Ain Shams University

Faculty of Engineering

Electronics and Communications Department

Design of a Digital-Output Capacitive Sensor Interface

A Thesis

Submitted in partial fulfillment of the requirements of a Master of Science degree in Electrical Engineering

Submitted by:

Muhammad Abdel-Rasoul Metwally Abdel-Hay El-Nafarawi

B.Sc. of Electrical Engineering

(Electronics and Communications Department)

Ain Shams University, 2009

Supervised by:

Prof. Dr. Khaled Wagih Sharaf

Dr. Ayman Hassan Ismail

Cairo, 2015

Ain Shams University

Faculty of Engineering

Electronics and Communications Department

Examiners' Committee

Name: Muhammad Abdel-Rasoul Metwally Abdel-Hay El-Nafarawi

Thesis: Design of a Digital-Output Capacitive Sensor Interface

Degree: Masters of Science in Electrical Engineering

Title, Name and Affiliation	**Signature**
Prof. Dr. El-Sayed Mostafa Saad Helwan University, Faculty of Engineering, Electronics & Communications Dept.	. . . . .
Prof. Dr. Mohamed Amin Dessouky Ain Shams University, Faculty of Engineering, Electronics & Communications Dept.	. . . . .
Prof. Dr. Khaled Wagih Sharaf Ain Shams University, Faculty of Engineering, Electronics & Communications Dept.	. . . . .

Date: 29/12/2015

Curriculum Vitae

Name: Muhammad Abdel-Rasoul Metwally Abdel-Hay El-Nafarawi

Date of Birth: 25/04/1987

Place of Birth: Cairo, Egypt

First University Degree: B.Sc. in Electrical Engineering

Name of University: Ain Shams University

Date of Degree: June 2009

Statement

This dissertation is submitted to Ain Shams University for the degree of Master of Science in Electrical Engineering (Electronics and Communications Engineering).

The work included in this thesis was carried out by the author at the Electronics and Communications Engineering Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt.

No part of this thesis was submitted for a degree or a qualification at any other university or institution.

Name: Muhammad Abdel-Rasoul Metwally Abdel-Hay El-Nafarawi

Date: 29/12/2015

Acknowledgment

All praise is due to ALLAH, Most Merciful, the lord of the worlds, who taught man what he knew not. I would like to thank ALLAH Almighty for bestowing upon me the chance, strength and ability to complete this work.

I wish to express my gratitude to my supervisors, Prof.Dr. Khaled Sharaf and Dr. Ayman Ismail for their exceptional guidance, encouragement, insightful thoughts and useful discussions. Dr. Khaled has always been a role model for me with the highest level of morals. I am deeply grateful to Dr. Ayman for his continuous encouragement, guidance and follow up without which this work wouldn't have seen the light. I learnt a lot from Dr. Ayman on the personal, professional and technical levels. May ALLAH reward him for his effort.

I would like also to thank my colleagues at ex-employer MEMS Vision LLC for being my thoughtful friends and for being my irreplaceable family at work. Eng. Mohammad Mamdouh for giving me the opportunity to design, propose, and implement different solutions for complex and challengeable systems for different applications. Thanks to Muhammad Swilam for introducing me to LaTeX and his very kind follow up and encouragement. Thanks to Ahmed Emara for his kind IT support at the beginning of this work.

I would like to express my appreciation to my professors specially Prof. Dr. Khaled Sharaf, Prof.Dr. Emad Hegazi, Prof.Dr. Hani Fikry, Prof.Dr. Mohamed Dessouky, Prof.Dr. Wael Fikry and Dr. Sameh Assem for their invaluable courses. I am also grateful to Eng. Ayman Ahmed and Ahmad Safwat for introducing me to the IC design field. It is also important to express my gratitude for the examination committee for their flexibility and understanding.

And, finally, I would like to express my love and gratitude to my family for their infinite love, unconditional care and unlimited support. This thesis is dedicated to my mother, and to the memory of my beloved father, Abdel-Rasoul El-Nafarawi. I miss him everyday, and I am sorry that he has not lived to see me graduate.

Muhammad Abdel-Rasoul Metwally Abdel-Hay El-Nafarawi
Electrical and Communications Department (ECE)
Faculty of Engineering
Ain Shams University
Cairo, Egypt
December 2015.

Abstract

Faculty of Engineering – Ain Shams University

Electronics and Communication Engineering Department

Thesis title: **"Design of a Digital-Output Capacitive Sensor Interface"**

Researcher Name: **Muhammad Abdel-Rasoul Metwally Abdel-Hay El-Nafarawi**

Degree: **Masters of Science in Electrical Engineering**

Abstract

This work presents a novel energy-efficient capacitance-to-digital converter (CDC) interface for capacitive pressure sensors. A new direct-capacitance-comparison technique (DCCT) is proposed and employed together with a successive approximation register (SAR) algorithm to resolve the sensor capacitance by, directly, comparing it to an on-chip binary-weighted capacitive DAC array (CAPDAC). This conversion technique, significantly, simplifies the process of capacitance-to-digital conversion and enables using less analog blocks.

The proposed interface circuit topology requires neither a high purity reference clock for digital conversion, nor a bandgap reference voltage. Furthermore, the interface does not have a capacitance-to-voltage converter (CTV),

which all add up to maximize the proposed solution energy-efficiency compared to other pressure sensors capacitive interface architectures.

It is, also, shown that the proposed new CDC employs an offset DAC array (OFFDAC that compensates for the sensor rest and co-integration parasitic capacitances. Therefore, the proposed CDC provides a dynamically zoomed digital-output code that corresponds to the range of the capacitance change only rather than sensor rest or parasitic capacitances. Also, the proposed CDC provides a very high capacitance readout linearity that ,considerably, outperforms some techniques proposed in literature.

The sensor rest, co-integration, and full-scale (FS) range capacitance can be easily adjusted using the proposed CDC. A complete system analysis shows how the power consumption and the comparator sensitivity are traded for sensor rest capacitance, the FS capacitance, and the ability to tolerate large parasitic capacitance.

The proposed 8-bit SAR-based CDC is designed and simulated using 0.18μm standard CMOS technology. For the reported power consumption, it can handle parasitic capacitance combined with rest capacitance up to four times larger than the sensor FS capacitance range. The CDC exhibits a capacitance sensing range from 4pF to 6pF, achieves a resolution and linearity of 7.26-bit and 8.2-bit, respectively, and a capacitance noise floor of $5.32aF/\sqrt{Hz}$, at 7.7μW power consumption and 36μs conversion time. The interface circuit occupies an active area of 0.2mm^2, and achieves a figure-of-merit (FoM) of 1.8pJ/step at 1.4V supply. Compared to the state-of-the-art implementations with similar performance, this solution provides a consid-

erable enhancement.

key words: Capacitance-to-digital converter (CDC), capacitive pressure sensors, direct-capacitance comparison technique, successive approximation register (SAR), energy-efficient interfaces, low-power interfaces.

THIS PAGE INTENTIONALLY LEFT BLANK

Summary

Faculty of Engineering – Ain Shams University

Electronics and Communication Engineering Department

Thesis title: **"Design of a Digital-Output Capacitive Sensor Interface"**

Researcher Name: **Muhammad Abdel-Rasoul Metwally Abdel-Hay El-Nafarawi**

Degree: **Masters of Science in Electrical Engineering**

Summary

The thesis is divided into six chapters as listed below:

Chapter 1

Chapter 1 provides the background, motivation, and objective of this work. The chapter, also, gives a brief summary for the thesis organization.

Chapter 2

Chapter 2 gives an overview on MEMS-based capacitive pressure sensing systems, where the principle of operation of pressure sensor devices is presented. Also, different systems' architectures are discussed and compared, listing examples from existing state-of-the-art system implementations.