Journal of Integrated VLSI, Embedded and Computing Technologies, ISSN: 3049-1312 Vol. 2, No. 1, 2025 (pp. 53-61)
RESEARCH ARTICLE
ECEJOURNALS.IN

Smart Sensors for Biomedical Applications: Design and Testing using VLSI Technologies

Giovanni F. Bianchi*
CRIM Lab, Scuola Superiore Sant'Anna, via Piaggio, 34, 56025Pontedera, Pisa 56100, Italy

Keywords:
Smart Sensors;
Biomedical Applications;
VLSI Technologies;
Sensor Design;
Testing and Validation

Corresponding Author Email:
biachif.giov@sssup.it

DOI: 10.31838/JIVCT/02.01.07

Received : 21.11.2024
Revised : 24.12.2024
Accepted : 25.01.2025

Abstract

By means of very large scale integration (VLSI) technologies, they have been rapidly developed as smart sensors for biomedical applications. These innovative devices are eliminating intrusiveness and thereby transforming healthcare by providing continuous monitoring, early diagnosis and targeted treatment. This article covers the VLSI smart sensors for biomedical field and brings the cutting edge design approaches, the testing methodologies and the emerging trends in it. As healthcare costs continue to increase, populations age, and, as a result, medical cost efficiency will become more and more important. potentials VLSI technologies are that of miniaturized, low power sensors that can easily embedded into wearable devices, implants and diagnostic tools. So, these smart sensors capture, relate and transmit the vital physiological data to more accurate and faster medical interventions. One of the unique technical and market opportunities and challenges for integrating VLSI techniques into biomedical sensor design is outlined. Engineers have a complex mess of requirements that while biocompatible, suitable for implantation, and reliable also want to optimize power consumption. Design and test considerations of VLSI based smart sensor, and direction in which novel and important areas are pointed out, are discussed in this article.

How to cite this article: Bianchi GF (2025). Smart Sensors for Biomedical Applications: Design and Testing using VLSI Technologies. Journal of Integrated VLSI, Embedded and Computing Technologies, Vol. 2, No. 1, 2025, 53-61

VLSI Technologies for Biomedical Sensor Design

Application of VLSI technologies in the biomedical sensor design has opened new possibilities of highly integrated, miniaturized device design. These advanced sensors benefit from the VLSI, and the performance, power consumption, and functionality are all improved associated with these.[1-4]

Advantages of such VLSI

However, biomedical sensor design can also be implemented using VLSI technologies, due to many key advantages afforded through them.

1. **Integration in very small form factors:** VLSI can be used to develop compact sensors with complex circuitry that have turned into an important enabling technology for the compact, implantable and wearable delivery of sensing.
2. It can provide long term monitoring and increase battery life of system through advanced VLSI design techniques by providing low power consumption.
3. These include high integration wherein several sensing, processing and communication functions are packaged on one chip to reduce the complexity of the system and its reliability.
4. **Advances in medical technology:** From the ability of mass producing VLSI based sensor manufactured at lower cost due to VLSI technology, more advanced medical technologies can be provided (Figure1).

Biomedical Sensors using CMOS Technology

One of the common advantages of CMOS technology employed for fabricating biomedical sensors is the requirement of low power supply in operation in such sensors in addition to high integration capacity and

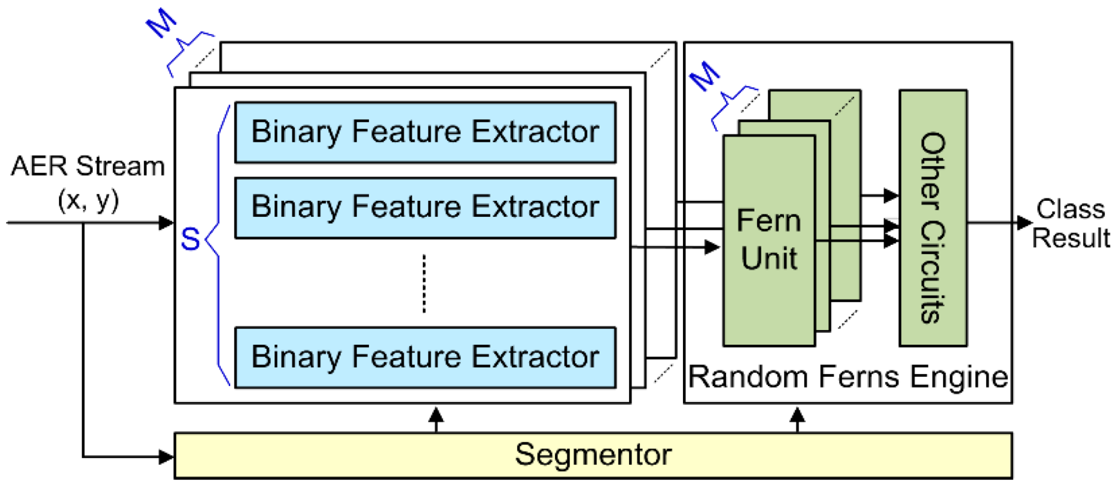

Fig. 1: Biomedical Sensors using CMOS Technology

compatibility with standard fabrication processes. Signal processing and data conversion can be integrated in analog and digital circuits on top of CMOS based sensor (also known as CMOS based sensor), e.g. electrochemical sensor for specific biomolecules detection, capacitive sensors for measuring physical parameters, i.e., pressure, acceleration.

Additionally, adult cardinals were tested using the pencil stylus that is principally intended for use in DCs to replace or complement related existing current inking methods. Using VLSI Technologies For Medical Imaging Applications. Specific parameters of physical interest that can be measured are pressure, acceleration and force at image sensors designed for medical imaging applications. Temperature sensors for body temperature monitoring applications.

Advance of very large scale integration (VLSI) has progressed the development of smart sensors in biomedical applications. These ingenious devices are revolutionising healthcare by allowing continuous monitoring, early diagnosis and personalized treatment strategies. The design approaches, testing methodologies and future trends in VLSI based smart sensors for biomedical field are presented in this article.

Given that healthcare costs are rising and populations are getting older, we need more efficient, cheaper forms of medical solutions. Repeatable out of the scanner, VLSI technologies are promising at providing a path to creating miniaturized, low power sensors that can be seamlessly embedded into wearable devices, implants, and diagnostic tools. By enabling the smart sensors to capture, process, and transmit vital physiological data in more timely and accurate ways, it allows for more accurate and timely medical interventions.

VLSI techniques will be integrated in biomedical sensor design and they present unique challenges and opportunities. Engineers have to navigate through a landscape filled with requirements: minimizing power consumption, maximizing biocompatibility and reliability. This article presents different aspects of the VLSI based smart sensor design and testing, such considerations, novel approaches and future directions in this very fast developing area.[5-9]

VLSI Technologies for Biomedical Sensor Design

The use of VLSI technology to design biomedical sensors has provided a new means of creating highly integrated, miniaturised devices. Using the benefits of VLSI, advanced sensors use these sensors to yield enhanced functionality, reduced power consumption, and improved performance.

Advantages of VLSI in Biomedical Sensors

Several key advantages for biomedical sensor design can be obtained by using VLSI technologies: VLSI: The circuitry can be integrated in tiny form factors, which leads to a development of the highly compact sensors for the implantable and wearable applications. Advanced VLSI design techniques can help tremendously in reducing power requirements so that battery life can be extended as well for long term monitoring. System complexity is reduced through high integration of multiple sensing, processing and communication functions onto a single chip, which also enhances reliability. Mass production of VLSI based sensors can provide the means for reduced subsequent manufacture ('Additive' cost) and thus make the user of advanced medical technologies more financially attractive.[10-11]

CMOS Technology in Biomedical Sensors

Compared with other technologies, COMS technology has become highly appealing for the design of biomedical sensors because of its low power consumption, high integration density, and possibility to be realized based on standard fabrication processes. Analog and digital circuits can be integrated on CMOS-based sensors in order to realize on-chip signal processing and data conversion (Table 1).

Material Selection and Biocompatibility

Implantable or long term wearable sensors are majorly considered on the basis of interiority. Materials and packaging techniques need be carefully selected so that the sensor does not cause adverse reactions or tissue damage. Biocompatible materials — these can be medical grade silicone or titanium or even specialized polymers like those that the body is familiar with well. Packaging techniques based on hermetic sealing using robust techniques to minimize contamination of the sensor electronics to bodily fluids and minimize the leakage of potentially harmful substances.

Surface treatment: Coating or surface treatments to modify tissues integration and reduce the risk of inflammation or rejection. Long term stability: Sensors with sufficient performance and integrity to again be useful after being in physiological environment for extended period of time. Data security and privacy is to be ensured as biomedical sensors usually retrieve sensitive health information.[12-14]

- **Encryption:** definition of the robust encryption algorithms to be implemented in order to protect data during storage and transmission.
- For secure access, wireless protocols and authentication mechanisms are used.
- Identifying how and when to anonymize or de-identify sensitive health data.
- The ease of compliance with relevant healthcare data protection regulations and standards.

Sensor Architectures for Innovative Biomedical Applications

As such, novel sensoris architectures are being developed that are enabling advancements in biomedical monitoring and diagnostics. This section pursues implementation of new sensors as VLSI to realize higher performance and functionality.

Multi-Modal Sensing Platforms

1. Cross validation of measurements can be obtained by integrated multiple sensing modalities on a single chip:
2. Electrochemical-mechanical hybrid sensors: The simultaneous bioelectrochemical and mechanical sensing of biochemical markers and physical parameters.
3. Optical-electrical sensors: Application of optical and electrical sensing capabilities with applications such as pulse oximetry and tissue characterization.
4. Challenge for developing multi-parameter vital sign monitors which incorporate the sensors that can simultaneously measure various vital signs (e.g., heart rate, blood pressure, temperature) on a single platform.

VLSI Based Biomedical Sensor Testing and Validation

The VLSI based biomedical sensors, however, need rigorous test and validation to achieve reliability,

Table 1: CMOS Technology in Biomedical Sensors

Design Parameter	Description	Impact on Biomedical Applications
Sensor Sensitivity	The ability of the sensor to detect small changes in the environment or biological signal	Crucial for early detection and monitoring of health conditions
Power Consumption	The amount of energy the sensor uses during operation	Important for portable, battery-powered biomedical devices
Size/Integration	Physical dimensions and integration of sensor components	Smaller sensors can be integrated into medical devices with minimal intrusion
Signal Processing	The ability to process and filter the acquired signals	Necessary for accurate data analysis in real-time monitoring

accuracy, and safetyness. This section discusses a few methods for testing of sensors, as well as considerations associated with the test when the test is used to ascertain the sensor performance or compliance with regulatory requirements.

In Vitro characterization and testing

Evaluation of sensorâ s performance under controlled laboratory conditions is in-vitro testing.

Electrical measurements: Very precise electrical measurements on precision electrical instruments and test setups and with precision, key electrical parameters such as sensitivity, linearity, dynamic range and noise performance quantify. Environmental testing: this takes the stability, robustness and subjecting sensors under different environmental conditions (temperature, humidity, pressure). Acceleration aging testing: This is a long term stability and reliability test of sensor components and packaging. Interference testing: Analyzing sensor susceptibility to electromagnetic interference, and other noise or artifact sources (Figure 2).

Biocompatibility Assessment and *In-Vivo* Testing

The sensor performance and biocompatibility are evaluated in living organisms, abbreviated as *in-vivo* testing. Sensor functionality and biocompatibility as well as potential long term effects were evaluated in preclinical trials using animal models. Histological analysis: Examination of tissue samples to observe the inflammation or adverse response to applied sensors.

Sensor performance and assessment in physiological environment and compared with the established clinical measurement techniques served as the functional testing. Animal model studies, long term implantation studies, sensor stability including drift and tissue integration over extended periods in animals.[15-17]

Standards and Regulatory Compliance

Thus, it is essential to ensure compliance with applicable regulatory standards guidelines to market biomedical sensors:

According to the FDA requirements for medical devices, you can refer to the process of premarket approval (PMA) or 510(k) clearance procedure of the USA FDA. Fulfills to ISO international standards, for instance ISO 13485 for the quality management in medical devices.

Electromagnetic compatibility (EMC) testing: showing that sensors do not interfere with other sensors medical equipment and/or obtained by external electromagnetic sources according to EMC

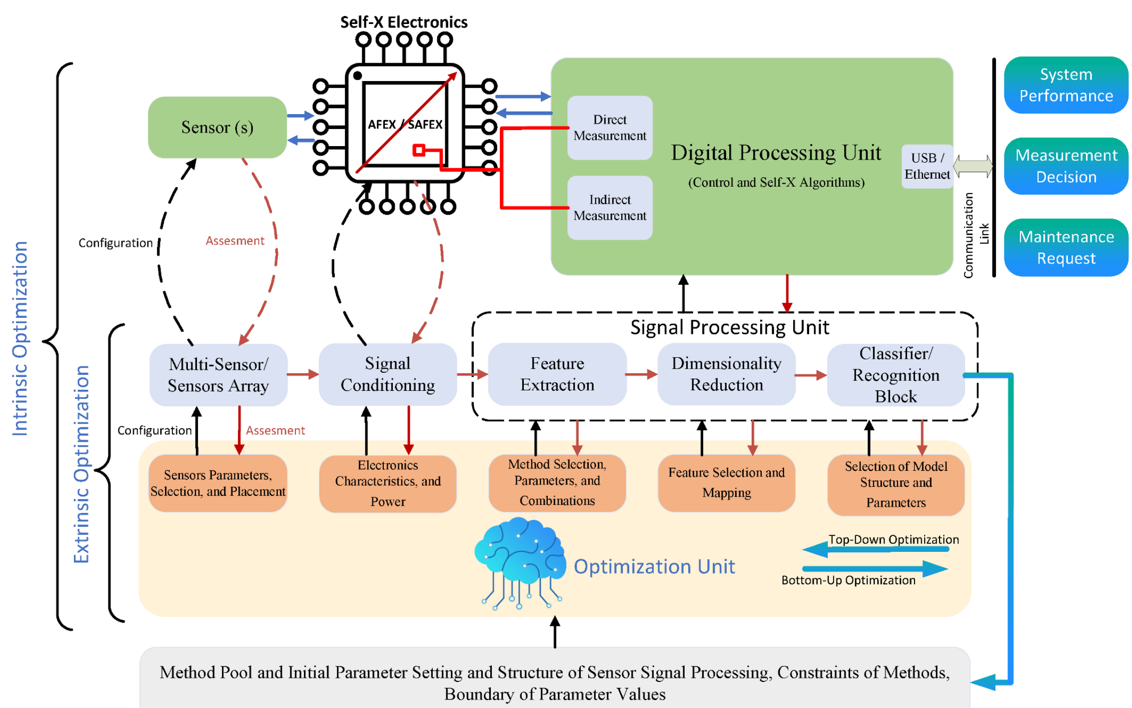

Fig. 2: Biocompatibility Assessment and In-Vivo Testing

industry standard. Biocompatibility testing: Does the testing according to ISO 10993 standards of the biocompatibility of the materials that is used in the sensor construction.[18-21]

Clinical Trials and Performance Validation

To demonstrate the efficacy and safety of a sensor, rigorous performance validation and robust clinical trials are needed: Performance testing, compared to gold standard measurement, under controlled bench test conditions.

Human subject clinical validation studies: These are human subject trials to test the sensor's performance in the real world clinical setting, and to gather accuracy, reliability and usability data. Statistical analysis includes determining accuracy, precision, and review of agreement with the reference method by means of comprehensive statistics analysis. Evaluating the practical aspects of sensor use in terms of user feedback as well as usability testing obtained from patients and healthcare professionals aimed to identify and improve potential.[22-23]

VLSI Based Sensors: Data Processing and Analysis Techniques

VLSI based biomedical sensors acquire and process raw signals, then only the first step in obtaining meaningful information is to extract the information from the raw signals. This chapter then proceeds and describes multiple data processing methodologies and methodologies at different data processing levels (off- and on-chip) to enhance sensor performance and to enable new diagnostic operations.[24-25]

On-Chip Signal Processing

Signal level processing is a method of reducing power consumption, lowering the amount of data to be transmitted, and allowing real time data analysis by integrating signal processing capabilities directly in the sensor chip. Conditioning and digitizing raw sensor signals using low noise amplifiers, filters and analog to digital converters (ADCs). Furthermore, it includes digital signal processing (DSP) cores which incorporate general signal processing algorithms implemented in efficient dedicated hardware. It includes techniques such as feature extraction—both for reducing the amount of information needed to transmit stored on chip algorithms which extract sensor data features relevant those.[26-27]

Standards and Regulatory Compliance

Thus, it is essential to ensure compliance with applicable regulatory standards guidelines to market biomedical sensors: According to the FDA requirements for medical devices, you can refer to the process of premarket approval (PMA) or 510(k) clearance procedure of the USA FDA. Fulfills to ISO international standards, for instance ISO 13485 for the quality management in medical devices. Electromagnetic compatibility (EMC) testing: showing that sensors do not interfere with other sensors medical equipment and/or obtained by external electromagnetic sources according to EMC industry standard. Biocompatibility testing: Does the testing according to ISO 10993 standards of the biocompatibility of the materials that is used in the sensor construction (Table 2).

Clinical Trials and Performance Validation

To demonstrate the efficacy and safety of a sensor, rigorous performance validation and robust clinical trials are needed:

Performance testing, compared to gold standard measurement, under controlled bench test conditions. Human subject clinical validation studies: These are human subject trials to test the sensor's performance in the real world clinical setting, and to gather accuracy, reliability and usability data. Statistical analysis includes determining accuracy, precision, and review of agreement with the reference method by means of comprehensive statistics analysis.

Table 2: Clinical Trials and Performance Validation

Testing Methodology	Description	Challenges
In-vitro Testing	Testing sensors on biological samples outside the living organism	Ensuring the sensor response accurately reflects real-world conditions
In-vivo Testing	Testing sensors inside living organisms or human models	Biocompatibility, long-term stability, and sensor performance inside the body
Environmental Testing	Testing sensor performance under various environmental conditions (temperature, humidity, etc.)	Variability in sensor performance based on environmental factors

Evaluating the practical aspects of sensor use in terms of user feedback as well as usability testing obtained from patients and healthcare professionals aimed to identify and improve potential.

VLSI Based Sensors: Data Processing and Analysis Techniques

VLSI based biomedical sensors acquire and process raw signals, then only the first step in obtaining meaningful information is to extract the information from the raw signals. This chapter then proceeds and describes multiple data processing methodologies and methodologies at different data processing levels (off- and on-chip) to enhance sensor performance and to enable new diagnostic operations. Signal level processing is a method of reducing power consumption, lowering the amount of data to be transmitted, and allowing real time data analysis by integrating signal processing capabilities directly in the sensor chip. Conditioning and digitizing raw sensor signals using low noise amplifiers, filters and analog to digital converters (ADCs). Furthermore, it includes digital signal processing (DSP) cores which incorporate general signal processing algorithms implemented in efficient dedicated hardware. It includes techniques such as feature extraction—both for reducing the amount of information needed to transmit stored on chip algorithms which extract sensor data features relevant those.

Using sensors based on very large scale integrated circuits (VLSI), patients are able to be monitored from afar with greater effectiveness, especially in the management of chronic disease:

Telehealth platforms: Enabling remote consultations and continuous health monitoring with some combination of various sensors and communication technologies. Sensors used for tracking patients' conformity to the medication, or lack thereof, along with meditations when required. Fall detection systems It can be used to alert a caregiver when an elderly or at risk person falls.

Sensors in homes or care facilities to monitor patients health by measuring air quality, temperature or anything else that may affect patient health. Although considerable progress has been made in VLSI based biomedical sensors, a number of obstacles still remain to be overcome. Finally, current and future research limitations and directions are discussed.

Energy Harvesting and Power Consumption.

One of the greatest challenges to long term, implantable, wearable sensors, is increasing energy efficiency. Finally, new circuit topographies and design techniques are developed to further reduce the power consumption as much as possible while it does not impact performance. Advanced energy harvesting: Novel energy harvesting mechanisms, such as piezoelectric, electret, thermoelectric or piezoelectric generators for self powered sensor operation. Efficient and safe wireless power transfer techniques for implantable devices. Intelligent power management of networks of interconnected sensors to maximize total system lifetime is referred to as energy aware sensor networks.

Long Term Stability and Biocompatibility

Challenges remain for ensuring long-term biocompatibility and stability of implantable sensors: by improving tissue integration and reducing foreign body responses with new biocompatible materials and surface treatments. This work is based on the development of sensors that automatically remain accurate for a very long time by calibration or some other type of drift compensation. Creating sensors (bioelectronics) that can dissolve or be absorbed by the body upon completing its use (transient electronics). Electrode interfaces with tissue: to facilitate design of these electrode interfaces to minimize tissue damage and allow for stable long term connections.

Miniaturization

Other challenges include further miniaturization and integration of sensor components.

1. **3D integration techniques:** Future 3D chip stacking and through silicon via (TSV) technology to maximize 3D chip stacking techniques in order to integrate higher levels in smaller and compact packages.
2. New materials and fabrication techniques to make flexible and stretchable electronics to conform sensors that will bend and fold around human body movements and conformalities.
3. Such nanomaterials and nanostructures could then serve as the surroundings of nano-scale sensing elements that are ultra sensitive, and highly specific.
4. **System-on-chip (SoC) integration:** Moving processing, power management, wireless communication capabilities onto a single chip.

Data Security and Privacy

Security and privacy concerns in biomedical sensor systems are still very important to address.

- **Implication 1**: Search for energy efficient encryption algorithms, apropos of the so called resource constrained sensor devices encryption.
- How to design robust authentication and key management protocols for interconnected biomedical sensors that have secure networks.
- **Privacy preserving data analytics:** Methods of data analysis that don't come at the cost of privacy (be it via federated learning or homomorphic encryption).
- **Regulatory frameworks:** Building the guidelines and standards for the security and privacy data in biomedical sensor application.

Emerging Sensing Modalities

New sensing modalities and measurement techniques can provide new opportunities in biomedical monitoring: Optical: Advancing Optical Sensing, a noninvasive form of Optical Sensing include, near infrared spectroscopy for measurement of various physiological parameters (e.g., tissue oxygenation), or photoplethysmography for measurement of pulse rate and oxygen saturation of arterial blood. Because cardiovascular disease causes, it will be able to develop highly sensitive and selective sensors for detecting specific biomarkers or metabolites in body fluids. Novel mechanical sensing modalities (acoustic or tactile sensors) for monitoring physiological (such as the underlying state of electrical activity (ECG)) or biomechanical (such as the heart rates (HR), dyad length of tethered tugs or tags) parameters. Multi functional sensing: Sensors capable of measuring multiple parameters simultaneously or themselves being able to vary according to sensing modalities.

Conclusion

This new age of healthcare monitoring and diagnosis would not have been brung with the design of Biomedical sensor with VLSI technologies. These advanced sensors have very high power efficiency and functionality by miniaturization and can be used in many applications, for instance wearable health monitors or implantable medical devices, due to the unprecedented capabilities of these sensors. In this thesis, an effort has been made to realize the full potential of VLSI-based biomedical sensors and to face the biochallenges such as long term biocompatibility, energy efficiency and data security while this field is becoming increasingly evolved. Emerging future sensors performance and capability advances are promising flexible electronics, neuromorphic computing, and nanosensors. The future of integration of patients' lives seamlessly with VLSI based biomedical sensors lies in their integration into the patient' lives seamlessly. Along with this maturation of these technologies and its widespread adoption, however, it can potentially revolutionize delivery of healthcare and these advances enable earlier disease detection, more effective treatment strategies, and better patient outcomes. The future developments in the VLSI based smart sensor field will depend on continued research and development efforts for the VLSI based smart sensor for biomedical application along with close association between the engineers, the medical, and the regulators for overcoming the current limits and realizing the maximum potential of the VLSI based smart sensor in biomedical application. With these innovations ongoing, we can expect a future with a ever-growing demand for advanced sensing technology to advance health, prevent disease and improve wellbeing across our world.

References:

1. Hamami, S., L., L. F., & Yadid-Pecht, O. (2007). CMOS image sensor employing 3.3 V 12-bit 6.3 MS/s pipelined ADC. Sensors and Actuators A: Physical, 135, 119–125.
2. Fowler, B., & Liu, X. (2007). Charge transfer noise in image sensors. In Proceedings of the 2007 International Image Sensor Workshop (pp. 51–54), Ogunquit, Maine, USA.
3. Mendis, S. K., Kemeny, S. E., Gee, R. C., Pain, B., Staller, C. O., Kim, Q., & Fossum, E. R. (1997). CMOS active pixel image sensors for highly integrated imaging systems. IEEE Journal of Solid-State Circuits, 32, 187–197.
4. Li, D.-C., Yang, P.-H., & Lu, M. S.-C. (2010). CMOS open-gate ion-sensitive field-effect transistors for ultrasensitive dopamine detection. IEEE Transactions on Electron Devices, 57(10), 2761–2767.
5. Meijer, G. C. M., Wang, G., & Fruett, F. (2001). Temperature sensors and voltage references implemented in CMOS technology. IEEE Sensors Journal, 1(3), 225–234.
6. Du, D., & Odame, K. (2013). A bandwidth-adaptive preamplifier. IEEE Journal of Solid-State Circuits, 48(7), 2142–2153.
7. Liang, X., Hu, P., Zhang, L., Sun, J., & Yin, G. (2019). MCFNet: Multi-layer concatenation fusion network for medical images fusion. IEEE Sensors Journal, 19(16), 7107–7119.

8. Potluri, P., Rajamani, S. K., Devi, V. B., Sampath, R., Vallabhuni, R. R., Mouleswararao, B., K, B., & Mubeen, S. (2022). Integrated spectral and prosody conversion with vocoder of voice synthesizer for human-like voice using deep learning techniques (Application No. 202241073323 A). The Patent Office Journal, 52/2022, India.
9. Hemanth, D. J., et al. (2013). Distance metric-based time-efficient fuzzy algorithm for abnormal magnetic resonance brain image segmentation. Neural Computing and Applications, 22(5), 1013–1022.
10. Jin, Q., et al. (2019). DUNet: A deformable network for retinal vessel segmentation. Knowledge-Based Systems, 178, 149–162.
11. Arslan, T., Haridas, N., Yang, E., Erdogan, A. T., & Howells, W. G. J. (2006). ESPACENET: A framework of evolvable and reconfigurable sensor networks for aerospace-based monitoring and diagnostics. In Proceedings of the 1st NASA/ESA Conference on Adaptive Hardware and Systems (AHS'06) (pp. 323–329).
12. Barrettino, D., Graf, M., Wan, H. S., Kirstein, K. U., Hierlemann, A., & Baltes, H. (2004). Hotplate-based monolithic CMOS microsystems for gas detection and material characterization for operating temperatures up to 500°C. IEEE Journal of Solid-State Circuits, 39(7), 1202–1207.
13. Lee, H.-Y., Chen, S.-L., & Luo, C.-H. (2008). A CMOS smart thermal sensor for biomedical application. IEICE Electronics Express, E91-C(1), 96–104.
14. Bharati, R., Jain, S., Jonnala, P., Mishra, R., Singh, M., Vallabhuni, R. R., Sriramam, Y. S. S., & Lalitha, R. V. S. (2022). Multi-task multi-kernel learning technique to assess and classify bio and psychological signals (Application No. 202211066338 A). The Patent Office Journal, 47/2022, India.
15. Tabata, H. (2015). Application of terahertz wave technology in the biomedical field. IEEE Transactions on Terahertz Science and Technology, 5(6), 1146–1153.
16. Taylor, Z. D., et al. (2015). THz and mm-wave sensing of corneal tissue water content: In vivo sensing and imaging results. IEEE Transactions on Terahertz Science and Technology, 5(2), 184–196.
17. Kaynak, C. B., et al. (2014). Modeling and characterization of BiCMOS embedded microfluidic platform for biosensing applications. In Proceedings of the IEEE Topical Conference on Biomedical Wireless Technology, Networks, and Sensing Systems (BioWireleSS) (pp. 46–48).
18. Wang, A. Y., Cho, S. H., Sodini, C. G., & Chandrakasan, A. P. (2001). Energy efficient modulation and MAC for asymmetric RF microsensor system. In Proceedings of the International Symposium on Low Power Electronics and Design (pp. 106–111).
19. Proakis, J. G. (2001). Digital communications (4th ed.). McGraw-Hill.
20. Fitch, J. P. (1987). Software and VLSI algorithms for generalized ranked order filtering. IEEE Transactions on Circuits and Systems, 34(5), 553–559.
21. Kar, B. K., & Pradhan, D. K. (1993). A new algorithm for order statistic and sorting. IEEE Transactions on Signal Processing, 41(8), 2688–2694.
22. Pedroni, V. A. (2004). Compact hamming-comparator-based rank order filter for digital VLSI and FPGA implementations. In Proceedings of the IEEE International Symposium on Circuits and Systems (Vol. 2, pp. 585–588).
23. Sangamithra, P., & Abishek, M. K. (2018). Modeling and analysis of touch screen-based wireless control of four motor robotic vehicle employing knowledge-based system and ensemble machine learning. International Journal of Electrical Engineering and Technology, 9(2), 75–82.
24. Nallusamy, T., Kannan, V., Sales, F. D. C. D., Logeshwaran, J., Vallabhuni, R. R., Mateen, S., Dharani, M., Kumar, C. M. S., Kumar, S., Singh, M., Kumar, S., & Venkataraman, Y. (2022). The detection of varied EEG pattern signal for chronic migraine patients using machine learning approach (Application No. 202241065256 A). The Patent Office Journal, 47/2022, India.
25. Kumar, A. G. C., Chandrappa, & Kumar, A. G. C. (2015). Real-time filter and fusion of multi-sensor data for localization of mobile robot. International Journal of Electronics and Communication Engineering and Technology (IJECET), 6(1), 49–57.
26. Sonar, N. S., & Mudholkar, R. R. (2014). Implementation of data error corrector using VLSI technique. International Journal of Electronics and Communication Engineering and Technology (IJECET), 5(5), 91–95.
27. Smith, L. S. (2010). Neuromorphic systems: Past, present, and future. Advances in Experimental Medicine and Biology, 167–182.
28. Abdullah, D. (2024). Enhancing cybersecurity in electronic communication systems: New approaches and technologies. *Progress in Electronics and Communication Engineering, 1*(1), 38–43. https://doi.org/10.31838/PECE/01.01.07
29. Abdullah, D. (2024). Leveraging FPGA-based design for high-performance embedded computing. *SCCTS Journal of Embedded Systems Design and Applications, 1*(1), 37-42. https://doi.org/10.31838/ESA/01.01.07
30. Rahim, R. (2024). Scalable architectures for real-time data processing in IoT-enabled wireless sensor networks. *Journal of Wireless Sensor Networks and IoT, 1*(1), 44-49. https://doi.org/10.31838/WSNIOT/01.01.07
31. Surendar, A. (2024). Emerging trends in renewable energy technologies: An in-depth analysis. *Innovative Reviews in Engineering and Science, 1*(1), 6-10. https://doi.org/10.31838/INES/01.01.02
32. Sathish Kumar, T. M. (2024). Developing FPGA-based accelerators for deep learning in reconfigurable com-

puting systems. *SCCTS Transactions on Reconfigurable Computing, 1*(1), 1-5. https://doi.org/10.31838/RCC/01.01.01

33. Jagan, B. O. L. (2024). Low-power design techniques for VLSI in IoT applications: Challenges and solutions. *Journal of Integrated VLSI, Embedded and Computing Technologies, 1*(1), 1-5. https://doi.org/10.31838/JIVCT/01.01.01
34. Muralidharan, J. (2023). Innovative RF design for high-efficiency wireless power amplifiers. *National Journal of RF Engineering and Wireless Communication, 1*(1), 1-9. https://doi.org/10.31838/RFMW/01.01.01
35. Sudha, M., Karthikeyan, S., Daniel, J., & Muthupandian, R. (2024). Wearable device for heart rate monitoring. *International Journal of Communication and Computer Technologies, 12*(1), 27-32. https://doi.org/10.31838/IJCCTS/12.01.03
36. Halily, R., & Shen, M. (2024). Directing techniques for high frequency antennas for use in next-generation telecommunication countries. *National Journal of Antennas and Propagation, 6*(1), 49–57.