

Contents

Abstract	vii
Zusammenfassung	ix
List of Symbols and Abbreviations	xv
1 Introduction	1
1.1 From the Internet of Things to the Internet of Humans	1
1.2 Challenges for the implementation of the IoT and IoH	2
1.3 Objectives and research questions	4
1.4 Rationale	4
1.5 Outline	5
2 State of the art	7
2.1 Thermal interfaces and energy conversion	7
2.1.1 Thermoelectric energy conversion	8
2.1.2 Interface to the human body	11
2.1.3 Interface to the environment	11
2.2 Electric interfaces	13
2.3 Summary and conclusions	14
3 Thermal energy harvesting potential of the human body	17
3.1 The human body as a heat source	17
3.1.1 Metabolism and heat generation	17
3.1.2 Thermoregulation and the role of the skin	18
3.1.3 Thermal comfort	19
3.1.4 Heat exchange between body and environment	20
3.2 Evaluation of harvesting potential	22
3.2.1 Study design	23
3.2.2 Data analysis and statistics	26
3.2.3 Skin contact resistance	30
3.2.4 Skin temperature	31
3.2.5 Heat flux variation based on body location and environment	32
3.2.6 Heat flux, harvested power and skin resistance for 56 subjects	34
3.2.7 User comfort	39
3.3 Chapter summary	40

4	Wearable thermoelectric harvesters	41
4.1	Thermoelectric energy conversion	42
4.1.1	Fundamentals	42
4.1.2	Conversion efficiency	46
4.1.3	Power optimization	48
4.1.4	TEG classification	52
4.2	Voltage conversion and storage	53
4.2.1	Classification of DC-DC converters	54
4.2.2	Characterization of DC-DC converters	55
4.2.3	Energy buffer	57
4.3	Minaturized harvester for sensor nodes	58
4.3.1	System overview	59
4.3.2	Power generation	60
4.4	Wristband harvester for multi-sensor bracelet	61
4.4.1	System overview	62
4.4.2	Harvester specifications	62
4.4.3	Experimental	63
4.4.4	Power generation	64
4.4.5	Total conversion efficiency	67
4.4.6	Application Case-Study	68
4.4.7	User comfort	69
4.5	Large-area forehead harvester for high power	70
4.5.1	System overview	70
4.5.2	Power generation	71
4.5.3	Wearability and comfort	72
4.6	Chapter Summary	74
5	Thermal interfaces	75
5.1	Skin interface	75
5.1.1	Concept	75
5.1.2	Fabrication	75
5.1.3	Characterization	76
5.1.4	Comparison with rigid interfaces	77
5.2	Environmental interface	80
5.2.1	Theory and modeling	80
5.2.2	Optimization of temperature sensitivity	86
5.2.3	System description	88
5.2.4	Fabrication	90
5.2.5	Experimental	92
5.2.6	Curvature, displacement and temperature sensitivity	93
5.2.7	Thermal resistance and heat flux	95

5.2.8	Mechanical robustness and thermocycling	96
5.3	Chapter summary	97
6	Soft electric interfaces	99
6.1	Biopotential readout on the human body	99
6.1.1	Origin and shape of biopotential waveforms	99
6.1.2	Electrode classification	101
6.1.3	The human skin	103
6.1.4	Electrical model of the electrode-skin interface	104
6.1.5	Electrode placement	105
6.1.6	Noise, artifacts, and interference	106
6.1.7	Filtering of biopotential signals	107
6.2	Bioinspired dry adhesion	108
6.3	Materials and methods	110
6.3.1	Fabrication	110
6.3.2	Geometry and layout of adhesive micropillars	112
6.3.3	Characterization methods	114
6.4	Soft epidermal biopotential electrodes	118
6.4.1	Electrode designs	118
6.4.2	Skin conformity	119
6.4.3	Electrode-skin impedance	120
6.4.4	Adhesive properties	122
6.4.5	Noise and motion artifacts	127
6.4.6	Skin reactions	130
6.5	Biopotential recordings	132
6.5.1	ECG under motion	132
6.5.2	EEG	136
6.6	Chapter summary	138
7	Wearable 6-CH EEG for long-term recordings	139
7.1	Motivation and objectives	139
7.2	System overview	140
7.3	Preliminary results	142
7.4	Chapter summary	145
8	Conclusion and Outlook	147
8.1	Summary and accomplishments	147
8.2	Discussion and outlook	149
A	Appendix	151
A.1	Process Runsheets	151

Contents

A.2 Properties of thermoelectric generators	156
A.3 Ethic approval of user study (excerpt)	156
A.4 TEG characterization setup (BA L. Wawrla)	172
Bibliography	183
Acknowledgement	201
Publications	203
Student projects	205
Curriculum vitae	207