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A Capacitive Measurement System for Gesture Recognition

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Abstract

A prototype is presented to reliably recognize finger gestures contactlessly by tracking the time history of capacitance variations of an electrode array. It is demonstrated that given sufficient resolution along the time line even rather large noise figures of the read-out electronics can be circumvented. The mechanical constraints result in the assumption of a rather smooth finger movement in 3D along premeditated or intended trajectories out of a predefined set of gestures. Regarding optimal electrical processing of the capacitance variations a shielding strategy is presented and its powerful suppression of body to ground capacitances and its variations due to varying environmental conditions is demonstrated.

Key words: mutual capacitance, capacitive proximity sensors, electrode design, human finger interaction, touchless gesture recognition.

1. Introduction

Numerous scientific publications discuss capacitive measurement systems in the context of touchless interaction with human hands or fingers [1, 2, 3]. Most of those are based on the self capacitance measurement principle [4] but typically suffer from the problem of the close proximity necessary between finger and sensor array (< 20 mm) and the rather large cycle time for a complete array readout (> 5 ms/capacitance to be measured). In this contribution we elaborate on a novel approach to allow larger standoff distances (> 40 mm) but still keeping the dense sampling in time (< 1 ms necessary for all sensors) to guarantee a non-aliased gesture recognition.

For touchless interaction with humans, a moderate spatial resolution of the measurement system is acceptable if the time resolution is sufficient to recognize smooth motions. The typically encountered small capacitance values and the rapid capacitance changes caused by finger movements render the system sensitive to interferences. Concerning this matter the measurement and online evaluation of the data is challenging and already partly discussed in [5, 6] for self capacitance methods. The capacitance measurements are used to estimate the finger position. These data (e. g.: position and velocity) are more meaningful and a feature extraction is much easier than processing the raw data. For that, mainly learning based approaches [7, 8] as Hidden Markov Models and Neuronal Networks are used. Those algorithms suffer from the problem that training is necessary and they are not easily extendable. Hence, in [9] Multi-Dimensional Time Warping, known form speech and signature recognition was presented as a promising alternative to avoid this disadvantage. However, for such an approach a mathematical relation of the capacitance depending on the 3D finger position is required. Therefore, it is an essential part of the current work to investigate the mathematical relation between capacitance and 3D finger position. Here, a variety of finger shapes as well as numerous possible environmental conditions and disturbances are not considered because the main target regarding touchless interaction is to recognize the user's intention only. In the case of incorrect interpretation an active feedback can inform the user how his behavior must be changed for a subsequent clear recognition.

The introduced measurement system is based on the mutual capacitance measurement principle. There are many possibilities for the realization concerning the shape and positioning of the electrodes, the potentials applied to the electrodes and the shielding strategy. Figure 1 shows a schematic of the newly developed measurement set-up consisting of a receive electrode with an area $a_\mathrm{e} \times a_\mathrm{e}$, a transmit electrode and a human finger. For measurements, a grounded brass cylinder with a diameter a_t and a height h_t above the sensor plane is used as an abstract model for an interacting finger, where the coordinates x_t, y_t and z_t describe the center position of its tip (denoted by an x in Fig. 1). In general, the human body capacitance to ground is about 150 pF [10]. This value is significantly larger than the maximal expected capacitance value in the gesture sensing application [11]. Therefore, a ground connected brass cylinder is a favorable simplification for a human finger.

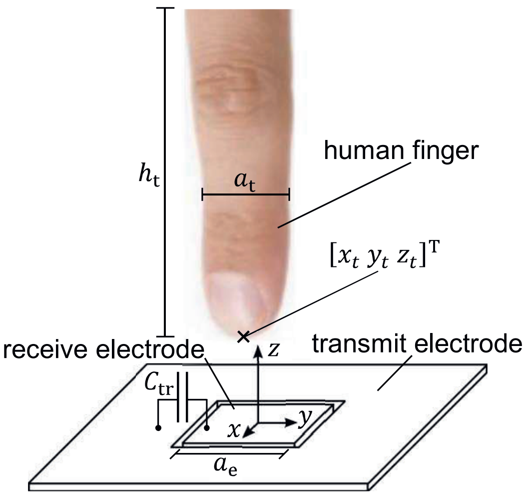

Fig. 1. Schematic of the measurement set-up.

The excitation signal is applied to the transmit electrode while the receive electrode is servoed to ground. Movements of the human finger influences the electric field between transmit and receive electrode. Thereby, the measured capacitance C_{tr} changes its value. Due to the large spatial extent of the transmit electrode, it also acts as shield and keeps the effect and influence of parasitic capacitances in check.

Table 1 shows the values of the dimensions in Fig. 1 which are used for all the presented simulation and measurement studies.

Tab. 1: Parameters used for simulation and measurement studies.

Description	Parameter	Value
Width of electrodes	a_{e}	10 mm
Diameter of cylinder	a_{t}	15 mm
Height of cylinder	h_{t}	55 mm

In section 'Electrode Configuration' the schematic of the measurement set-up of Fig. 1 is modeled as lumped circuit. With this simplification the measurement can be clearly examined with regard to the shape and positioning of the electrodes, the potentials applied to the electrodes and the shielding strategy. Further in section 'Hardware' a single-channel prototype of the capacitive measurement system for gesture recognition is presented. This is followed by section 'Results' which investigate the mathematical relation of the measured capacitance depending on the 3D finger position. For that, simulation studies are shown and compared to measurements of the newly developed hardware. Finally, section 'Conclusion' discusses advantages and disadvantages as well as possible improvements. Moreover, an outlook presents open problems for further studies.

2. Electrode Configuration

Figure 2 illustrates a general lumped circuit model for electric field sensing in the context of mutual capacitance measurement with an interacting human finger [12]. There are four equipotential surfaces: the potential of the human finger, the potential of the transmit electrode T, the potential of the receive electrode R and ground potential GND. Between each electrode a capacitance is modeled, resulting in six capacitances C_{tr}, C_{to}, C_{tg}, C_{ro}, C_{rg} and C_{og}.

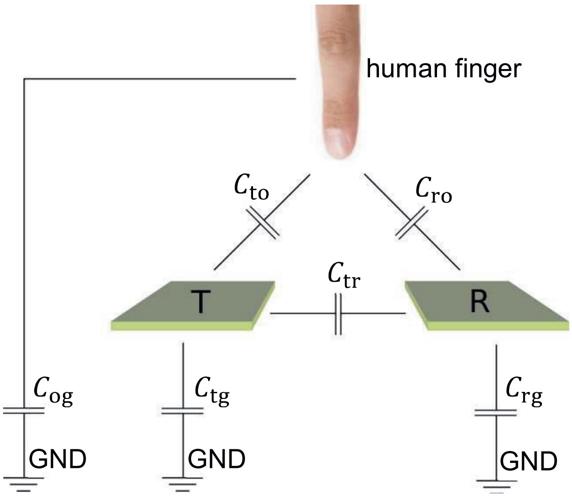

Fig. 2. Lumped circuit model for electric field sensing in the context of mutual capacitance measurement.

For 3D position estimation at least three independent capacitance measurements are necessary. To guarantee a fixed measurement time (independent of the number of measurement channels) an electrode configuration which allows simultaneous operation of all capacitance measurement channels must be realized. At any point in time a single measurement of the multi-channel set-up is described by the lumped circuit in Fig. 2 without any coupling between different measurement channels. Furthermore, to keep the measurement problem trackable, a measurement system is advantageous, which detects influences of finger movements concerning C_{tr} only. An elegant approach is the utilization of a sinusoidal signal with a certain frequency and the measurement of the displacement current caused at the receive electrode in Fig. 1. Capacitance measurement with harmonious signals was already partially discussed in [13]. Thus, C_{tr} is directly measured while the other capacitances can be neglected. In addition, the single-channel system can easily be extended to a multi-channel system by inserting several receive electrodes. The excitation signal u_t given through

$$u_\mathrm{t} = \hat{U}_\mathrm{t}\sin(2\pi f_\mathrm{t} t) \quad (1)$$

with the amplitude $\hat{U}_\mathrm{t}$, the frequency f_t and the time variable t is applied to the transmit electrode. The voltage (1) causes a displacement current i_c at the transmit electrode, which is calculated via

$$i_\mathrm{c} = C_\mathrm{tr}\frac{du_\mathrm{t}}{dt} = \underbrace{C_\mathrm{tr}\hat{U}_\mathrm{t}2\pi f_\mathrm{t}}_{\hat{\imath}_\mathrm{c}}\cos(2\pi f_\mathrm{t} t) \quad (2)$$

with the amplitude $\hat{\imath}_\mathrm{c}$ and the capacitance C_tr between the transmit electrode and the receive electrode. This current is measured with a transimpedance amplifier, which servos the potential of the transmit electrode to ground. Thereby, the amplitude $\hat{U}_\mathrm{r}$ of the output voltage of the transimpedance amplifier follows to

$$\hat{U}_\mathrm{r} = R_\mathrm{a}\hat{\imath}_\mathrm{c} = R_\mathrm{a}C_\mathrm{tr}\hat{U}_\mathrm{t}2\pi f_\mathrm{t} \quad (3)$$

with the transimpedance resistor R_a. Table 2 summarizes the parameters for the measurement.

Tab. 2: Parameters for the measurement.

Description	Parameter	Value
Excitation amplitude	$\hat{U}_\mathrm{t}$	1 V
Excitation frequency	f_t	100 kHz
Resistor	R_a	820 kΩ

3. Hardware

Figure 3 shows a single-channel prototype of the capacitive measurement system for gesture recognition. The main parts are the Nucleo-F429 development board from STMicroelectronics, the signal processing board with the synchronous demodulator chip ADA2200 from Analog Devices, the ADC board with an eight-channel 18 bit SAR-ADC chip and the electrode structure (cf. Fig. 1) for sensing capacitance changes caused by a human finger.

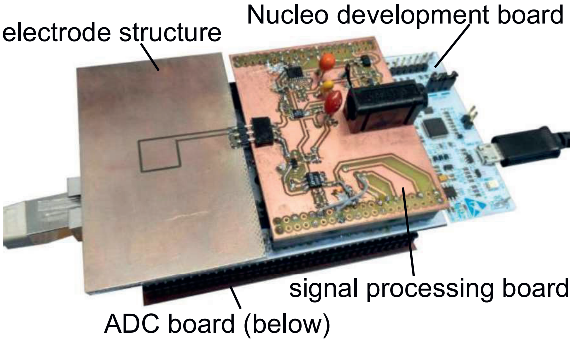

Fig. 3. Single-channel prototype of the capacitive measurement system for gesture recognition.

For the generation of the sinusoidal excitation signal the harmonics of a square wave signal with fundamental frequency f_t are suppressed by an analogue low pass filter. Subsequent the amplitude of the filtered signal is amplified and fed to the transmit electrode. This voltage signal causes a displacement current in the receive electrode, which is converted into a voltage signal again with a transimpedance amplifier. The output signal of the transimpedance amplifier is analogous processed with synchronous demodulation scheme, then digitized and averaged using an FIR-Filter. This processing enables an excellent rejection of interference signals with frequencies differing from the transmit frequency. Narrow band noise still can be a problem but if necessary even frequency hopping can be used.

4. Results

The simulations studies were performed using the COMSOL Multiphysics environment and the schematic of the measurement set-up in Fig. 1 was used. Further for capacitance measurements the prototype depicted in Fig. 3 was utilized.

The following illustrations are used to investigate relations between the capacitance C_{tr} and the position $[x_\mathrm{t}\, y_\mathrm{t}\, z_\mathrm{t}]^\mathrm{T}$ of an interacting object. An enormous advantage of the introduced electrode configuration is that contour lines[1] of C_tr in xy-planes can be assumed to be circular [5, 6, 11]. Hence, it is sufficient to consider object movements in the xz-plane (y_t = 0 mm) only. In Figure 4 the simulated contour lines in this plane are compared to an ellipse approximation indicated through

$$\frac{{x_\mathrm{t}}^2}{{p_x}^2} + \frac{{z_\mathrm{t}}^2}{{p_z}^2} = 1\,. \quad (4)$$

The parameters p_x and p_z are directly calculated via (4) with the simulated data along the x-axis (z_t = 1 mm) and the z-axis (x_t = 0 mm). The ellipse approximation (4) is a convenient fit for the contour lines in the xz-plane (cf. Fig. 4). It is to be noted that in Fig 4 a nonlinear scale for the values of the contour lines is used.

Considering the previous insights the trend of C_tr along the x-axis and z-axis is adequate to determine the total dependency of the 3D object position. The circular and elliptic contour lines in the xy- and xz-plane follow to contour surfaces of ellipsoids in the xyz-space. A similar approach for the self capacitance measurement principle is presented in [14]. A further simplification of the ellipsoid surfaces through spheri-

[1] A contour line of a function of two variables is a curve along which the function has a constant value. It is a cross-section of the three-dimensional graph of the function $f(x, y)$ parallel to the xy-plane.

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cal surfaces, which is still a sufficiently accurate approximation in the gesture sensing application, enables the use of algorithms (e. g. extended Kalman filter) known from GPS positon estimation for this application.

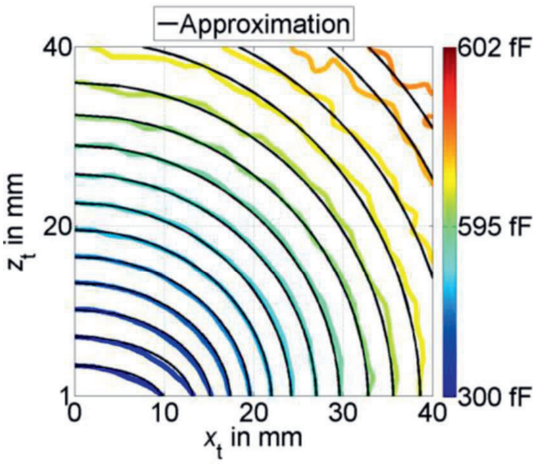

Fig. 4. Simulated and approximated contour lines of C_{tr} in the xz-plane for y_t = 0 mm.

Figure 5 shows the simulation and an approximation of C_{tr} over z_{t} for $x_{\mathrm{t}} = 0\,\mathrm{mm}$. Here the approach $\tilde{C}_{\mathrm{tr},z}$ given through

$$\tilde{C}_{\mathrm{tr},z} = p_1 + \frac{p_2}{(p_3 + z_{\mathrm{t}})^2} \qquad (5)$$

is an adequate approximation of C_{tr}. The parameters p_1, p_2 and p_3 are determined via least squares fitting based on the measurement data. In [15] a similar approach as in (5) is suggested but with a different exponent in the denominator.

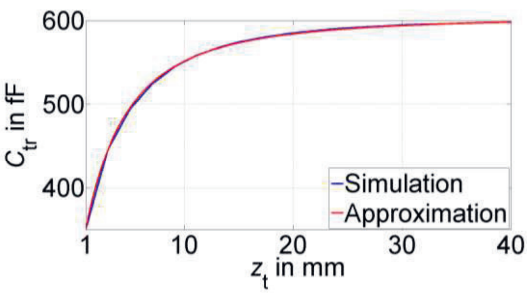

Fig. 5. Simulation and approximation of C_{tr} over z_t for x_t = 0 mm.

Figure 6 illustrates the simulation of C_{tr} over x_{t} for $z_{\mathrm{t}} = 1\,\mathrm{mm}$. Three sections (I), (II) and (III) are distinguished. In (I) the receive electrode is completely covered by the test object. Thus, the capacitance nearly remains constant. Section (II) is characterized by an almost linear trend. This applies as long as the bases of the receive electrode and the test object are overlapping. In section (III) the test object is even further away (no overlapping anymore) and the characteristic is similar to (5).

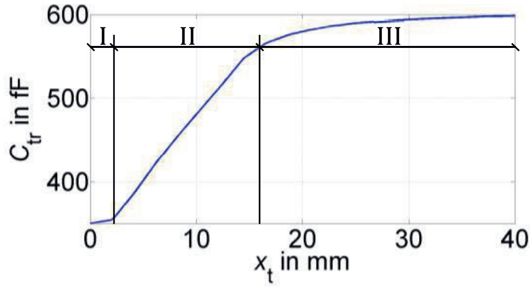

Fig. 6. Simulation of C_{tr} over x_t for z_t = 1 mm.

In the following the simulation data are compared to the measurement values. The measurement data contain additional offset capacitances caused by different environmental influences and the discrete hardware set-up. This offset is neglected in simulation studies. Therefore, in the following figures the measurement data are adapted to the simulation data by adding an appropriate offset (calculated via least square fitting).

Figure 7 shows the simulation and the measurement of C_{tr} over z_{t} for different values of x_{t}. In the considered range is a fairly good match between simulation and measurement. The best fit is at $x_{\mathrm{t}} = 0\,\mathrm{mm}$.

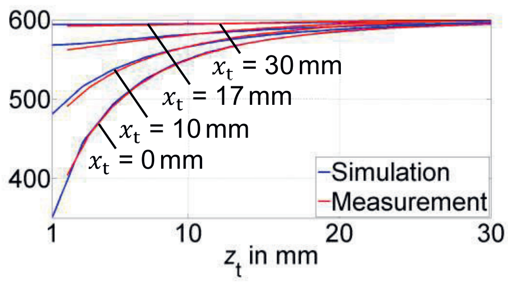

Fig. 7. Simulation and Measurement of C_{tr} over z_t for different values of x_t.

In Fig. 8 the simulation and the measurement of C_{tr} over x_{t} for different values of z_{t} can be seen. As in the previous figure there is also an adequate match between simulation and measurement. Only for $z_{\mathrm{t}} = 2\,\mathrm{mm}$ slight deviations can be recognized.

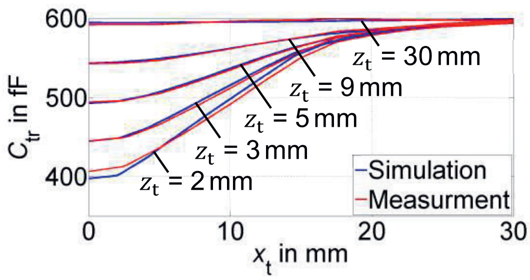

Fig. 8. Simulation and Measurement of C_{tr} over x_t for different values of z_t.

5. Conclusion

This work presents a newly developed prototype of a capacitive measurement system for gesture recognition. A sophisticated design of the electrode configuration was introduced in combination with a shielding strategy which circumvents the effect of parasitic capacitances. Furthermore, the measurement system can be easily extended to several measurement channels as it is necessary for position estimation of a moving human finger. The mathematical relation between the measured capacitance and the finger position was investigated and an approach was suggested, how the position estimation can be implemented in future work. In further studies a comprehensive physical modeling of the measured capacitance could provide additional insights.

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