

UNIVERSITAT POLITÈCNICA DE VALÈNCIA



UNIVERSITAT  
POLITÈCNICA  
DE VALÈNCIA

Tactile and Touchless Sensors Printed on Flexible  
Textile Substrates for Gesture Recognition

Ph. D. Thesis / Tesis Doctoral

by

Josué Ferri Pascual

Advisors:

Raúl Llinares Llopis  
Eduardo García Breijo

Tesis presentada para la obtención del grado de Doctor por la Universitat Politècnica de València

Thesis presented to obtain the PhD from the Universitat Politècnica de València

Valencia, July 2020



# Table of Contents

TABLE OF CONTENTS.....	III
FIGURE LIST.....	VII
TABLE LIST.....	XIII
ACRONYMS.....	XV
<b>1. INTRODUCTION.....</b>	<b>1</b>
1.1. STATE OF THE ART.....	2
1.1.1. <i>Smart Textiles</i> .....	2
1.1.2. <i>Components of Smart Textiles</i> .....	2
1.1.3. <i>Sensor Types</i> .....	3
1.1.4. <i>Sensing Technologies</i> .....	3
1.1.5. <i>Manufacturing Processes</i> .....	7
1.1.6. <i>Controller</i> .....	8
1.2. MOTIVATION AND SCOPE.....	9
1.3. OBJECTIVES.....	10
1.4. CONTEXT .....	11
1.4.1. <i>SmartLife</i> .....	11
1.4.2. <i>Screentex</i> .....	12
1.4.3. <i>Flexitex</i> .....	13
1.5. THESIS OVERVIEW.....	14
1.6. SCIENTIFIC PUBLICATIONS .....	15
1.7. ACADEMIC CONTRIBUTIONS .....	16
<i>International Journals:</i> .....	16
<i>International Conferences:</i> .....	16
1.8. RIGHTS.....	17
<b>2. 2D TOUCHPAD SENSOR PRINTED ON TEXTILE SUBSTRATE .....</b>	<b>27</b>
2.1. INTRODUCTION .....	28
2.2. DESIGN AND WORKING PRINCIPLE.....	29
2.2.1. <i>Sensor Pattern</i> .....	30
2.2.2. <i>Textile Touchpad Design</i> .....	31
2.2.3. <i>Design of Electronic System</i> .....	33
2.3. MATERIALS AND METHODS.....	33

2.3.1.	<i>Sensor Development</i> .....	33
2.4.	RESULTS.....	38
2.4.1.	<i>Physical Parameters</i> .....	38
2.4.2.	<i>Electrical Parameters</i> .....	38
2.4.3.	<i>4.3. Design Using Different Types of Fabrics</i> .....	40
2.4.4.	<i>Design Reducing the Size</i> .....	40
2.4.5.	<i>Operation</i> .....	41
2.5.	CONCLUSIONS.....	42
<b>3.</b>	<b>A 2D TOUCH TEXTILE SENSOR WITH AN ELECTROLUMINESCENT DISPLAY .....</b>	<b>47</b>
3.1.	INTRODUCTION .....	48
3.2.	MATERIALS AND METHODS .....	49
3.2.1.	<i>Device Architecture Development</i> .....	49
3.2.2.	<i>Electronic Systems Development</i> .....	53
3.3.	RESULTS AND DISCUSSION.....	54
3.3.1.	<i>Physical Parameters</i> .....	54
3.3.2.	<i>Electroluminescent Display Results</i> .....	57
3.3.3.	<i>2D Touchpad Results</i> .....	59
3.3.4.	<i>Final Design</i> .....	60
3.4.	CONCLUSIONS .....	61
<b>4.</b>	<b>A TEXTILE 3D GESTURE RECOGNITION TEXTILE SENSOR .....</b>	<b>67</b>
4.1.	INTRODUCTION .....	68
4.2.	DESIGN AND WORKING PRINCIPLE .....	70
4.2.1.	<i>Working Principle</i> .....	70
4.2.2.	<i>Microchip Sensor Design</i> .....	74
4.2.3.	<i>Textile 3D Gesture Sensor Design</i> .....	80
4.3.	MATERIALS AND METHODS .....	84
4.3.1.	<i>Materials</i> .....	84
4.3.2.	<i>Sensor Development</i> .....	86
4.3.3.	<i>Measurements</i> .....	87
4.4.	RESULTS AND DISCUSSION .....	87
4.5.	CONCLUSIONS .....	101
<b>5.</b>	<b>A BOOSTED TEXTILE 3D GESTURE RECOGNITION TEXTILE SENSOR .....</b>	<b>107</b>
5.1.	INTRODUCTION .....	108
5.2.	MATERIALS AND METHODS .....	109
5.2.1.	<i>Electronic Design</i> .....	110
5.2.2.	<i>Materials</i> .....	113
5.2.3.	<i>Manufacturing</i> .....	114
5.2.4.	<i>Sensor Development</i> .....	116
5.2.5.	<i>Measurement</i> .....	118

5.3.	RESULTS AND DISCUSSION .....	118
5.4.	CONCLUSION .....	128
<b>6.</b>	<b>CONCLUSIONS.....</b>	<b>133</b>
6.1.	CONCLUSIONS .....	134
6.2.	FUTURE RESEARCH LINES.....	136



# Figure List

Figure 1. Textile electrodes to be used as ECG and EMG sensors. Source: AITEX. ....	3
Figure 2. Resistive sensor structure for touch applications. Source: Screenshot Project from AITEX. ....	4
Figure 3. Conductive plates printed on fabric working as electrodes. Source: Screenshot Project from AITEX.....	4
Figure 4. Surface capacitive sensor. Source: Own elaboration.....	5
Figure 5. Projected capacitive sensor. Source: Flexitex Project from AITEX.....	6
Figure 6. Self-capacitance sensor. Source: Own elaboration based on Walker, G. et al. [91]. ....	6
Figure 7. Mutual-capacitance sensor. Source: Own elaboration based on Walker, G. et al. [91].....	7
Figure 8. 3D gesture sensor. Source: Own elaboration based on Microchip design recommendations. ....	7
Figure 9. Printing technologies: inkjet, screen and flexography. Source: Flexitex Project from AITEX.....	8
Figure 10. Source: Smartlife Project from AITEX. ....	12
Figure 11. Thesis diagram.....	15
Figure 12. (a) Diamond pattern; and (b) 2D array sensors in the case of single layer or two layers. ....	30
Figure 13. Two Layers Design (TLD): (a) Vertical or X layer; (b) dielectric layer; (c) Horizontal or Y layer; and (d) the complete design. ....	32
Figure 14. One Layer Design (OLD): (a) conductive layer for connection tracks; (b) dielectric layer with via-holes; (c) X-Y layer; and (d) the complete design. ....	33
Figure 15. Pinholes in the dielectric layer; and (b) detail of pinhole. ....	34
Figure 16. (a) First conductive layer, above for TLD and below for OLD; (b) dielectric layer; (c) second conductive layer; and (d) complete Design. ....	36
Figure 17. (a) Two-layer design; and (b) one-layer design magnification views.....	38

Figure 18. (a) Capacitance distribution on OLD; and (b) capacitance distribution on TLD. .....	39
Figure 19. Two-layer design: (a) “released” signal; and (b) “pressed” signal.....	39
Figure 20. One-layer design: (a) “released” signal; and (b) “pressed” signal. ....	40
Figure 21. Capacitances and failures for each type of fabric and design.....	40
Figure 22. Touchpads with the same design but different size.....	41
Figure 23. (a) Performance test on a curved surface touching two different points; and (b) performance test touching on the same point but on a flat and a curved surface, obtaining the same result. ....	41
Figure 24. ELD + 2D touchpad architecture: All the design on one side of the textile (a); Using the textile itself as a separating element, on one side the ELD and on the other one the 2D touchpad sensor (b). ELD: electroluminescent display.....	50
Figure 25. ELD Design: Conductive silver electrode (a); dielectric layer (b); Phosphor layer (c); and clear conductor (d). ....	51
Figure 26. Different types of fabrics used as substrates. ....	51
Figure 27. 2D Touchpad Design: Vertical or X layer (a); dielectric layer (b); and Horizontal or Y layer (c). ....	53
Figure 28. Electronic System Block Diagram (a); real electronic system applied to a mouse control in a mobile phone (b). ....	53
Figure 29. Electroluminescent Display layers profilometry (a). 2D Touchpad layers profilometry, in this case fabrics A and B are studied in order to value the insulator layer (b). ....	55
Figure 30. Cotton fibers without PEDOT: PSS (a) and after the screen printing of PEDOT: PSS (b).....	56
Figure 31. SEM micrograph showing device cross-section. Fabric_A (a) and Fabric_C (b). In a box, in the bottom right corner of each figure, the virgin fabric is shown...	57
Figure 32. Chromaticity diagram according to the CIE 1931 standard. ....	58
Figure 33. Train of pulses sent by the Touch Controller. Normal signal (a) and disturbed signal (b).....	60
Figure 34. ELD + 2D touchpad architecture with ITO EMI shield. ELD: electroluminescent display; ITO: indium tin oxide; EMI: electromagnetic interferences. ....	60
Figure 35. 2D touchpad with ELD on and off (a). Redesign in order to turn on only the zone that has been touched (b). The design has been manufactured with Fabric_A...	61
Figure 36. Field lines generated by the transmission Tx electrode. The reception Rx electrodes are located inside of the generated field. On the left side of the Figure, the field lines are shown when they are not modified by any conductor object.	



	On the right side of the Figure, a hand is causing a modification of the field lines, leading to a variation in the signal received by the Rx electrodes. Source: Microchip Technology Inc.....	71
Figure 37.	Gestures recognized by the internal algorithm of MGC3130: approach detection, position tracking in 3D, sensor touch (touch, multitouch, tap, and double tap), flick gestures, circle gestures, and airwheel. Source: Microchip Technology Inc. ....	71
Figure 38.	Standard sensor used by Microchip. It consists of a first layer where four Rx electrodes are located on each of the cardinal points as well as a central Rx electrode. This layer is separated from the bottom layer that contains the Tx electrode by a dielectric. The ground plane layer is optional and would be located below the Tx electrode layer. The sensitive area is just delimited by the four perimeter Rx sensors. Source: Microchip Technology Inc. ....	72
Figure 39.	MGC3130 Block Diagram, composed of an analog front-end module that allows to generate the transmission Tx signal and receive the signals from the 5 Rx electrodes. The signals, properly processed, are transferred to the Signal Processing Unit that, together with the GestIC library, processes and converts them into the different programmed gestures. Lastly, there is a communication block with a host. Source: Microchip Technology Inc.....	73
Figure 40.	Equivalent simplified circuit of the combination sensor-MGC3130. Source: Microchip Technology Inc.....	74
Figure 41.	Basic scheme of the gesture sensor recommended by Microchip. Source: Microchip Technology Inc.....	75
Figure 42.	Variation of signal deviation received by Rx in function of the distance of the hand to the sensor and of the Rx electrode width.....	76
Figure 43.	An op-amp buffer must be inserted between the Tx pin and the Tx electrode in case $C_{TxGND}$ is greater than 1 nF. Source: Microchip Technology Inc. ....	77
Figure 44.	Basic design parameters recommended by Microchip. Source: Microchip Technology Inc. ....	77
Figure 45.	General characteristics of the $95 \times 60$ sensor from Microchip. Source: Microchip Technology Inc.....	78
Figure 46.	Crosscut of the PCB of the $95 \times 60$ sensor; dimensions and number of layers. Source: Microchip Technology Inc.....	78
Figure 47.	(a) Waveform of the transmission signal, (b) the received Rx signal with no object modifying the field lines, (c) the received Rx signal with an object modifying the field lines. ....	80
Figure 48.	3DS-1 design with four layers: (a) ground plane layer, (b) transmission Tx electrode, (c) dielectric layer between Rx and Tx layers and vias, (d) Rx electrode layer.....	81

Figure 49. Cross-section of the 3DS-1 sensor. In addition to the 4 layers shown in Figure 48 the textile substrate between the ground plane layer and the Tx electrode layer can be observed. ....	82
Figure 50. 3DS-2 design with four layers. Ground plane layer (a). Dielectric layer between Tx and ground layer (b). Transmission Tx layer (c). Rx layer (d).....	82
Figure 51. Cross-section of the 3DS-2 sensor. In addition to the 4 layers shown in Figure 50, the textile substrate between the Rx layer and the Tx electrode layer can be observed.....	83
Figure 52. 3DS-1 Design with two construction structures: (a) the textile substrate acting as a dielectric between the Tx electrode and the ground plane (sensor name 3DS_1a) and (b) the textile substrate acting as a mere base (sensor name 3DS_1b).....	88
Figure 53. 3DS-1 Sensor. ....	88
Figure 54. Transmission signal waveform (a), a signal deformation can be observed due to a capacitance of $C_{TxGND} > 1nF$ . Regenerated signal obtained coupling an AO between the Tx pin and the Tx electrode (b). Receiving Rx signal with direct connection (c) between the Tx pin and the Tx electrode. Receiving Rx signal with AO (d) between the Tx pin and the Tx electrode. ....	91
Figure 55. 25× Magnified view of the printing of the conductive ink on the Type D textile (a) and on the Type E textile (b).....	92
Figure 56. 25× Magnified view of the printing of the dielectric and conductive inks on: (a) Type D textile with dielectric Creative 127-48D and a layer of silver ink, (b) Type D textile with dielectric EMS DI-7542 and a layer of silver ink,(c) Type D textile with dielectric INKRON IPD-670 and a layer of silver ink, (d) Type E textile with dielectric Creative 127-48D and a layer of silver ink, (e) Type E textile with dielectric EMS DI-7542 and a layer of silver ink and (f) Type D textile with dielectric IPD-670 and a layer of silver ink.....	93
Figure 57. 3DS-2 Design with two construction structures: (a) the textile substrate acting as a dielectric between the Tx electrode and Rx electrode (sensor named 3SD_2a) and (b) the textile substrate covered with polyurethane (sensor named 3SD_2b). ....	94
Figure 58. Sensor 3DS-2a.....	94
Figure 59. Waveform of the transmission signal (a) with buffer due to the capacitance $C_{TxGND} > 1nF$ , (b) receiving RX signal with direct connection between the Tx pin and the Tx electrode and (c) receiving RX signal with op-amp between the Tx pin and the Tx electrode. ....	96
Figure 60. “Artificial hand” provided by Microchip. It is made of styrofoam covered by copper and connected to ground. Some blocks of styrofoam with no covering allow to move the “artificial hand” away from the sensor.....	97

Figure 61. Signal Deviation of the different sensors in function of the distance of the hand from the surface of the sensor. The $C_{TxRxN}$ value, in brackets in the legend, has been included as a reference to assess the relationship between capacitance and sensitivity. This relationship is the same in any of the associated capacities. ....	97
Figure 62. Approach detection.....	99
Figure 63. Flick north to south.....	99
Figure 64. Flick west to east. ....	100
Figure 65. Airwheel. ....	100
Figure 66. Complete portable system.....	101
Figure 67. 3D Sensor used as a Wireless mouse with a mobile phone. ....	101
Figure 68. Standard (left) and Boosted (right) sensors used by Microchip. The standard version consists of 5 RX electrodes on top layer plus a TX electrode on an inner layer. The boosted version has 4 RX and 1 TX electrodes on the top layer. The sensing space is the same in terms of area but is lower in volume in the case of the standard version. Source: Microchip Technology Inc.....	111
Figure 69. Basic design parameters recommended by Microchip for a) Standard sensor and b) Boosted sensor. Source: Microchip Technology Inc. ....	112
Figure 70. Boosted sensor design: Ground plane layer (a) and Tx-Rx electrodes (b).....	115
Figure 71. 3D gesture sensor developments with the three E-textile technologies: (a) screen-printing, (b) embroidery and, (c) direct application of conductive textile, and with the PCB material (d). ....	117
Figure 72. Frequency response of fabric relative permittivity. ....	118
Figure 73. Values of the equivalent capacitor circuit: a) parallel capacitance $C_p$ , b) parallel resistance $R_p$ , c) impedance and d) phase value. ....	119
Figure 74. “Artificial hand” provided by Microchip made of styrofoam covered by copper and connected to ground. ....	121
Figure 75. Signal Deviation of the different sensors in function of the distance of the hand from the surface of the sensor. The smallest graph is the magnification of the 10 cm limit. ....	122
Figure 76. Flexible 3D Boosted sensor manufactured. ....	122
Figure 77. a) Capacitance variation depending on the humidity at a fixed temperature of 20 °C, b) Capacitance variation depending on the temperature at a fixed humidity of 40% RH.....	123
Figure 78. Normalized resistance variation in a conductor pattern used in the three technologies (fabric, thread and ink) versus number of washes.....	123
Figure 79. a) appearance of the silver ink before washing and, b) after 5 washes.....	124

Figure 80. a) Appearance of the silver ink coated with a heat-sealed film before washing and, b) after 5 washes. The bubbles generated between the substrate and the film and the degeneration of the silver ink are observed..... 124

Figure 81. Characterization of the sensors using an artificial hand: a) PCB reference sensor fixing  $Z = 0$  position. b) Textile sensor fixing  $Z = 0$  position. c) PCB reference sensor fixing  $Z = 3$  cm position. d) Textile sensor fixing  $Z = 3$  cm position. e) PCB reference sensor fixing  $Z = 5$  cm position. f) Textile sensor fixing  $Z = 5$  cm position. .... 125

Figure 82. Two of the gestures used in the validation: a) flick from north to south and b) flick from west to east. .... 126

# Table List

Table 1. Failures rate (%) for TLD when 1–3 layers of dielectric ink are used. ....	35
Table 2. Failures rate (%) for OLD when 1–3 layers of dielectric ink are used.....	35
Table 3. Final layer thickness depending on mesh value and number of layers. ....	36
Table 4. Capacitance (pF) for TLD when 1–3 layers of D2081009D6 ink are used.....	37
Table 5. Capacitance (pF) for OLD when 1–3 layers of D2081009D6 ink are used. ....	37
Table 6. Capacitance (pF) for OLD and TLD when 1–3 layers of D2070209P6 ink are used for mesh of 175 inches. ....	38
Table 7. Characteristics of the different fabrics used. ....	52
Table 8. Light characteristics of the different samples used. ....	59
Table 9. Values of $C_{TxRx}$ [5–30 pF].....	79
Table 10. Real values of $C_{TxGND}$ [ $<1$ nF]. ....	79
Table 11. Values of $C_{RxGND}$ [5–30 pF]. ....	79
Table 12. Fabric characteristics (I): composition and ligament. ....	84
Table 13. Fabric characteristics (II): size and weight characteristics. ....	85
Table 14. Silver ink characteristics. ....	85
Table 15. Dielectric ink characteristics. ....	86
Table 16. Polyurethane characteristics. ....	86
Table 17. Relative permittivity of the dielectric inks $\epsilon_r$ @100 kHz.....	89
Table 18. Relative permittivity of fabrics $\epsilon_r$ @100 kHz. ....	89
Table 19. Capacitance values of 3DS-1a-TA (pF). ....	89
Table 20. Capacitance values of 3DS-1b-TA (pF). ....	90
Table 21 . Capacitance values of 3DS-2-TA (pF). ....	92
Table 22. Relative permittivity of the polyurethanes. ....	93
Table 23. Capacitance values of 3DS-2a and 3DS-2b (pF). ....	95

Table 24. Values of $C_{TXRX}$ : theoretical nominal capacity ( $C_n$ ), with Edge effect ( $C_{edge}$ ) and real values ( $C_{real}$ ) (pF).....	98
Table 25. Fabric characteristics.....	113
Table 26. Silver ink characteristics.....	114
Table 27. Embroidery thread silver characteristics.....	114
Table 28. Conductive fabric plain characteristics.....	114
Table 29. Capacitance values (pF) at 104 Hz.....	120
Table 30. Gesture conducted tests results for the 3DBS_Screen sensor.....	127
Table 31. Comparison between proposed Sensors.....	127