Multimodal Intelligent Sensing in Modern Applications

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Dedication

To Allah, the most merciful and compassionate, who guides us through every challenge in life. His love and grace sustain us always and we dedicate this book to him, seeking his continued guidance and blessings.

To my parents, Khalil and Ilfaz, who have nurtured me with unconditional love, sacrifice, and wisdom. To my brothers, Habib and Waheed for their wholehearted assistance. To my wife, Faiza, for her being a great support system through thick and thin. To my son, Musaab, for filling my life with immense love and joy.

Masood Ur Rehman

To my wife, Mariyam, for her unwavering support, love, and patience throughout the journey of editing this book. Her encouragement has been invaluable. To my daughters, Zainab and Yusra, thank you for your joy and the inspiration you bring into my life every day. This accomplishment would not have been possible without the strength and motivation you all gave me.

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To my biggest inspiration, my parents, Jamshed Iqbal and Nuzhut Jamshed
my support system, wife: Aqsa Tariq, and my son: Zohaan Ali.

Muhammad Ali Jamshed

To my parents for all their love and for raising me in a way I am proud of. To my wife Nasira for her resolute support. To my daughters Saba, Bisma, and Hadiya for cherishing and elating my life with all the bliss and love.

Naeem Ramzan

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Masood Ur Rehman received a BSc degree in electronics and telecommunication engineering from UET, Lahore, Pakistan in 2004 and an MSc and PhD in electronic engineering from Queen Mary University of London, UK, in 2006 and 2010, respectively. He worked at QMUL as a postdoctoral research assistant till 2012 before joining the Centre for Wireless Research at the University of Bedfordshire as a Lecturer. He served briefly at the University of Essex and then moved to the James Watt School of Engineering at the University of Glasgow as an Assistant Professor in 2019. He currently works as an Associate Professor at the University of Glasgow. His research interests include compact antenna design for 6G, Industry 5.0, and Global Navigation Satellite Systems; flexible, wearable and implantable sensors and systems; bio-electromagnetics and exposure of biological tissues to RF; mmWave and nano-communications for body-centric networks and wireless sensor networks in industrial automation, healthcare and environmental monitoring, and device-to-device and human-to-human communications. He has worked on several projects supported by industrial partners and research councils. He has contributed to a patent and authored/coauthored 7 books, 13 book chapters, and over 200 technical articles in leading journals and peer-reviewed conferences. He is a Fellow of the Higher Education Academy (UK), a Senior Member of the IEEE, a Member of the IET and BioEM and part of the technical program committees and organizing committees of several international conferences, workshops, and special sessions. He is a committee member of IEEE APS/SC WG P145, IEEE APS Best Paper Award committee and Pearson's focus group on formative assessment. He is acting as an editor of PeerJ Computer Science, associate editor of IEEE Sensors Journal, IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology, IEEE Access, IET Electronics Letters and Microwave & Optical Technology Letters, topic editor for MDPI Sensors, editorial advisor to Cambridge Scholars Publishing, and lead guest editor of numerous special issues of renowned journals. He is chair of the IEEE UKRI Section Young Professionals Affinity Group, vice-chair of the IEEE UKRI Section APS/

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Ahmed Zoha is an Associate Professor at the James Watt School of Engineering, University of Glasgow, and a globally recognized expert in artificial intelligence, machine learning, and smart energy systems. With a PhD from the 6G/5GIC Centre at the University of Surrey and over 15 years of experience, he has contributed to cutting-edge research in AI-driven 5G networks, healthcare technologies, and smart energy monitoring, earning prestigious accolades including IEEE Best Paper Awards and endorsement as a UK exceptional talent by the Royal Academy of Engineering. He serves as an Associate Editor for the *Journal of Big Data and Frontiers in Communication and Networks*, as well as a Guest Editor for several Q1 journals. His work, widely cited and recognized in both academia and industry, supports scalable technological solutions that benefit vulnerable populations and advance the Sustainable Development Goals (SDGs).

Muhammad Ali Jamshed has been with the University of Glasgow since 2021. He is endorsed by the Royal Academy of Engineering under the exceptional talent category and was nominated for the Departmental Prize for Excellence in Research in 2019 and 2020 at the University of Surrey. He is a Fellow of the Royal Society of Arts, a Fellow of Higher Education Academy UK, a Senior Member of the IEEE, an Editor of IEEE Wireless Communication Letters, and an Associate Editor of IEEE Sensor Journal, IEEE Communication Standard Magazine and IEEE IoT Magazine. He is Co-inventor of one patent and has more than 70 publications in top-tier international journals, including IEEE Transactions and Magazines, flagship IEEE COMSOC conferences, such as ICC, VTC, INFOCOM, WCNC, etc. He is an Editor of four books. He has been the Lead Guest Editor for Special Issues in IEEE Wireless Communications Magazine (2024–2025), IEEE Communications Standards Magazine (2024–2025), and IEEE Internet of Things Magazine (2023–2024). He has been serving as General Chair for over 10 workshops at IEEE international conferences such as IEEE GLOBECOM 2024, IEEE VTC Fall 2024, IEEE MECOM 2024, IEEE CAMAD 2023, IEEE WCNC 2023, IEEE PIMRC 2022–2023, IEEE GLOBECOM 2023, IEEE VTC Spring 2022–2023, IEEE CAMAD 2023, and IEEE CAMAD 2019. He has been a TPC Member at IEEE ICC 2022–2024 IEEE VTC Spring 2024, IEEE GLOBECOM 2023, and Sessions Chair at IEEE VTC Spring 2022 and IEEE WCNC 2019 and 2023. He is a founding member of the IEEE Workshop on Sustainable and Intelligent Green Internet of Things.

Naeem Ramzan received an MSc degree in telecommunication from the University of Brest, France, in 2004, and a PhD in electronics engineering from Queen Mary University of London, London, UK, in 2008. Currently, he is a Full Professor of Artificial Intelligence and Computer Engineering and the Director of the Artificial Intelligence, Virtual Communication, Network (AVCN) Institute at the University of West of Scotland. Before that, he was a senior research fellow and lecturer at Queen Mary University of London from 2008 to 2012. He is a Fellow of the Royal Society of Edinburgh, a Senior Member of the IEEE, Senior Fellow of the Higher Education Academy (HEA), Cochair of MPEG HEVC verification (AHG5) group and a voting member of the British Standard Institution (BSI). In addition, he holds key roles in the Video Quality Expert Group (VQEG) such as Co-chair of the Ultra High Definition (UltraHD) group; Co-chair of the Visually Lossless Quality Analysis (VLQA) group; and Co-chair of the Psycho-Physiological Quality Assessment (PsyPhyQA). He has been a lead researcher in various nationally or EU-sponsored multimillion-funded international research projects. His research interests are cross-disciplinary and industry-focused and include video processing, analysis and communication, video quality evaluation, Brain-inspired multimodal cognitive technology, Big Data analytics, Affective computing, IoT/smart environments, natural multimodal human–computer interaction, eHealth/connected Health. He has a global collaborative research network spanning both academia and key industrial players. He has been the Lead supervisor/supervisor for about 30 postdoctoral research fellows and PhD research students. He has published over 250 articles in peer-reviewed journals, conferences, and book chapters including standardized contributions. His paper was awarded Best Paper Award 2016 of the IEEE Transaction on Circuit and System for Video Technology and three conference papers were selected for Best Student Paper awards in 2015/2016. He was awarded the Scottish Knowledge Exchange Champion award in 2023 and 2020 and only academics in Scotland got this award twice. He received STARS (Staff Appreciation and Recognition Scheme) award in 2014 and 2016 for "Outstanding Research and Knowledge Exchange" (University of the West of Scotland) and was awarded the Contribution Reward in 2009 and 2011 for outstanding research and teaching activities (Queen Mary University of London). He has chaired/cochaired/organized more than 25 workshops, special sessions, and tracks at International conferences.

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Preface

In recent years, there has been a significant surge in the utilization of the Internet of Things (IoT) and wireless sensors to meet escalating demands for high data rates, low latency, and ultrareliable communication in 5G/6G systems. Various strategies are under development utilizing intelligent sensing platforms to address these growing needs. Using multiple sensors has proven to be an effective approach to enhance reliability, efficiency, and user experience in diverse application scenarios across healthcare, transportation, environmental monitoring, industrial automation, and entertainment industries.

Incorporating data from multiple modalities such as visual images, radiation levels, texture details, and behavioral patterns captured by sensors like light, temperature, humidity, vision, and motion enhances the information assimilation process, leading to precise decision-making. While offering immense benefits, multi-modal sensing presents significant challenges such as energy efficiency, mobility, reliability, interference mitigation, reliability, security, and real-time processing requirements.

In an interconnected world, seamless integration of IoT with intelligent sensing platforms is essential to deliver transformative solutions. The customization and diversification of intelligent sensors require efficient techniques for designing and integrating sensors, as well as extracting valuable insights from vast amounts of multimodal data. This involves leveraging advanced sensor design, robust big data analytics, and stringent security measures to promote sustainability, spur innovation, and explore new possibilities.

To date, there is a lack of comprehensive literature that addresses design, implementation, and analytical techniques for multimodal intelligent sensing. A dedicated book focusing on these crucial aspects will not only bridge this gap but also educate readers on the key aspects of efficient sensor networks, laying the groundwork for future advancements in a smart and interconnected world. This book is a structured effort in this direction that explores the cutting-edge advancements and challenges in the realm of multimodal sensing, discussing both software and

hardware solutions. It covers a broad spectrum of topics in multimodal intelligent sensing for a range of applications, bringing together experts from various disciplines including wireless communications, signal processing, and sensor design.

Key topics discussed include sensor design, deployment efficiency, energy management, data fusion, and information extraction through machine learning, deep learning, and federated learning to showcase the latest developments in this dynamic field. By considering challenges and future prospects, the book caters to a diverse readership within the scientific community.

Chapter 1 delves into the realm of multimodal intelligent sensing, uncovering the various sensor types and the integration of multiple sensors for enhanced capabilities. The chapter also explores the applications of multimodal sensing in different sectors and the challenges and opportunities that come with this dynamic field.

Chapter 2 focuses on antennas for wireless sensors, emphasizing their crucial role as the sensory gateway for wireless networks. Readers will gain insights into fundamental antenna parameters, fabrication methods, and the different types of antennas utilized in sensing networks.

Chapter 3 discusses the sensor design for environmental monitoring, shedding light on combating deforestation through wireless sensor networks and the design considerations involved in creating effective systems for environmental conservation.

Chapter 4 explores the applicability of wireless sensors for multimodal health monitoring, detailing the use of wearable and implantable sensors, multimodal healthcare sensing devices, and the use of AI methods in healthcare systems for enhanced monitoring and diagnosis.

Chapter 5 shifts gears to sensor design for industrial automation, highlighting the role of multimodal sensing in revolutionizing industrial processes. From RF sensors to vision sensors, this chapter explores the design considerations and challenges faced in implementing multimodal sensing in industrial settings.

Chapters 6 and 7 probe hybrid neuromorphic federated learning for activity recognition and multimodal beam prediction in drone communication networks, respectively, showcasing the integration of cutting-edge technologies to enhance sensing capabilities in diverse applications.

Chapter 8 studies the domain of mind-wandering through multiple wearable sensors with the aim of detecting mind-wandering episodes through deep learning and paving ways to improve the detection of students' learning and concentration levels.

Chapters 9 and 10 investigate the advancements in remote infant monitoring systems and telehealth patient monitoring, emphasizing the design of multimodal wearable systems and secure telehealth systems for improved patient care and monitoring.

Chapter 11 explores the ethical considerations involved in the development of multimodal intelligent tutoring systems, respectively, highlighting the balance between innovation and ethical responsibility in the deployment of such systems.

Lastly, Chapter 12 paves the way for the future of multimodal intelligent sensing in the deep learning era, outlining the challenges, perspectives, and ethical considerations that will shape the evolution of sensor technology in the years to come.

This book serves as a comprehensive guide for researchers, engineers, and professionals interested in the advancements and applications of multimodal intelligent sensing systems. Each chapter offers insights, practical considerations, and future directions to inspire further innovation and exploration in this vibrant field.

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Advances in Multi-modal Intelligent Sensing

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Intelligent sensing systems play a crucial role in various fields, enabling the acquisition of valuable data for analysis, monitoring, and decision-making processes. Multi-modal intelligent sensing, with its capability to gather information from multiple sensor types and sensing parameters, has emerged as a powerful tool in diverse applications. This chapter aims to provide a comprehensive overview of multi-modal intelligent sensing, offering insights into the diverse sensor types, sensing parameters, application scenarios, and data analysis tools associated with this rapidly evolving field.

1.1 Multi-modal Intelligent Sensing

Multi-modal intelligent sensing refers to the use of multiple sensor types, such as optical, acoustic, thermal, and chemical sensors, to capture and analyze different aspects of the environment or a system. By combining data from various sensors, multi-modal sensing systems can provide a more comprehensive and holistic view of the monitored phenomenon, leading to better insights and decision-making [1].

A simple example is a system designed to monitor a remote environment, such as a home or office, with a view to enhancing security. Such a system might use a variety of sensing devices including visible light cameras, LiDAR, infra-red motion detectors, and contact microphones, each capturing unique types of data as shown in Figure 1.1. The behavior of this environment could be quite complex,

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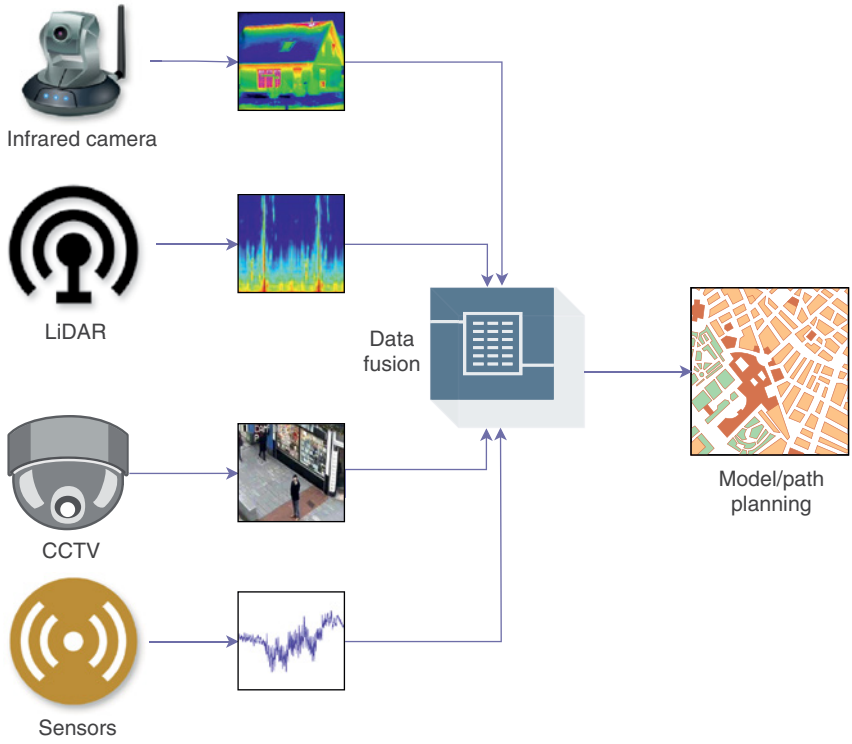

Figure 1.1 Multi-modal intelligent sensing.

for example, the sound of a door opening followed by an increase in infra-red activity and ending with the turning off of a light, could be automatically interpreted as a sequence involving an entry into the environment by an unwanted visitor (door opening), followed by movement to a specific location (increase in infra-red activity), and culminating in an attempt to allay suspicion by simulating the turning off of a light. The analysis of this complex behavior would be greatly enhanced if the system could automatically determine spatio-temporal relationships between events and classify these events into a taxonomy based on their threat to security. This could be achieved by using the information provided by the various sensing devices, organizing this information into one unified data structure through data fusion, with each type of data being a mode, and building a symbolic or semantic model of the observed events through automatic learning and reasoning using methods from artificial intelligence. The intelligent agent, influenced by this understanding, then executes actions or generates outputs accordingly [2].

The components and functionalities of this simple example can be tailored to various applications by selecting appropriate sensors, data fusion methods, and