Signal-Processing Algorithms for Sensor Arrays: A Brief Review

Sergio Dominguez-Gimeno
Dept. of Electronic Engineering
and Communications
University of Zaragoza
Teruel, Spain
e-mail: sdominguezg@unizar.es

Raul Igual-Catalan
Dept. of Electric Engineering
University of Zaragoza
Teruel, Spain
e-mail: rigual@unizar.es

Inmaculada Plaza-Garcia
Dept. of Electronic Engineering
and Communications
University of Zaragoza
Teruel, Spain
e-mail: inmap@unizar.es

***Abstract*—A sensor array is a special topology of sensors in which all of them fulfill a common function. These sensor arrays have a wide variety of applications and nature. As the signals produced by these arrays highly depend on them, very different processing algorithms can be designed for them. In this paper, a brief review of the families of algorithms that are applied to sensor arrays is given. A total of 171 papers have been analyzed and percentages of usage of each family of algorithms are provided. The algorithms found are very diverse and highly depend on the application of sensor arrays. However, it has been found that very different arrays can accomplish the same task and can be processed in the same way.**

***Keywords*-sensor array; algorithms; machine learning; numerical methods; review.**

I. Introduction

Sensor arrays are arrangements of several sensors in the same device. These arrays are based on different technologies, like resistive arrays [1], capacitive arrays [2], triboelectric arrays [3], piezoelectric arrays [4], etc. This topology allows very diverse applications like aerospace [5], surgery [6][7], gas classification [8], bidimensional pressure distribution sensing [9], or damage monitoring in structures [10]. In this article, special attention is paid to the processing algorithms used to treat the signals the sensor arrays provide. A global classification of the types of algorithms is also provided.

The remainder of the paper is organized as follows: In Section II, the search and selection procedure is explained; in Section III, the algorithms found are classified by families and some examples of use are listed; in Section IV, the results are discussed; and in Section V, some conclusions are drawn.

II. Methods

A systematic search on sensor arrays in the *Web Of Science* (WOS) database is conducted to provide a general vision of the field. In order to cover all possible technologies on sensing arrays, the title keywords searched, together with the number of selected results, are: “Resistive Sensor Array” (RSA, 45 results), “Piezoresistive Sensor Array” (PRSA, 32 results), “Capacitive Sensor Array” (CSA, 57 results), “Inductive Sensor Array” (ISA, 6 results), “Diode Sensor Array” (DSA, 6 results), “Transistor Sensor Array” (TSA, 24 results), “Piezoelectric Sensor Array” (PSA, 66 results), “Triboelectric Sensor Array” (TrSA, 14 results), “Fiber-optic Sensor Array” (FSA, 14 results), “Hall-effect Sensor Array” (HSA, 6 results), and “Bioimpedance Sensor Array” (BSA, 2 results).

Searches were performed in January 2023, and repeated in September 2023. All results from 2016 to September 2023 were taken for analysis. Journals, magazines, and conferences were considered in the searches. A total of 322 papers were found. The title and abstract of each paper was examined and results not related to the aim of this research were discarded. This led to 316 studies. The content of the studies was then examined, discarding those not related to the topic of this review, or those that did not mention the processing algorithms. This lead to a total of 171 papers selected to be deeply analyzed. This is a brief review to study the current state of the art of sensor array processing algorithms.

III. Results

The different families of algorithms found are listed in this section. A summary of them can be seen in Figure 1.

A. Classic signal processing algorithms

1) FFT-based algorithms: The most common technique for frequency analysis is the Fast Fourier Transform (FFT) [11], followed by the Wavelet Transform (WT) [12]. Other techniques are Short-Time FT (STFT) [4], Power Spectral Density (PSD) [2][10][13], the Discrete Cosine Transform (DCT) [14], the Hilbert Transform (HT) [15], and, finally the S-Transform [16]. These are applied works whose sensors have a frequential response, like PSA [14][17], for example, for Structure Health Monitoring (SHM). In [10], the PSD is obtained to calculate a Crack Growth Index (CGI), which allows fatigue sensing in structures. Capacitive Micromachined Ultrasonic Transducers (CMUTs) can be based on CSA, so they must be analyzed in the frequency domain [8]. They can be used to detect Volatile Organic Compounds (VOCs) or Liquids (VOLs). In [18], frequency analysis is used to obtain vibrations of the flexible solar panels of a satellite and compensate them, using a PID algorithm. Zhang et al. [16] assess power transformers isolation through ultrasound signals obtained with a fiber-optic sensor array and processed with the S-Transform. In [19], a HSA for magnetometry is developed and magnetic noise is studied similarly.

2) Tracking algorithms: Several works use algorithms to follow the position of a certain object. In [20], a CSA is used for contact-less hand tracking. In the field of surgery, instruments can be tracked inside the human body using HSA [7]. HSAs are also used in [21] for microrobot position tracking. In [22],

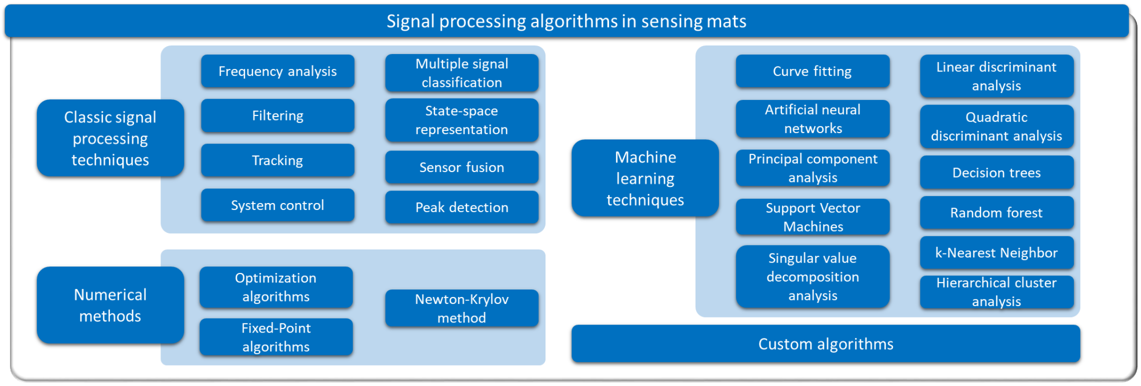

Figure 1. Families of processing algorithms found during this work that are applied for sensor array signal processing.

particle tracking is performed with Time-of-Flight diode-based imaging sensors.

3) Fusion algorithms: It is the combination of the information of different sensors for enhanced sensing. It is common in the field of Inertial Measurement Units (IMUs): signals from the accelerometer, the gyroscope and the magnetometer are combined to compensate for their measurements [23]. In [24], an IMU and a PRSA are combined for smart ping-pong monitoring. The number and type of racket strokes are recorded.

4) Other processing techniques: Digital filtering has also been frequently found due to its importance in sensor post-processing. For example, band-pass and high-pass filters were found to be used to reject AC-power noise [25]. In [26], a radiation waste location system is developed through a FSA. The position readout is refined by applying a Savitzky-Golay filter. Multiple SIgnal Classification (MUSIC) is an algorithm that is applied for SHM using PSA [12]. For vehicle monitoring during aerospace launch, a state-space approach is adopted in [5]. It is performed using an IMU based on FSA. Finally, peak detection in IMU signals is applied in [24] to count the number of strokes with the ping-pong racket.

B. Machine Learning algorithms

Artificial Intelligence (AI) is a current trend in software for all kind of purposes. In this work, applications of different AI techniques to sensor arrays are explained. Machine Learning (ML) and Deep Learning (DL) algorithms found during this research are listed below:

1) Curve fitting: This is the most common technique used in the ML family, found in 31.2% of the articles. It is mainly used to obtain a mathematical relationship between the physical phenomena and the electric signal output of the sensor array. For example, Ko et al. [3] developed a PSA that was able to detect wind speed and direction. It showed a quadratic relationship between the wind speed and its output voltage.

2) Neural Network (NN): Neural Networks are the most popular DL algorithms in all fields, used for regression or classification. NN algorithms have been reported in the field of breathing sensors, for example, for diabetes diagnosis [27], but also in classification of VOCs with PSAs [28], or hand gesture classification with PRSA [29]. Backpropagation NNs, are applied in [17] to detect transverse cracks in railways. Convolutional NNs are used in [13] to obtain the cardiac pulse at the wrist from a BSA. In [30], a PRSA that is able to detect multi-touch points is calibrated with a NN with single-touch signals. PRSA calibration is also performed in [31], in this case, with a Wavelet NN. A different approach is made in [32]: a FET-based physical NN for the prevention of ulcers in bedridden patients is manufactured in standard CMOS.

3) Principal Component Analysis (PCA): A very popular technique to deal with high amounts of data that can help reduce the dimensionality in a problem by analyzing dependencies between considered features. It has been found to be frequently applied in classification of VOCs and VOLs [28]. Yoon et al. [8] use PCA to classify different VOCs through a CSA. They were able to detect Toluene, Acetone, Ethanol and Methanol using only three dimensions.

4) Support Vector Machines (SVM): These allow the expansion of the number of considered classification features. In [29], SVMs show the best classification results for hand gesture recognition among other ML techniques.

5) k-Nearest Neighbor (kNN): This method groups information into classes through a “neighbor voting” system. It is applied for roughness object recognition in [33], with high accuracy. Also used in [24], to classify different types of racket hits. In [34], a non-contact gesture recognition system based on an ISA is proposed. Gestures are classified using kNN, SVM and RF.

6) Hierarchical Cluster Analysis (HCA): This ML algorithm is used in [28] for VOC classification. Clusters are groups created depending on several features of training data. Then, sensed gases are classified into the available clusters.

7) Decision Trees (DT) and Random Forest (RF): A feature-based supervised algorithm of low computational cost. It has been found to be applied within an anti-vandalism system developed with FSA [11]. Also in [33], for robotic finger motion detection and object properties recognition, showing high accuracy.

8) Linear Discriminant Analysis (LDA) and Quadratic Discriminant Analysis (QDA): LDA and QDA are two statistical ML algorithms used in [29] for hand gesture recognition with a PRSA.

9) Singular Value Decompositon Analysis (SVDA): This reduces the amount of data to work with, based in a matrix factorization. It used is in [35] to detect objects immersed in sand using electrical capacitance tomography.

C. Numerical methods (NM)

In [9], Least-Squares (LSQR), Levenberg-Marquardt, Fixed-Point (FP), and Newton-Krylov algorithms are tested for crosstalk correction in RSA. Thus, readout accuracy of RSAs can be increased with post-processing methods [1][36]. LSQR showed the highest accuracy, at the cost of considerable processing time, while FP showed the highest computational speed with reasonable accuracy. Orthogonal Matching Pursuit (OMP) is another optimization greedy search algorithm that is used in [14] for SHM through PSAs. These PSAs are based on sound waves traveling inside the materials, and the OMP reconstruct these signals.

D. Classic statistical techniques

Classic statistical techniques are found in [27] and applied in breathing sensor arrays. For example, Discriminant Factor Analysis can be used to recognize the sensor that performs the best within an array.

E. Custom algorithms

Other algorithms that have not been able to fit into other families are grouped here. A custom image algorithm for damage imaging in a cylindrical pipe is proposed is [37]. In [38], a wind speed and direction detection algorithm is designed for a PRSA. An algorithm that fuses electromagnetic and magnetic signals is applied for Unexploded Ordnance (UXO) detection with an ISA in [39]. This leads to longer detection distances.

IV. Discussion

Processing algorithms sorted by their number of occurrence are represented in Figure 2. Only the most frequent algorithms are shown. FFT is the most popular technique in frequency analysis, closely followed by NN, in AI algorithms. The ML family of algorithms has the highest percentage of use (17.7% total). This is explained as ML classification algorithms, like NN, SVM, PCA, etc. are very versatile and are becoming very popular lately. Frequency analysis (FFT, WT, PSD, etc.) are the second most common techniques (17.3% total), followed by Numerical Methods, as optimization approaches have demonstrated to be very applicable to solve sensor array inaccuracies. The most commonly found technologies in sensor arrays have been PSA and CSA.

FFT-based algorithms (FFT, PSD, WT, etc.) are usually fast and lightweight algorithms that can easily run on any general-purpose PC. However, in embedded systems with few resources, they may run out of RAM. NN-based algorithms require large training data sets and long iterative training-testing processes, but in return they provide high processing speed, mainly when parallelized on Graphics Processing Units (GPUs). NNs are difficult to train in embedded systems due to this fact. Currently,

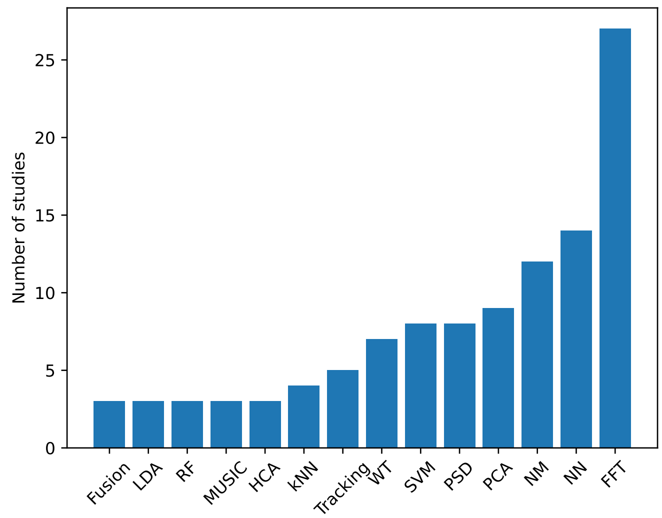

Figure 2. Processing algorithms applied to sensor arrays sorted by the number of occurrences.

NNs perform better than other typical ML algorithms (such as PCA, kNN, HCA, SVM, etc.). However, the latter methods require fewer computer resources because they have fewer parameters.

V. Conclusion and Future Work

Sensor arrays have very diverse applications and, therefore, the processing algorithms applied to them are very varied. Results show that none of the considered families of algorithms is predominant in use. Further research will be conducted in the future to provide a comprehensive view of the entire field. Nowadays, there is a lack of application of modern AI models in various sensor domains. In the coming years, AI is expected to take its place in the field of sensor arrays, making use of neural networks such as Large Language Models. Modelling of non-idealities, sensor design assistance, circuit analysis, didactic tools, etc. can be expected as applications of AI in the near future.

References

[1] J. Martinez-Cesteros, C. Medrano-Sanchez, I. Plaza-Garcia, and R. Igual-Catalan, "Uncertainty analysis in the inverse of equivalent conductance method for dealing with crosstalk in 2-d resistive sensor arrays," *IEEE Sensors Journal*, vol. 22, no. 1, pp. 373–384, 2022. DOI: 10.1109/JSEN.2021.3129668.

[2] W. Gao *et al.*, "A high-resolution mems capacitive force sensor with bionic swallow comb arrays for ultralow multiphysics measurement," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 7, pp. 7467–7477, 2022. DOI: 10.1109/TIE.2022.3203756.

[3] H.-J. Ko, D.-S. Kwon, S. Pyo, and J. Kim, "Curved flap array-based triboelectric self-powered sensor for omnidirectional monitoring of wind speed and direction," *Nano Energy*, vol. 102, p. 107 717, 2022. DOI: 10.1016/j.nanoen.2022.107717.

[4] Y.-Y. Liu, Y.-X. Lv, and H.-B. Xue, "Intelligent wearable wrist pulse detection system based on piezoelectric sensor array," *Sensors*, vol. 23, no. 2, 2023, ISSN: 1424-8220. DOI: 10.3390/s23020835.

[5] H. Gutierrez *et al.*, “Fiber optic sensor arrays for real-time virtual instrumentation and control of flexible structures,” in *Structural Health Monitoring, Damage Detection & Mechatronics, Volume 7*, Springer, 2016, pp. 9–22. DOI: 10.1007/978-3-319-29956-3_2.

[6] D. Son, S. Yim, and M. Sitti, “A 5-d localization method for a magnetically manipulated untethered robot using a 2-d array of hall-effect sensors,” *IEEE/ASME transactions on mechatronics*, vol. 21, no. 2, pp. 708–716, 2015. DOI: 10.1109/TMECH.2015.2488361.

[7] N. Fischer, J. Kriechbaum, D. Berwanger, and F. Mathis-Ullrich, “Compliant hall-effect sensor array for passive magnetic instrument tracking,” *IEEE Sensors Letters*, vol. 7, no. 3, pp. 1–4, 2023. DOI: 10.1109/LSENS.2023.3250971.

[8] I. Yoon *et al.*, “A capacitive micromachined ultrasonic transducer-based resonant sensor array for portable volatile organic compound detection with wireless systems,” *Sensors*, vol. 19, no. 6, p. 1401, 2019. DOI: 10.3390/s19061401.

[9] C. Medrano-Sanchez, R. Igual-Catalan, V. H. Rodriguez-Ontiveros, and I. Plaza-Garcia, “Circuit Analysis of Matrix-Like Resistor Networks for Eliminating Crosstalk in Pressure Sensitive Mats,” *IEEE Sensors Journal*, vol. 19, no. 18, pp. 8027–8036, 2019. DOI: 10.1109/JSEN.2019.2918592.

[10] X. Kong *et al.*, “Sensing distortion-induced fatigue cracks in steel bridges with capacitive skin sensor arrays,” *Smart Materials and Structures*, vol. 27, no. 11, p. 115 008, 2018. DOI: 10.1088/1361-665X/aadbfb.

[11] Z. Ren, K. Cui, and Y. Sun, “Pipeline anti-vandalism monitoring system based on time division multiplexing interferometric fiber optic sensor array,” *Optical Fiber Technology*, vol. 62, p. 102 470, 2021. DOI: 10.1016/j.yofte.2021.102470.

[12] T. Fu, Y. Wang, L. Qiu, and X. Tian, “Sector piezoelectric sensor array transmitter beamforming music algorithm based structure damage imaging method,” *Sensors*, vol. 20, no. 5, p. 1265, 2020. DOI: 10.3390/s20051265.

[13] B. Ibrahim and R. Jafari, “Cuffless blood pressure monitoring from a wristband with calibration-free algorithms for sensing location based on bio-impedance sensor array and autoencoder,” *Scientific reports*, vol. 12, no. 1, pp. 1–14, 2022. DOI: 10.1038/s41598-021-03612-1.

[14] Y. Sun and F. Gu, “Compressive sensing of piezoelectric sensor response signal for phased array structural health monitoring,” *International Journal of Sensor Networks*, vol. 23, no. 4, pp. 258–264, 2017. DOI: 10.1504/IJSNET.2017.083531.

[15] L. Si and Q. Wang, “Rapid multi-damage identification for health monitoring of laminated composites using piezoelectric wafer sensor arrays,” *Sensors*, vol. 16, no. 5, p. 638, 2016. DOI: 10.3390/s16050638.

[16] Z. Zhang *et al.*, “Oil-paper insulation partial discharge ultrasonic multifrequency sensing array based on fibre-optic fabry–perot sensor,” *High Voltage*, vol. 7, no. 2, pp. 325–335, 2022. DOI: 10.1049/hve2.12123.

[17] Y. Yang *et al.*, “Evaluation of the transverse crack depth of rail bottoms based on the ultrasonic guided waves of piezoelectric sensor arrays,” *Sensors*, vol. 22, no. 18, p. 7023, 2022. DOI: 10.3390/s22187023.

[18] I. M. da Fonseca, D. A. Rade, L. C. Goes, and T. de Paula Sales, “Attitude and vibration control of a satellite containing flexible solar arrays by using reaction wheels, and piezoelectric transducers as sensors and actuators,” *Acta Astronautica*, vol. 139, pp. 357–366, 2017. DOI: 10.1016/j.actaastro.2017.07.018.

[19] H. Nhalil, M. Schultz, S. Amrusi, A. Grosz, and L. Klein, “Parallel array of planar hall effect sensors for high resolution magnetometry,” *Journal of Applied Physics*, vol. 133, no. 20, p. 204 501, May 2023. DOI: 10.1063/5.0151569.

[20] Y. Ye, C. He, B. Liao, and G. Qian, “Capacitive proximity sensor array with a simple high sensitivity capacitance measuring circuit for human–computer interaction,” *IEEE Sensors Journal*, vol. 18, no. 14, pp. 5906–5914, 2018. DOI: 10.1109/JSEN.2018.2840093.

[21] G. Geron, C. Prelle, H. Al Hajjar, J. Terrien, and M. U. Khan, “Characterization of a magnetic localization method based on hall effect sensor array for microrobot position tracking,” *Journal of Micro-Bio Robotics*, pp. 1–13, 2023. DOI: 10.1007/s12213-023-00154-9.

[22] F. Piron, D. Morrison, M. R. Yuce, and J.-M. Redoute, “A review of single-photon avalanche diode time-of-flight imaging sensor arrays,” *IEEE Sensors Journal*, vol. 21, no. 11, pp. 12 654–12 666, 2020. DOI: 10.1109/JSEN.2020.3039362.

[23] J.-O. Nilsson and I. Skog, “Inertial sensor arraysa literature review,” in *2016 European Navigation Conference (ENC)*, IEEE, 2016, pp. 1–10. DOI: 10.1109/EURONAV.2016.7530551.

[24] M. Yang *et al.*, “Arrayed piezoresistive and inertial measurement unit sensor-integrated assistant training tennis racket for multipoint hand pressure monitoring and representative action recognition,” *Science China Technological Sciences*, pp. 1–11, 2023. DOI: 10.1007/s11431-022-2377-7.

[25] W. Xia, P. Che, M. Ren, X. Zhang, and C. Cao, “A flexible p (vdf-trfe) piezoelectric sensor array for orientation identification of impulse stress,” *Organic Electronics*, vol. 114, p. 106 729, 2023. DOI: 10.1016/j.orgel.2022.106729.

[26] J. H. Park *et al.*, “Feasibility study on fiber-optic inorganic scintillator array sensor system for muti-dimensional scanning of radioactive waste,” *Nuclear Engineering and Technology*, vol. 55, no. 9, pp. 3206–3212, 2023. DOI: 10.1016/j.net.2023.06.002.

[27] A. D’Amico, G. Ferri, and A. Zompanti, “Sensor systems for breathprinting: A review of the current technologies for exhaled breath analysis based on a sensor array with the aim of integrating them in a standard and shared procedure,” *Breath analysis*, pp. 49–79, 2019. DOI: 10.1016/B978-0-12-814562-3.00004-7.

[28] D. Li *et al.*, “Virtual sensor array based on piezoelectric cantilever resonator for identification of volatile organic compounds,” *ACS Sensors*, vol. 7, no. 5, pp. 1555–1563, 2022. DOI: 10.1021/acssensors.2c00442.

[29] D. Esposito *et al.*, “A piezoresistive array armband with reduced number of sensors for hand gesture recognition,” *Frontiers in neurorobotics*, vol. 13, p. 114, 2020. DOI: 10.3389/fnbot.2019.00114.

[30] M. Kim, H. Choi, K.-J. Cho, and S. Jo, “Single to multi: Data-driven high resolution calibration method for piezoresistive sensor array,” *IEEE Robotics and Automation Letters*, vol. 6, no. 3, pp. 4970–4977, 2021. DOI: 10.1109/LRA.2021.3070823.

[31] J. Zhang *et al.*, “Design, fabrication, and implementation of an array-type mems piezoresistive intelligent pressure sensor system,” *Micromachines*, vol. 9, no. 3, p. 104, 2018. DOI: 10.3390/mi9030104.

[32] A. K. M. Mahfuzul Islam *et al.*, “Programmable neuron array based on a 2-transistor multiplier using organic floating-gate for intelligent sensors,” *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 7, no. 1, pp. 81–91, 2017. DOI: 10.1109/JETCAS.2016.2628411.

[33] B. Fang *et al.*, “A petal-array capacitive tactile sensor with micro-pin for robotic fingertip sensing,” in *2020 3rd IEEE International Conference on Soft Robotics (RoboSoft)*, IEEE, 2020, pp. 452–457. DOI: 10.1109/RoboSoft48309.2020.9116047.

[34] F. Khatoon, M. Ravan, R. K. Amineh, and A. Byberi, “Hand gesture recognition pad using an array of inductive sensors,” *IEEE Transactions on Instrumentation and Measurement*, vol. 72, pp. 1–11, 2023. DOI: 10.1109/TIM.2023.3280526.

[35] C. Tholin-Chittenden and M. Soleimani, “Planar array capacitive imaging sensor design optimization,” *IEEE Sensors Journal*, vol. 17, no. 24, pp. 8059–8071, 2017. DOI: 10.1109/JSEN.2017.2719579.

[36] S. Dominguez-Gimeno, C. Medrano-Sanchez, R. Igual-Catalan, J. Martinez-Cesteros, and I. Plaza-Garcia, “An optimization approach to eliminate crosstalk in zero-potential circuits for reading resistive sensor arrays,” *IEEE Sensors Journal*, vol. 23, no. 13, pp. 14 215–14 225, 2023. DOI: 10.1109/JSEN.2023.3277714.

[37] S. Guorong *et al.*, “Guided wave focusing imaging detection of pipelines by piezoelectric sensor array,” *Journal of Sensors*, vol. 2022, no. 1, p. 4 731 341, DOI: 10.1155/2022/4731341.

[38] J. Chen, P. Liu, J. Hu, J. Yang, and C. Chen, “Design of an array of piezoresistive airflow sensors based on pressure loading mode for simultaneous detection of airflow velocity and direction,” *Review of Scientific Instruments*, vol. 93, no. 2, p. 025 001, 2022. DOI: 10.1063/5.0073669.

[39] H. Liu *et al.*, “Active detection of small uxo-like targets through measuring electromagnetic responses with a magneto-inductive sensor array,” *IEEE Sensors Journal*, vol. 21, no. 20, pp. 23 558–23 567, 2021. DOI: 10.1109/JSEN.2021.3107842.

 ISBN: 978-1-68558-208-1