig. 7. Measured data for rod-, spiral- and plate-shaped electrodes

Discarding the rod-shaped electrode, it is obvious that output voltage decreases exponentially as body-to-electrode distance increases. This is expected since the relation between the distance and capacitance is inversely proportional. Discrepancies among measurements for spiral- and plate-shaped electrodes are not significant and might be caused by variations in hand positioning during the measurement procedure.

5 Curve fitting

In this section, a 3rd degree polynomial function will be fitted in measured data for plate shaped electrode, in order to define a functional relation between the output voltage V_O and body-to-electrode distance d. Measured data is presented in Table 1.

d [cm]	V_0 [V]
1	7.17
2	6.7
3	5.4
4	5
5	4.3
6	3.97
7	3.7
8	3.57
9	3.43

d [cm]	V_0 [V]
10	3.34
11	3.29
12	3.23
13	3.18
14	3.13
15	3.12
16	3.09
17	3.08

Table 1. Measured data for the plate shaped electrode

A 3rd degree polynomial function to be fitted in this measured data is defined as:

$$f(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 \quad (5)$$

Vertical least squares fitting proceeds by finding the sum of the squares of the vertical deviations of a set of 17 data points from function f:

$$R^2 = \sum_k \left[y_k - f(x_k, a_0, a_1, ..., a_{16}) \right] \quad (6)$$

The square deviations from each point are summed, and the resulting residual is then minimized to find the best fit line [6]. The condition for R^2 to be a minimum is that each partial derivation for a given parameter equals zero:

$$\frac{\partial (R^2)}{\partial a_i} = 0 \quad (7)$$

These lead to equations (8):

$$\frac{\partial(R^2)}{\partial a_0} = 2\sum_k \left(a_0 + a_1 x_k + a_2 x_k^2 + a_3 x_k^3 - y_k\right) = 0$$
$$\frac{\partial(R^2)}{\partial a_1} = 2\sum_k \left(a_0 x_k + a_1 x_k^2 + a_2 x_k^3 + a_3 x_k^4 - x_k y_k\right) = 0$$
$$\frac{\partial(R^2)}{\partial a_2} = 2\sum_k \left(a_0 x_k^2 + a_1 x_k^3 + a_2 x_k^4 + a_3 x_k^5 - x_k^2 y_k\right) = 0$$
$$\frac{\partial(R^2)}{\partial a_3} = 2\sum_k \left(a_0 x_k^3 + a_1 x_k^4 + a_2 x_k^5 + a_3 x_k^6 - x_k^3 y_k\right) = 0$$

Or in matrix form (9):

$$\begin{bmatrix} 17 & 153 & 1785 & 23409 \\ 153 & 1785 & 23409 & 327369 \\ 1785 & 23409 & 327369 & 4767633 \\ 23409 & 327369 & 4767633 & 71397705 \end{bmatrix} \cdot \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} 68.69 \\ 529.42 \\ 5830.7 \\ 74700 \end{bmatrix}$$

By solving this equation system the solution vector is obtained:

$$\begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} 8.4166 \\ -1.2031 \\ 0.0931 \\ -0.0024 \end{bmatrix} \quad (10)$$

The solution vector yields the coefficients for the 3rd degree polynomial function (11):

$$f(x) = 8.4166 - 1.2031x + 0.0931x^2 - 0.0024x^3$$

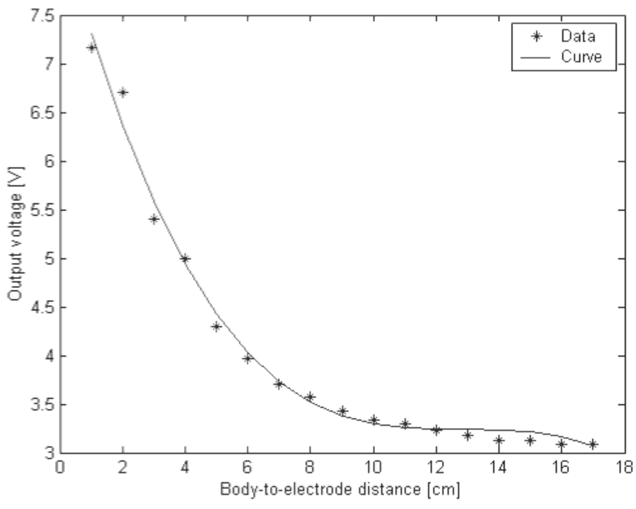

Fig. 8. Measured data for the plate-shaped electrode and the fitted curve

Figure 8. presents the measured data for the plate-shaped electrode and the fitted curve. It is obvious that the curve fits the measured data with minor deviations which may be ignored.

Finally, an approximated relation between the distance and the output voltage may be defined as (12):

$$V_0 = 8.4166 - 1.2031 \cdot d + 0.0931 \cdot d^2 - 0.0024 \cdot d^3$$

6 Conclusion

This paper has presented the design of a capacitive proximity sensor based on technology used in an electronic musical instrument known as theremin. This device is capable of detecting and measuring the proximity of a nearby human body, while having no physical contact with the body.

The starting point in the design procedure was theremin's operation principle and block diagram from which an electronic scheme was derived. Each block in the diagram was replaced by corresponding electronic circuit. Once the device was practically realized and calibrated, output voltages were measured for specific electrode shapes while changing the body distance. The results have confirmed that this device provides a DC output voltage inversely proportional to the body distance. Considering the electrode shape influence, it is shown that plain electrodes provide the best results and that the sensing range is proportional to electrode area.

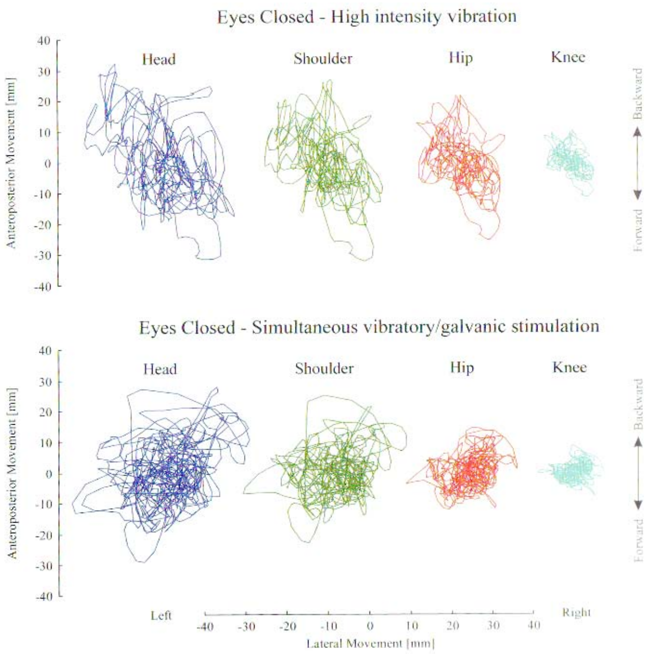

Fig. 9. A posturogram example [4]

The device presented in this paper might be used as a sensing device in posturography, a specialized clinical assessment technique used to quantify postural control in upright stance. In this technique spontaneous body sways and reactions are measured in order to detect certain postural imbalances (balance disorders). Figure 9. presents a typical set of posturograms where each curve presents body sways measured at head, shoulder, hip and knee area [4].

Placing a conductive plate behind an upright standing patient and connecting the plate as a theremin antenna results in a proximity sensor which measures the forward-backward (anteroposterior) movement. Another plate might be added to the right- or left-hand side of the patient in order to measure left-right (lateral) movement. Two-dimensional body sways can be measured in this manner.

Using this sensor in a human posture identification system should be useful since there is no need for additional sensors mounted on a human body. One sensor by itself can only detect a movement towards or away from the electrode. For advanced applications, a sensor array may be used so that any kind of movement in a sensing range can be identified.

Other techniques used for motion capture purposes, such as Vicon, Optotrak or Xsens, incorporate additional markers and similar devices that need to be mounted on a human body in order to perform the measurements. This method may be unpleasant for the vast majority of patients, as opposed to the novel approach presented in this paper.

In future work a vertical array of sensors will be used in order to measure body sways at head, shoulder, hip and knee area. A computer interface for data acquisition is another subject for future exploration, as well as system calibration issue, since the local oscillator in each sensor needs to be calibrated before each measurement. In case of theremin as a musical instrument, the calibration procedure is performed manually and is an iterative process, since one must approach the instrument to calibrate it, therefore changing the resonant frequency of the variable oscillator as well. A remote calibration might be a solution to this problem, as it may be performed from a distance, not influencing the variable oscillator while calibrating the local oscillator. In this way all the sensors in the array may be calibrated during the system initialization procedure.

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