Faculty of Engineering
Current and Future Research

GIU Berlin is an integrated and diverse environment for research and teaching and aims to develop research excellence in three strategic priorities: 1) Intelligent solutions, 2) Sustainability, and 3) Resilience. Engineering faculty and graduate students engage in conducting interdisciplinary, creative, and impactful research aiming to contribute to these overarching objectives of the University's research mission by focusing on the major areas of data and computing science, media engineering and technology, information engineering and technology, electronics, and mechatronics engineering. At the Faculty of Engineering, theoretical and applied research is conducted in two main research groups, Data Science & AI and Smart Systems, across three engineering disciplines (MET, IET, and MECH) by developing methods and solutions with applications ranging from biomedical engineering to remote sensing; IoT systems and edge computing to smart sensors, smart systems, and smart cities; distributed networks to autonomous mobile robots (Figure 1).

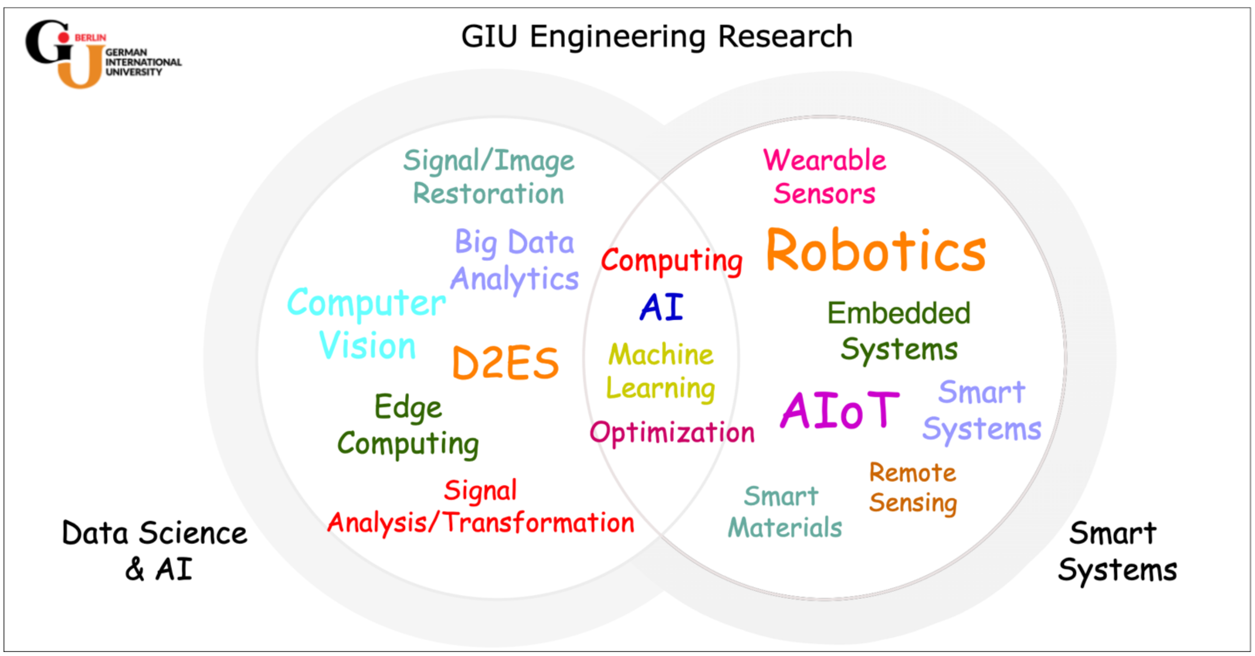

Figure 1. GIU-Berlin Faculty of Engineering Research

Data Science and AI research comprises all stages from data acquisition and data management to machine learning and data analysis algorithm development to data analytics and data-driven applications. In the era of digitalization and big data, this research is fundamental for developing data-driven methods and efficient and innovative solutions to problems across all engineering disciplines. One important focus area is the development of efficient machine learning and deep learning technologies for real-world signal processing in embedded systems. Further application areas include patient-specific diagnostics in healthcare, predictive maintenance and structural health monitoring, remote sensing, smart cities, autonomous robots with enhanced control and adaptability, smart grids, autonomous driving, smart materials, artificial intelligence of things, and computer vision applications. Developed tools and technologies based on data science and AI in these fields enhance the efficient use of resources, optimal running of processes, better prediction of adverse events, and adaptability to changes which are critical in improving sustainability and resilience of systems.

The Smart Systems group combines theoretical, software, and hardware expertise in the research fields of data science and machine learning, computer vision, embedded systems, and mechatronics to design autonomous systems that can learn and adapt from data. These intelligent systems are transforming many areas such as healthcare, manufacturing, smart cities, transportation and logistics, energy, education, finance, agriculture, and the environment. Research focus areas include developing smart autonomous systems to be secured and distributed on complex hardware IoT infrastructures for managing big data with real-time and limited energy constraints, personalized and advanced warning systems for healthcare, remote active fire detection and flood detection systems, intelligent transportation systems, autonomous mobile robots, and controlled environment agriculture.

The current and future research agenda in the Faculty of Engineering under the Data Science & AI and Smart Systems research groups can be discussed in detail under the following main branches: the development of discrete event systems, data science and intelligent systems, communication networks, the internet of things and edge computing, autonomous mobile robots, and smart materials. The research undertaken by both research groups is pivotal to the university's research strategy and directly contributes to its research objectives.

CURRENT AND FUTURE RESEARCH IN THE DEVELOPMENT OF DISCRETE EVENT SYSTEMS

The research of the D2ES, *Development of Discrete Event Systems*, focuses on developing smart autonomous systems to be secured and distributed on complex hardware IoT infrastructures for managing big data with real-time and limited energy constraints. It addresses two main areas: Artificial Intelligence and Cybersecurity of D2ES. AI is applied to improve the system's quality of services as well as to improve performance of different development solutions and techniques of hardware, software components and network traffics in complex infrastructures. The interdisciplinary approach of the D2ES research group also integrates the latest developments in fields such as business intelligence, e-health, smart design, etc. The second research area is the cybersecurity of D2ES where we are interested in finding advanced solutions to secure complex hardware, software and big data systems in local computers, the communication network and on cloud architectures. The different research areas are applied to various types of smart applications such as: Smart agriculture, smart factories, smart transportation systems, smart tourism, smart e-health, smart grids, smart cities, smart devices, ..etc (Figure 2. Research Strategy and Prospects of the D2ES research group).

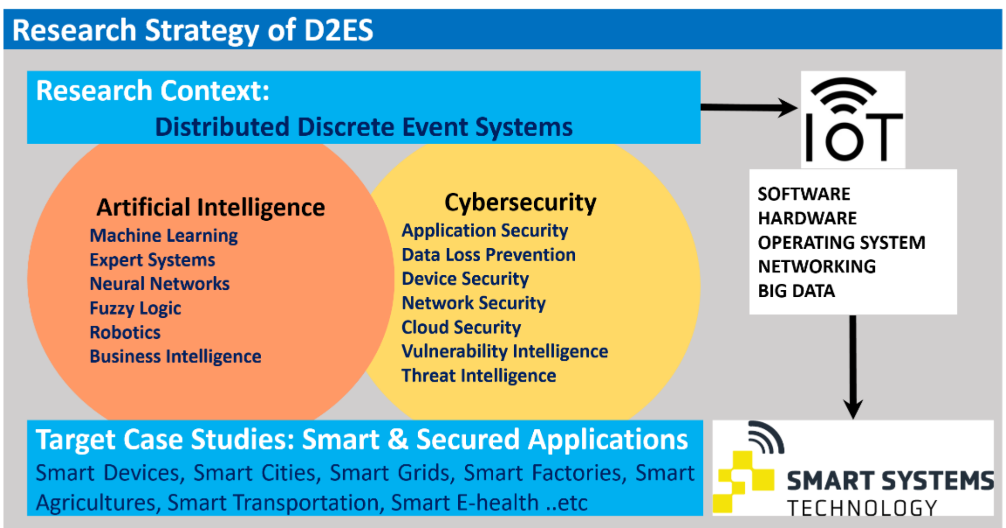

Figure 2. Research Strategy and Prospects of the D2ES research group

The research activities at D2ES are classified into three levels: activities on the functional development level, operational (execution) level, and advanced level (AI, Big Data, and Security) (Figure 3. Development steps of Distributed Discrete Event Systems).

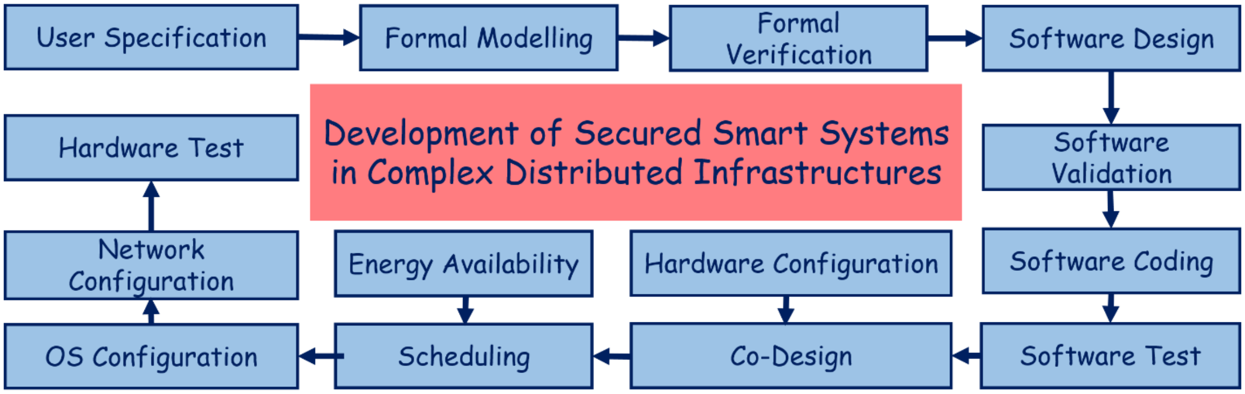

Figure 3. Development steps of Distributed Discrete Event Systems D2ES

- *D2ES Research on Functional Level*: The development of these smart systems starts from the initial user specification, to the formal modeling with Petri Nets, Timed Automata and other formalisms. We are interested in particular in proposing new advanced solutions for formal verification of complex hierarchical and stochastic models of these systems.
- *D2ES Research on Operational Level*: D2ES is interested in new solutions for the design and validation of complex software as well as their efficient coding. On one hand, D2ES is also interested in optimizing the test of complex smart software that we assume reconfigurable at run-time, in addition to be interested in the co-design of hardware and software parts, i.e., the deployment of complex software in networked hardware devices. On the other hand, D2ES is interested in the scheduling of threads as well as the exchanged messages on the communication network that links the system devices under real-time and energy constraints. The OS configuration for managing complex software and the network configuration are also considered in the research activities of D2ES. Finally, the hardware test of complex distributed smart systems by following the JTAG technology is also included in our research activities where we are working to improve the test exhaustively.
- *Advanced D2ES Research*: We aim in our research group D2ES to improve the performance of smart systems by using advanced techniques of machine, deep or reinforcement learning for autonomously improving the quality of service as well as the temporal behavior and the energy availability and consumption. We are also interested in proposing new advanced solution for big data management as well as working on securing the system in devices as well as in the communication network.
- *D2ES Application Areas*: These different contributions are applied to different case studies of applications with different constraints in the areas of smart grids, smart cities, smart buildings, smart manufacturing, smart health, smart transportation systems, smart agriculture, smart devices, business intelligence etc.

The research group D2ES is intensively publishing these different solutions in prestigious international journals and conferences as well as in patents:

- https://scholar.google.com/citations?user=KMWEF3cAAAAJ&hl=fr

- https://dblp.org/pid/41/586.html
- https://patents.google.com/?inventor=khalgui&oq=khalgui
- https://www.researchgate.net/profile/Mohamed-Khalgui
- https://www.linkedin.com/in/mohamed-khalgui-298aa48/

CURRENT AND FUTURE RESEARCH IN THE DATA SCIENCE AND INTELLIGENT SYSTEMS

Data science and intelligent systems research comprises innovative and cutting-edge research in machine learning theory, deep learning, computer vision, pattern recognition, and signal processing with applications to a wide range of information technology processes and systems. Current and future research prospects include devising new core machine learning paradigms and applications to develop intelligent and autonomous system solutions processing biomedical, remote sensing, and electrical data from sensors. Recent application domains include real-world problems such as near real-time analysis of remote sensing imagery, personalized and advanced warning systems for healthcare, patient-specific biomedical signal processing and analysis, biomedical and audio signal restoration, and early fault diagnosis and domain adaptation for predictive maintenance.

Examples of recent and/or ongoing research include:

- T Ince, S Beninati, O Devecioglu, S Frasier, M Gabbouj (2024). Water Region Segmentation in SAR Images Based on Compact Operational UNets. IGARSS 2024 Proceedings, 9295-9299.
- Blind Restoration of Real-World Audio by 1D Progressive Operational GANs (T Ince, O Devecioglu, S Kiranyaz, and M Gabbouj), arXiv preprint arXiv:2212.14618, 2022.
- S Kiranyaz, J Malik, M Yamac, M Duman, I Adalioglu, E Guldogan, T Ince, M Gabbouj (2023). Super Neurons. IEEE Transactions on Emerging Topics in Computational Intelligence. doi:10.1109/TETCI.2023.3314658.
- Robust Peak Detection for Holter ECGs by Self-Organized Operational Neural Networks (M Gabbouj, S Kiranyaz, T Ince, J Malik, MU Zahid, M Chowdhury, A Khandakar, A Tahir), IEEE Transactions on Neural Networks and Learning Systems, TNNLS-2021-P-16170, doi: 10.1109/TNNLS.2022.3158867, 2022.
- Self-organized Operational Neural Networks with Generative Neurons (S Kiranyaz, J Malik, HB Abdallah, T Ince, A Iosifidis, M Gabbouj), Neural Networks, 140:294-308, doi: 10.1016/j.neunet.2021.02.028, 2021.
- Operational Neural Networks (S Kiranyaz, T Ince, A Iosifidis, M Gabbouj), Neural Computing and Applications, 32, 6645–6668, 2020.
- Personalized Monitoring and Advance Warning System for Cardiac Arrhythmias (S Kiranyaz, T Ince, M Gabbouj), Scientific Reports - Nature, 7, doi: 10.1038/s41598-017-09544-z, 2017.
- Real-Time Motor Fault Detection by 1D Convolutional Neural Networks (T Ince, S Kiranyaz, L Eren, M Askar, M Gabbouj), IEEE Transactions on Industrial Electronics, 63(11), 7067 – 7075, 2016.

- A Generic and Robust System for Automated Patient-specific Classification of Electrocardiogram Signals (T Ince, S Kiranyaz, M Gabbouj), IEEE Transactions on Biomedical Engineering 56(5), 1415-1426, 2009.
- Method and apparatus for performing motor-fault detection via convolutional neural networks, US Patent 10,586,153, June 2016.
- Personalized ECG monitoring for early detection of cardiac abnormalities, US Patent 10,856,763, March 2017.
- Operational Neural Networks and Self-Organized Operational Neural Networks with Generative Neurons, U.S. Patent App. No: 17/566,281, Dec. 2021.
- Generalized Operational Perceptrons: New Generation Artificial Neural Networks, US Patent 12,033,071, 2024.

CURRENT AND FUTURE RESEARCH IN COMMUNICATION NETWORKS

The Communication Networks research focuses on resource allocation and optimization in distributed networks. It combines optimization theory, analytical and numerical telecommunication network performance evaluation methods, machine learning, and a comprehensive understanding of state-of-the-art network capabilities and resources. While the primary focus is on wireless distributed networks, the research also extends to resource allocation in cloud computing and edge networks, with applications in smart electrical networks as well. The goal is to develop techniques, algorithms, and approaches that can be integrated into distributed devices. Additionally, the research aims to provide network planning and management tools to enhance performance while minimizing costs and resource usage.

Example publications related to this research are listed below:

- Yves Lemieux, Mohamed Ashour Tallal Elshabrawy, “Quality of service (QoS) mechanism in an internet protocol (IP) network”, United States Patent No: US 6,968,374 B2, Issued: November 22, 2005
- S. M. Azzam, T. Elshabrawy and M. Ashour, "A Bi-Level Framework for Supply and Demand Side Energy Management in an Islanded Microgrid," in IEEE Transactions on Industrial Informatics, vol. 19, no. 1, pp. 220-231, Jan. 2023
- M. Zamzam, T. Elshabrawy and M. Ashour, "A Minimized Latency Collaborative Computation Offloading Game Under Mobile Edge Computing for Indoor Localization," in IEEE Access, vol. 9, pp. 133861-133874, 2021
- P. Edward, M. El-Aasser, M. Ashour, and T. Elshabrawy, "Interleaved Chirp Spreading LoRa as a Parallel Network to Enhance LoRa Capacity," in IEEE Internet of Things Journal, vol. 8, no. 5, pp. 3864-3874, 1 March1, 2021
- T Elshabrawy, E Shereen, M Ashour, J Robert, "Report success probability/battery liftime analysis of dense IEEE 802.15. 4-based metering networks with hidden nodes", IEEE Sensors Journal 17 (7), 2017 2259-2266
- Tallal Elshabrawy, Ezzeldin Shereen, and Mohamed Ashour, “Throughput Evaluation of Dynamic Frame Slotted ALOHA for Spatially Distributed RFID Tags,” IEEE VTC-Fall 2016, Sept 2016,

- Mohamed Ashour, Sherry Micheal, Ahmed Khaled, Tallal Elshabrawy, Hany Hammad, "Preprocessing Dependent Image Theory Based Ray Tracing Algorithm for Indoor Coverage Solution", IEEE WCNC 2014, Apr. 2014
- Ramy Atawia, Mohamed Ashour, Tallal El Shabrawy, Hany Hammad, "Indoor Distributed Antenna System Planning with Optimized Antenna Power Using Genetic Algorithm", Proceedings of the IEEE 78th Vehicular Technology Conference (VTC Fall), Oct 2013
- Mohamed Esam, Mohamed Ashour, "Cooperative Game Strategy for IEEE 802.11s Mesh WLAN Power Management," Communications (ICC), 2011 IEEE International Conference on , vol., no., pp.1,5, 5-9 June 2011
- Mohamed Ashour, Tho Le-Ngoc, "End-to-end delay margin balancing approach for routing in multi-class networks" ACM Wireless Networks, 2007 Vol 13 issue 3 pp. 311-322
- Nicolae Iuoras, Tho Le-Ngoc, Mohamed Ashour, Tallal Elshabrawy, "An IP-Based Satellite Communication System Architecture For Interactive Multimedia Services", International Journal of Satellite Communications (Special Issue on QoS for Satellite IP), Vol 21, Issue 4-5 , Pages 401 – 426

Current and Future Research in IoT Systems and Edge Computing

Our journey in IoT is characterized by the establishment of state-of-the-art laboratories, critical advancements in hardware security, and the development of smart systems that promise a future where interconnectedness is not just an idea, but a reality. As a team, we have led transformative projects in AI and machine learning while fostering a new wave of technological trailblazers. Below, we outline our core research interests, seminal projects, and our vision for the path ahead:

- IoT System Prototyping & Co-Design: Focusing on creating prototypes that reflect the coalescence of design and functionality, we are at the helm of initiatives that push the boundaries of what connected devices can achieve.
- Secure IoT Frameworks: Our efforts in constructing secure and resilient frameworks are crucial to ensuring the privacy and safety of IoT ecosystems.
- AI-Driven IoT: We explore the synergy between AI and IoT, particularly in automating and enhancing the intelligence of systems for everyday applications.
- Embedded Computing: Innovations in near-memory architecture are a testament to our commitment to creating efficient computing paradigms that cater to the burgeoning data needs of modern systems.
- Sustainable IoT Design: In the pursuit of sustainability, we advocate for low-power, high-efficiency IoT systems that address the pressing concerns of energy conservation.

In the past years we led such transformative projects in AI and machine learning while fostering a new wave of technological trailblazers. Below, we outline our core research interests:

- **IoT System Prototyping & Co-Design**: Focusing on creating prototypes that reflect the coalescence of design and functionality, I am at the helm of initiatives that push the boundaries of what connected devices can achieve.
- **Secure IoT Frameworks:** efforts in constructing secure and resilient frameworks are crucial to ensuring the privacy and safety of IoT ecosystems.
- AI-Driven IoT: we explore the synergy between AI and IoT, particularly in automating and enhancing the intelligence of systems for everyday applications.
- **Embedded Computing**: Innovations in near-memory architecture are a testament to my commitment to creating efficient computing paradigms that cater to the burgeoning data needs of modern systems.
- **Sustainable IoT Design**: In the pursuit of sustainability, we advocate for low-power, high-efficiency IoT systems that address the pressing concerns of energy conservation.

Highlighted Projects:

- Physical Layer Security of IOT Devices using Power Analysis: In this work, we propose a low-power security solution that deters impersonation attacks against iot nodes. We suggest using power consumption-based PUF as a Fingerprint to distinguish a rogue node from an original one. Our presented idea entails using a small low power circuit for Side-Channel Power Analysis. This acts as a genuine identifier of different end device under test at both hardware and software levels. Our design will include the channel model of the transceiver as well. We consider embedding our Fingerprint within the data packets sent by the transmitter. The receiver will extract the output, i.e., the Fingerprint, and use it to verify the transmitter's identity. It can authenticate both the transmitter's position and power settings without overwhelming its limited energy. We have published a Paper using this technique [C1], and it was awarded as the best paper in the ICM'19 Conference. We are working further, and used different regression and machine learning methods to extract more information and we are publishing a journal paper soon.

- Near Memory Computing Techniques: Systems are being impacted by the data explosion. We confront a dilemma in transporting data back and forth from SSDs to CPUs when the amount of data in our world grows from tens of terabytes to hundreds of terabytes inside a server. It'll be an energy issue, and there will be various system bottlenecks. In conventional processors, Data from DRAM memory must be transferred to the CPU before any processing can be performed. This data movement is expensive because it has a long latency and uses a lot of energy to send the data across the pin-limited memory channel. As a new paradigm in computer architecture, many people are researching adding logic layers within DRAM to perform a near memory computing techniques. This was possible due to the high internal band-width available within 3D-stacked DRAM (which is much greater than the bandwidth available in the narrow memory channel between DRAM and the CPU). As a result,

NMC topologies can free up critical bandwidth on the bandwidth-constrained memory channel while lowering system energy usage. Last year, we have started to explore such topic and initiated two projects related to it namely:
  - Homomorphic Encryption using NMC
  - Compressed Sensing for retrospective Computing
- Design and Implementation of hardware Internet of Things (IoT) Adaptive Security Supporting System. In this project we are proposing the design and implement “A new hardware based security ASIP (Application Specific instruction processor) that can be integrated in different internet of things (IoT) systems supporting different levels of security and is transparent to different communication platforms including ZigBee, BLE and LTE systems”. This platform should have the following features:
  - The hardware security module will be designed, implemented and integrated with each node to secure the data before sending it from the devices.
  - Different security levels (light, medium and high) will be provided according to the priority level of the device and its power abilities. Considering the security level, the complexity of security technique will be estimated and implemented between the devices, local server and cloud server.
  - Different security aspects will be taken care of, this includes secure booting, Key management, Trust setup, Cryptography, Authentication, and key distribution mechanisms.
  - On the other hand, a security API will be explored and implemented into the local server/cloud.

To achieve the above goals, we started by exploring the key management and the secure booting low power mechanisms and design new techniques to be implemented on our propose chip. The new key management protocol was accepted as a paper [C6] in a recent conference. Also, the project was accepted by Itida for an initial funded ARP where our finding were published at [J3]. We are working on a more extended version of this proposal to apply to the NTRA fund proposal shortly.

- Trust Management for Advanced Metering Infrastructure: Integrity and Misbehaviour can pose more sensitive threats in an IoT environment. Receiving or transmitting false data can result in numerous problems to the network. This can be done by node compromise attack with the intent of committing fraud, tampering, or erasing storage. The conventional approach to ensuring integrity of a message requires the message signature by its creator. By verifying the digital signature on the message, the receiver can be assured of its integrity. However, this procedure is computationally expensive. Numerous techniques based on public-key encryption, as well as physically unclonable functions (PUF) were proposed to get over this problem. We are exploring this problem with the help of Parallel and Distributed Systems at the University of Stuttgart, we are proposing the use of PUF techniques to investigate and model different approaches that will enable proper data integrity and for the transmitted data that adheres to the low bandwidth and power requirements of adhoc networks.

- Privacy and Anonymization Techniques: Lately, I have been interested as well on privacy issues in IOT. we are working on a new decentralized access control scheme for secure distributed data storage supports anonymous authentication. The whole technique will be based on distributed Attribute-Based Encryption (ABE) and its interaction with the cloud. The Cloud includes a key distribution center (KDC) that authenticates different users and distributes keys with different authorization levels. Attribute Based Encryption (ABE), as a solution to these threats. It supports restricted secret keys that enable a key holder to learn a specific function of encrypted data, but learn nothing else about the whole data. ABE generates keys based on a set of attributes. During decryption the set of attributes must match cipher text attributes in order to retrieve the message correctly. In this thesis the Ciphertext Policy Attribute based encryption was implemented (CP-ABE). We have built a software model of this algorithm [C5]. We are conducting more research in this direction, and trying to integrate with a more experienced researches with a stronger mathematical back ground.
- IP watermarking techniques: High complexity and minimal chip area are two most important characteristics of today's VLSI (Very Large Scale Integration) systems. Short time to market and high complexity makes it mostly impossible to design modern systems from scratch. Reusable virtual components or Intellectual Property blocks (IPs) are most effective when it comes to reducing cost and development time. IP designs are considered essential in the new System-on-a-Chip (SOC) revelation, yet there are a lot of concerns related to sharing IP designs. On the developer side, sharing such IP could pose high security risk to the company investment. Although watermarking process is the only way to detect an IP after selling it, it is still looked at as a complementary process and it is still facing many challenges, some of which are:

Watermarking Automation: The users prefer to have a fully automated watermarking technique in order to minimize the effort and time to market needed by the watermarking process.

- Watermarking Industrial size designs: Most watermarking techniques work on small designs, watermarking a real industrial size design is a real challenge. Heading to multi-core System-On-a-Chip, where each core should be an IP, will leads to a real challenge for IP watermarking techniques.
- Watermark Extraction: Many people tend to propose IP watermarking proposals, yet visibility, as well as controllability problems puts a lot of constraints on the watermarking process, as we cannot detect it in many cases. Users of any watermarking tool needs an automated detection tool to extract their authentic watermark even from the manufactured design.
- I'm conduct further research concerning IP watermarking techniques. My main research goal is to contribute in Developing an Industrial Size Watermarking Framework. As I mentioned above, the main watermarking challenge is related to IP size that we can watermark. I believe developing a frame work that automatically define and watermark different designs is really essential. Different techniques and

tools can be used and integrated with each other, and then we can develop this frame work by changing tool modules.

Vision for the Future: we envisage an expanded role for IoT laboratories to become hubs of innovation and learning. Through these labs, we plan to extend our reach into new research dimensions such as:

- IoT Security Challenges: Advancing research in security protocols to tackle the increasing threats in a hyper-connected world.
- Power Profiling and Side-Channel Attacks: Utilizing my decade-long experience in digital design to address vulnerabilities at the hardware level.
- Low Power Wide Area Networks & Edge Computing: Building the infrastructure for next-generation IoT systems that optimize performance from chip to cloud.
- System-on-A-Chip Design and Verification: Integrating co-design strategies to streamline the development of complex, multi-core SoC designs.
- IoT Prototyping & Co-Design: Enhancing our prototyping capabilities to reflect the intricacies of IoT systems and their real-world applications, including intelligent transportation and health monitoring wearables.

Details about these works can be found in these publications:

[1].S. Hosny, M. W. El-Kharashi, A. T. Abdel-Hamid, Survey on compressed sensing over the past two decades, Memories-Materials, Devices, Circuits and Systems 4 (2023).

[2].MM Farag, M Fouad, AT Abdel-Hamid, “Automatic Severity Classification of Diabetic Retinopathy Based on DenseNet and Convolutional Block Attention Module” IEEE Access, 2022, 38299-38308.

[3].YM Amin, AT Abdel-Hamid, “A Simulation Model of IEEE 802.15. 4 GTS Mechanism and GTS Attacks in OMNeT++/MiXiM+ NETA”, Comput. Inf. Sci. 11 (1), 78-89.

[4].Nahla Taha, AT Abdel-Hamid and Bassem Abdullah, “Detection of Multiple Sclerosis Using Convolutional Neural Network: A Comparative Study”, 2023 10th International Conference on Soft Computing & Machine Intelligence (ISCMI 2023).

[5].MA Fouad, AT Abdel-Hamid, “On detecting IOT power signature anomalies using hidden Markov model (HMM)” 2019 31st International Conference on Microelectronics (ICM), 108-112 (Best Paper Award)

[6].O. Mahmoud, H. Kopp, A. T. Abdelhamid and F. Kargl, "Applications of Smart-Contracts: Anonymous Decentralized Insurances with IoT Sensors," 2018 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData), 2018, pp. 1507-1512

CURRENT AND FUTURE RESEARCH IN MECHATRONICS

One of the main focal points in the mechatronics research has been the development and evaluation of advanced control and estimation methods for *autonomous mobile robots*. This includes the development of quantized and deep neural network-supported path-following control algorithms, tailored for implementation on microcontrollers. This involves optimizing the performance of path-following robots using deep learning models while considering the hardware constraints of microcontrollers. Recent work introduced a novel concept called path primitives, aiming to reduce the computational requirements of optimization-based control algorithms.

- J. Pohlodek, B. Morabito, C. Schlauch, P. Zometa, and R. Findeisen. Flexible development and evaluation of machine-learning-supported optimal control and estimation methods via HILO-MPC, pages 1-25, International Journal of Robust and Nonlinear Control, 2024
- P. Zometa and T. Faulwasser. Towards predictive path-following control using deep neural networks and path primitives. In 2024 European Control Conference (ECC), pages 1–6, 2024
- P. Zometa and T. Faulwasser. Quantized deep path-following control on a microcontroller. In 2023 European Control Conference (ECC), pages 1–6, 2023

Recent research on controlled environment agriculture (CEA) has involved the development of optimal control techniques tailored for greenhouses, using low-cost hardware:

- K. K. Sathyanarayanan, P. Sauerteig, P. Zometa, and S. Streif. Quantized deep neural network based optimal control of greenhouses on a microcontroller. In 2024 European Control Conference (ECC), pages 1–6, 2024

The strategic concept for both areas of research has revolved around the integration of advanced machine learning techniques with optimal control methods to address real-world challenges. In autonomous mobile robots, the strategy focused on enhancing motion control performance and computational efficiency. The implementation of microcontrollers ensured that the solutions remain practical and feasible for real-world applications.

In the realm of controlled environment agriculture, the strategic emphasis has been on sustainability. The research aims to develop control methods that not only optimize crop growth but also minimize resource usage. The development of accurate growth models through sparse system identification further strengthens this practicality of the approach, ensuring that the control strategies are derived from limited real-world data.

Looking forward, current research aims to fuse these two domains: autonomous mobile robots and controlled environment agriculture. The goal is to develop autonomous mobile systems that help optimize agricultural environments. These systems might rely on advanced machine learning techniques for optimized control and estimation, focusing on precision agriculture, resource optimization, and sustainable farming practices. The integration of mobile robots within controlled agricultural environments presents a promising pathway to not only enhance agricultural productivity but also promote sustainable practices.

Another major research area under mechatronics is concentrated on smart materials and structures through collaborations with international colleagues at the University of British Columbia, Canada, Laboratoire Brestois de Mécanique et des Systèmes, France, International Research Center for Mathematics & Mechanics of Complex Systems, Italy, Isfahan University of Technology, Iran, University of Toledo, USA, University of Calabria, Italy, and Warsaw University of Technology, Poland. This includes modeling, production, characterization, and application of thermal and ferromagnetic shape memory alloys (SMAs), which are classes of smart materials with the capability of remembering their original configuration by recovering large inelastic deformations upon heating or magnetization. This key property, together with other resultant behaviors, make SMAs suitable candidates for smart sensors and actuators in active control of various mechatronic systems. Details about these works can be found in these publications:

- Kadkhodaei, M., Rajapakse, R. K. N. D., Mahzoon, M., and Salimi, M., "Modeling of the cyclic thermomechanical response of SMA wires at different strain rates", Smart Materials and Structures, Vol. 16, No. 6, pp. 2091-2101, 2007
- Rezaei D.A., H., Kadkhodaei, M., and Nahvi, H., "Analysis of Nonlinear Free Vibration and Damping of a Clamped-Clamped Beam with Embedded Pre-Strained SMA Wires", Journal of Intelligent Material Systems and Structures, Vol. 23, No. 10, pp. 1107-1117, 2012
- Amrollahipour, R., Kadkhodaei, M., and Kameli, P., "Behaviors of ferromagnetic shape memory alloy Ni-Mn-Ga under incomplete magneto-mechanical loading-unloading cycles", Advanced Engineering Materials, Vol. 16, No. 11, 1362-1369, 2014
- Alipour, A., Kadkhodaei, M., and Ghaei, A., "Finite Element Simulation of SMA Wires Using a UMAT: Parametric Study on Heating Rate, Conductivity and Heat Convection", Journal of Intelligent Material Systems and Structures, Vol. 26, No. 5, pp. 554-572, 2015
- Shirani, M., and Kadkhodaei, M., "One dimensional constitutive model with transformation surfaces for phase transition in shape memory alloys considering the effect of loading history", International Journal of Solids and Structures, Vol. 81, pp. 117-129, 2016
- Jafarzadeh, S., Shirani, M., Kadkhodaei, M., and Gheibgholami, E. "Phenomenological constitutive modeling of ferromagnetic shape memory alloys considering the effects of loading history on reorientation start conditions", Continuum Mechanics and Thermodynamics, Vol. 31, pp. 1065-1085, 2019
- Book Chapter: Karamooz-Ravari, M. R., Kadkhodaei, M., and Elahinia, M., "Microplane Modeling for Inelastic Responses of Shape Memory Alloys" in "Dynamics, Strength of Materials and Durability in Multiscale Mechanics", Springer, pp. 303-328, 2021
- Falahian, A., Asadi, P., Tajmir Riahi, H., and Kadkhodaei, M., "An experimental study on a self-centering damper based on shape-memory alloy wires", Mechanics Based Design of Structures and Machines, Vol. 51, No. 7, pp. 3779-3802, 2023

Additionally, the group investigated various kinds of static and dynamic electro-thermo-mechanical loadings and the corresponding responses for different configurations of SMA components to be utilized in innovative, smart systems. Shape setting techniques have been developed to produce shape memory alloys in any desired forms with predefined characteristics:

- Heidari, M., Kadkhodaei, M., Barati, M. and F Karimzadeh, F., "Fabrication and modeling of shape memory alloy springs", Smart Materials and Structures, Vol. 25, No. 12, pp. 125003, 2016
- Alipour, A., Kadkhodaei, M., and Safaei, M., "Design, analysis and manufacture of a tension-compression self-centering damper based on energy dissipation of pre-stretched

superelastic shape memory alloy wires", Journal of Intelligent Material Systems and Structures, Vol. 28, No.15, pp. 2129-2139, 2017
- Shayanfard, P., Kadkhodaei, M., and Jalalpour, A., "Numerical and Experimental Investigation on Electro-Thermo-Mechanical Behavior of NiTi Shape Memory Alloy Wires", Iranian Journal of Science and Technology, Transactions of Mechanical Engineering, Vol. 43 (Suppl 1), pp. S621-S629, 2019
- Jahanbazi Asl, F., Kadkhodaei, M., and Karimzadeh, F., "The effects of shape-setting on transformation temperatures of pseudoelastic shape memory alloy springs", Journal of Science: Advanced Materials and Devices, Vol. 4, No., 4, pp. 568-576, 2019
- Mohammad Hashemi, Y, Kadkhodaei, M., and Salehan, M., "Fully coupled thermomechanical modeling of shape memory alloys under multiaxial loadings and implementation by finite element method", Continuum Mechanics and Thermodynamics, Vol 31, No. 6, pp. 1683-1698, 2019
- Sattari, M., Kadkhodaei, M., Akbarzadeh, S., Gholami, R., and Beheshti, A., "Wear in superelastic shape memory alloys: A thermomechanical analysis", Wear, Vol. 488-489, p. 204139, 2022

Current research focus is on energy harvesting using SMA elements of different geometries.

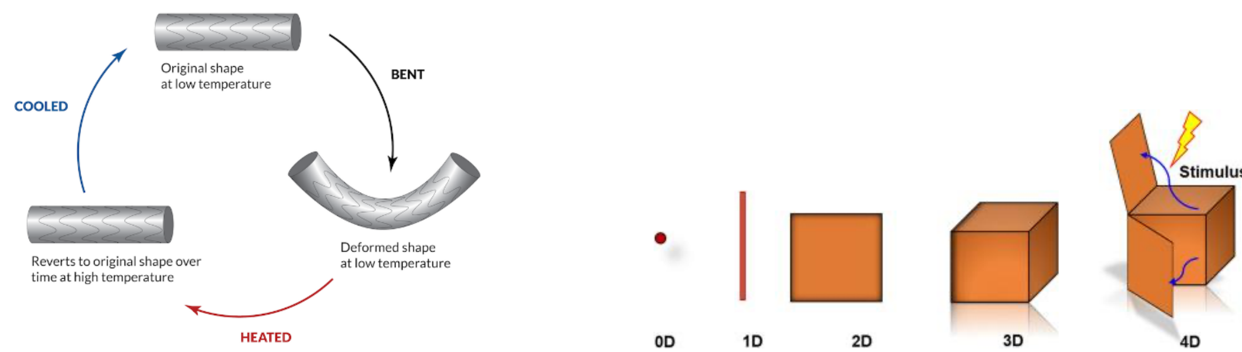

Figure 4. Shape setting techniques to produce shape memory alloys in any desired forms

3D printing techniques, as well 4D printing approaches in additive manufacturing of parts with time-varying configurations, have found widespread applications in various industrial, medical, civil, and art areas. The works on 3D/4D printing have been related to modeling and finite element simulation of additively manufactured parts made of polymers or SMAs, as well as 4D printing of polymeric and metallic shape-memory materials, to produce smart parts with customized characteristics and to predict the mechanical behavior of the products in response to different stimuli. Typical works include:

- Karamooz, M.R., Kadkhodaei, M., and Badrossamay, M., and Rezaei, R., "Numerical Investigation on mechanical properties of cellular lattice structures fabricated by fused deposition modeling", International Journal of Mechanical Sciences, Vol. 88, pp. 154-161, 2014
- Taheri Andani, M., Haberland, CH., Walker, J. M., Karamooz, M. R., Sadi Turabi, A., Saedi, S., Rahmanian, R., Karaca, H., Dean, D., Kadkhodaei, M., and Elahinia, M., "Achieving biocompatible stiffness in NiTi through additive manufacturing", Journal of Intelligent Material Systems and Structures, Vol. 27, No. 19, pp. 2661-2671, 2016
- Karamooz, M.R., Nasr Esfahani, S., Taheri Andani, M., Kadkhodaei, M., Ghaei, A., Karaca, H., and Elahinia, M., "On the effects of geometry, defects, and material asymmetry on the mechanical response of shape memory alloy cellular lattice structures", Smart Materials and Structures, Vol. 25, No. 2, 025008, 2016

- Karamooz, M. R., Taheri, M., Kadkhodaei, M., Saedi, S., Kraca, H., and Elahinia M., "Modeling the cyclic shape memory and superelasticity of selective laser melting fabricated NiTi", International Journal of Mechanical Sciences, Vol. 138-139, pp. 54-61, 2018
- Keshavarzan, M., Kadkhodaei, M., and Forooghi, F., "An investigation into compressive responses of shape memory polymeric cellular lattice structures fabricated by vat polymerization additive manufacturing", Polymer Testing, Vol. 91, p. 106832, 2020
- Zamani, M. R., Kadkhodaei, M., Badrossamay, M., and Foroozmehr, E., "Adjustment of the scan track spacing and linear input energy to fabricate dense, pseudoelastic Nitinol shape memory alloy parts by selective laser melting", Journal of Intelligent Material Systems and Structures, Vol. 33, No. 13, pp. 1719-1730, 2022

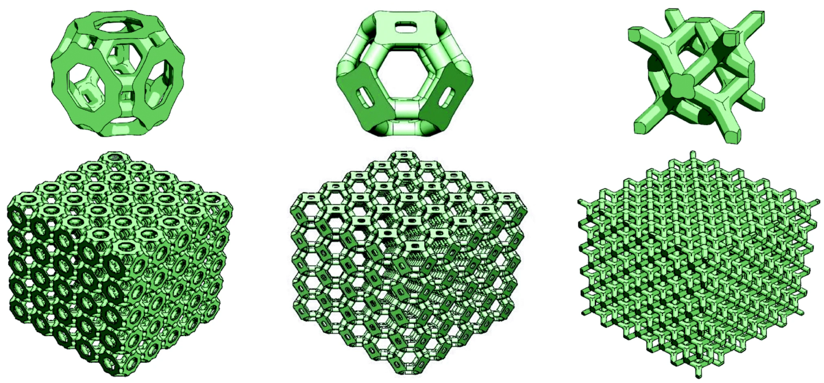

Figure 5. 3D/4D printing related to modeling and finite element simulation of additively manufactured parts made of polymers or SMAs

The group is currently working on functionally graded cellular structures.