# Contents

**1 Introduction** ........ 1
1.1 Preface ........ 1
1.2 Thesis Statements ........ 2
1.3 Objectives ........ 2
1.4 Contributions ........ 4
1.5 Publications ........ 6
1.6 Thesis Outlines ........ 9

**2 Background** ........ 11
2.1 Radar Fundamentals ........ 11
2.1.1 Radar Equation ........ 12
2.1.2 Frequency Modulated Continuous Wave Radar ........ 13
2.1.2.1 Chirp ........ 14
2.1.2.2 Simplified FMCW Radar ........ 14
2.1.2.3 Target Range ........ 15
2.1.2.4 Fast Fourier Transform ........ 17
2.1.2.5 Range Resolution ........ 19
2.1.2.6 Target Velocity ........ 20
2.1.2.7 Vibrating Source ........ 22
2.1.2.8 Angle Estimation ........ 23
2.2 Artificial Neural Networks ........ 25
2.2.1 Multiple Layer Perceptron ........ 25
2.2.2 Convolutional Neural Network ........ 26
2.2.2.1 Convolutional Layer ........ 27

2.2.2.2 Pooling Layer ..... 28
2.2.2.3 Dense or Fully Connected Layer ..... 29
2.2.2.4 Nonlinearity Layer ..... 29
2.2.3 Long Short-Term Memory Networks ..... 29
2.2.4 Temporal Convolutional Networks ..... 31
2.2.5 Generative Adversarial Networks ..... 33
2.2.5.1 GAN Loss Function ..... 33
2.2.5.2 Boundary-seeking GAN ..... 34
2.3 Spiking Neural Networks ..... 35
2.3.1 General Spiking Neural Network Architecture ..... 36
2.3.2 Leaky Integrate and Fire Model ..... 36
2.3.3 Encoding Schemes ..... 38
2.3.3.1 Rate-based Encoding ..... 38
2.3.3.2 Temporal Encoding ..... 39
2.4 Neural Engineering Object (Nengo) Simulator ..... 41
2.4.1 NengoDL ..... 41
2.5 Legendre Memory Unit ..... 41
2.6 Federated Learning ..... 42
2.7 Differential Privacy ..... 42
2.7.1 Laplacian Noise Addition Mechanism ..... 43

**3 Signal Processing Chain with Spiking Neural Networks for Radar-based Gesture Sensing** ..... 45
3.1 Introduction ..... 45
3.1.1 State-of-the-Art ..... 46
3.1.1.1 2D Range Doppler Images ..... 47
3.1.1.2 Detection Algorithm ..... 50
3.1.1.3 Clustering ..... 51
3.1.1.4 Radar Feature Images ..... 52
3.1.1.5 Deep Classifiers ..... 54
3.1.2 Limitations of State-of-the-Art ..... 54
3.1.3 Proposed Solutions ..... 55
3.2 Hardware ..... 57
3.2.1 System Parameters ..... 59
3.2.2 Signal Model ..... 60
3.3 Dataset and Experimental Setup ..... 61
3.4 Gesture Sensing Using Range-Doppler Images ..... 62
3.4.1 Signal Processing Chain ..... 62
3.4.1.1 Target Detection ..... 63

3.4.1.2 Gesture Classification ........ 63
3.4.2 Architecture & Learning ........ 64
3.4.2.1 Architecture ........ 64
3.4.2.2 Model Testing ........ 64
3.4.3 Results & Discussion ........ 65
3.4.3.1 Dataset ........ 65
3.4.3.2 Classification Results ........ 66
3.4.3.3 Discussion ........ 66
3.4.4 Conclusion ........ 68
3.5 Optimized Gesture Sensing Using Range-Doppler Images ........ 68
3.5.1 Signal Processing Chain ........ 68
3.5.2 Architecture & Learning ........ 69
3.5.2.1 Loss Function ........ 69
3.5.2.2 Model Testing ........ 70
3.5.3 Results & Discussion ........ 70
3.5.3.1 Dataset ........ 70
3.5.3.2 Classification Results ........ 70
3.5.3.3 Discussion ........ 70
3.5.4 Conclusion ........ 73
3.6 Gesture Sensing Using Range-Doppler and Angle Images ........ 74
3.6.1 Signal Processing Chain ........ 74
3.6.1.1 Preprocessing ........ 74
3.6.1.2 Coherent Pulse Integration ........ 74
3.6.1.3 Moving Target Indication Filtering ........ 74
3.6.1.4 Target Detection ........ 76
3.6.1.5 Range-Doppler Image ........ 76
3.6.1.6 Angle of Arrival Estimation ........ 76
3.6.1.7 Data Generation For the Model ........ 76
3.6.2 Architecture & Learning ........ 77
3.6.2.1 Architecture ........ 78
3.6.2.2 Loss Function ........ 78
3.6.2.3 Learning Schedule and Weight Initialization ........ 79
3.6.2.4 Model Testing ........ 79
3.6.2.5 Model Hyperparameters ........ 79
3.6.3 Results & Discussion ........ 81
3.6.3.1 Dataset ........ 81
3.6.3.2 Results ........ 81
3.6.3.3 Discussion ........ 82

3.6.4 Conclusion ........ 87
3.7 Gesture Recognition System Using Raw ADC Data ........ 88
3.7.1 Signal Processing Chain ........ 88
3.7.1.1 Moving Target Indication Filtering ........ 88
3.7.2 Architecture & Learning ........ 89
3.7.3 Results & Discussion ........ 90
3.7.3.1 Dataset ........ 90
3.7.3.2 Results ........ 90
3.7.3.3 Discussion ........ 91
3.7.4 Conclusion ........ 93
3.8 Mimicking Fourier Transforms with Spiking Neural Networks ........ 93
3.8.1 Signal Processing Chain ........ 93
3.8.1.1 Raw Data ........ 94
3.8.1.2 Moving Target Indication Filtering ........ 94
3.8.2 Architecture & Learning ........ 95
3.8.2.1 Training ........ 97
3.8.2.2 Testing ........ 98
3.8.3 Results & Discussion ........ 98
3.8.3.1 Dataset ........ 98
3.8.3.2 Results ........ 98
3.8.3.3 Discussion ........ 98
3.8.4 Conclusion ........ 109
3.9 Spiking Neural Networks-based Gesture Sensing on FPGA ........ 110
3.9.1 Building a Model in Nengo ........ 111
3.9.2 Model Transformation to Lower Level Code ........ 112
3.9.3 Implementation on the FPGA ........ 113
3.9.4 Conclusion ........ 113

**4 Radar-based Air-writing for Embedded Devices** ........ 115
4.1 Introduction ........ 115
4.1.1 State-of-the-Art ........ 116
4.1.1.1 Range Estimates ........ 118
4.1.1.2 Target Localization with Trilateration ........ 118
4.1.1.3 Trajectory Smoothening Filters ........ 119
4.1.1.4 Trajectory Reconstruction and Classification ........ 120
4.1.2 Limitations of State-of-the-Art ........ 120

4.1.3 Proposed Solutions .... 120
4.2 Hardware .... 122
4.2.1 System Parameters .... 124
4.3 Dataset and Experimental Setup .... 124
4.4 Air-writing With Sparse Network of Radars .... 126
4.4.1 Signal Processing Chain .... 126
4.4.2 Proposed System .... 127
4.4.3 Architecture & Learning .... 131
4.4.3.1 Architecture .... 131
4.4.3.2 Loss Function .... 133
4.4.3.3 Weight Initialization & Learning Schedule .... 133
4.4.4 Results & Discussion .... 134
4.4.4.1 Dataset .... 134
4.4.4.2 Reconstruction Results .... 134
4.4.4.3 Classification Results .... 137
4.4.4.4 Discussion .... 137
4.4.5 Conclusion .... 140
4.5 Radar Trajectory-based Air-writing Recognition .... 141
4.5.1 Signal Processing Chain .... 141
4.5.2 Proposed Solution .... 141
4.5.3 Architecture & Learning .... 143
4.5.3.1 Loss Function .... 144
4.5.4 Results & Discussion .... 144
4.5.4.1 Dataset .... 144
4.5.4.2 Classification .... 144
4.5.4.3 Discussion .... 145
4.5.5 Conclusion .... 149
4.6 Radar-based Air-Writing Using Spiking Neural Networks .... 149
4.6.1 Signal Processing Chain .... 149
4.6.2 Architecture & Learning .... 151
4.6.3 Results & Discussion .... 151
4.6.3.1 Dataset .... 151
4.6.3.2 Data Augmentation .... 152
4.6.3.3 Hyperparameters .... 152
4.6.3.4 Performance Evaluation .... 153
4.6.3.5 Estimated Energy Consumption .... 154
4.6.4 Conclusion .... 156

4.7 Radar-based Air-Writing System Using Spiking Legendre Memory Unit ........ 156
4.7.1 Signal Processing Chain ........ 157
4.7.2 Architecture & Learning ........ 157
4.7.2.1 Architecture ........ 158
4.7.2.2 Model Training and Testing ........ 159
4.7.3 Results & Discussion ........ 159
4.7.3.1 Dataset ........ 159
4.7.3.2 Classification Performance ........ 160
4.7.3.3 Discussion ........ 160
4.7.3.4 Performance Evaluation ........ 164
4.7.4 Conclusion ........ 164

**5 Time Series Forecasting of Healthcare Data** ........ 165
5.1 Introduction ........ 165
5.1.1 State-of-the-Art ........ 166
5.1.2 Limitations of the State-of-the-Art ........ 169
5.1.3 Proposed Approaches ........ 169
5.2 Hardware ........ 171
5.3 Dataset ........ 172
5.4 Synthetic and Private Smart Health Care Data Generation Using GANs ........ 173
5.4.1 Data Processing Pipeline ........ 173
5.4.1.1 Data Collection and Imputation ........ 174
5.4.2 Architecture & Learning ........ 175
5.4.2.1 Generator Network ........ 175
5.4.2.2 Discriminator Network ........ 176
5.4.2.3 Learning Rule ........ 177
5.4.3 Results & Discussion ........ 177
5.4.3.1 Experiments ........ 177
5.4.4 Conclusion ........ 182
5.5 Time-Series Forecasting on User Health Data Streams ........ 182
5.5.1 Data Processing Pipeline ........ 182
5.5.1.1 The Clustering Mechanism ........ 183
5.5.1.2 Data Model for Training SNNs ........ 184
5.5.1.3 Clustered Federated Learning and Differential Privacy ........ 185
5.5.2 Architecture & Learning ........ 185
5.5.2.1 Loss Function ........ 186

5.5.2.2 Learning Schedule ........................ 186
5.5.2.3 Model Testing ........................ 186
5.5.2.4 Model Hyperparameters ........................ 187
5.5.3 Evaluation Methodology ........................ 187
5.5.3.1 Dataset ........................ 187
5.5.3.2 Performance Metrics ........................ 188
5.5.4 Results & Discussion ........................ 189
5.5.4.1 Baseline Model ........................ 189
5.5.4.2 Clustered Federated Learning ........................ 190
5.5.4.3 Differentially Private Learning ........................ 191
5.5.4.4 Differentially Private Federated Learning ...... 192
5.5.4.5 Energy Estimation of SNN Model ........................ 193
5.5.5 Conclusion ........................ 194

**6 Conclusion and Future Directions** ........................ 195
6.1 Summary of the Results ........................ 196
6.2 Future Work ........................ 199

**Bibliography** ........................ 201