New Trends in Smart Sensors for Industrial Applications—Part I

IN MODERN industry, productivity, quality, reliability, and safety heavily depend on the performance of the sensors employed. They form an interface between the production equipment and the surrounding environment providing feedback based on the results of the executed operations. Thus, sensors can be found in an extremely wide range of applications in industrial systems, in which they play a very important role.

The first element in any control and measurement system is the sensor itself. Sensor performance defines the performance of the control/measurement system and that of the industrial system as a whole. It is not possible to distinguish between correct and incorrect information provided by a sensor, unless additional information provided by another sensor is used. This validates the statement: *No machine can perform better than its sensors*.

A characteristic feature of sensors in industrial applications is nonoptimal working conditions. Often sensors used in industry have to deliver excellent performance in harsh and inaccesible environments (e.g., very high or very low temperature, high humidity, vacuum, aggressive treatment, vibrations, interferences, limited space, reduced power consumption, etc.) without the possibility of periodic calibration. The replacement of such sensors can be very complex, time consuming, and therefore, very expensive, even when the sensor itself is of low cost. That is why, in addition to fulfilling their primary role, sensors used in industry have to possess additional functionality features such as self-diagnostics, self-calibration, autonomous operation with minimum power consumption, wired or wireless sensor network (WSN) compatibility, and a small form factor. Also, along with the increased functionality, industrial sensors need to be extremely robust and reliable. In order to meet all the aforementioned requirements, such sensors need to possess a certain level of intelligence or smartness.

This "Special Section on New Trends in Smart Sensors for Industrial Applications" of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, will be published in two issues of the journal. In this issue, the first 13 papers are presented.

In item 1) of the Appendix, the design and development of an energy-autonomous, wireless, strain monitoring system for an aircraft is introduced. The energy required for this sensor is harnessed from the environmental temperature during take-off and landing of the aircraft by means of an innovative thermoelectric energy harvester. The wireless strain monitoring architecture can be extended to other industrial monitoring applications as well.

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In item 2) of the Appendix, an unmanned aerial vehicle (UAV)-based approach is proposed for automatic detection of surface cracks on wind turbine blades. In this data-driven model, the effectiveness of crack detection has been validated with UAV images taken from a commercial wind farm. Monitoring the condition of the wind turbine blade is valuable, and the approach presented gives promising results.

In item 3) of the Appendix, a sensor that directly measures the flow-induced shear stress in a wind tunnel wall is presented. It is a piezoelectric sensor designed to detect shear stress alone while suppressing the effect of normal stress due to vortex lift-up. The piezoelectric shear stress sensor prototype developed has a sensitivity of 56.5 ± 4.6 pC/Pa during turbulent wind currents.

In item 4) of the Appendix, an online sensor system that monitors the condition of power transmission belts is presented. Static charge that accumulates in a transmission belt, when it is in motion, is detected using a smart electrostatic sensor unit. The sensor unit converts the induced charge into proportional voltage signals. From this signal, the belt speed and vibration are measured using cross-correlation and spectral analysis.

In item 5) of the Appendix, a noncontact measurement system for overhead line voltage measurement is reported. The sensor developed is batteryless and exhibits high thermal stability. The measurement scheme exploits both the electro-optic effect in $LiNbO_3$ and the stray capacitance present in the air.

In item 6) of the Appendix, the design, development, and evaluation of a nitrate sensor suitable for application in the agricultural industry is discussed. The sensor unit uses a specially designed planar interdigital sensor. The sensor developed is temperature-compensated and incorporates a WiFi-based Internet of Things (IoT). The system developed can be used for water quality monitoring in industrial, agricultural or urban environments.

In item 7) of the Appendix, the authors report a technology that employs force sensors with an end effector as an interface. A method to compute the contact position for a structure-variable end effector, in order to expand the range of application, is also presented.

In item 8) of the Appendix, a special electronic nose with a sensor array of 34 sensors is developed to detect common bacteria such as *S. aureus*, *P. aeruginosa,* and *E. coli* that may be present in a wound. After analyzing 480 samples of experimental data, a recognition rate of 86.54% of the test set was achieved, without sensor array optimization. To simplify the sensor array and improve the recognition rate for bacterial samples, a number of schemes have been investigated, the results of which are provided in this paper.

In item 9) of the Appendix, the utilization of a new wireless platform for next-generation liquid sensing is demonstrated. This scheme makes use of paper-microfluidics and RFID technology. The fabrication of RFID tags and the required microfluidics are realized using inkjet printing and additive manufacturing that keeps the cost of manufacturing low.

In item 10) of the Appendix, the optical performance of SOI lateral p-i-n diodes with four different backside reflectors placed below them, i.e., gold, aluminum, substrate, and black-silicon reflectors, are investigated and the results presented. Industrial applications cover compact, portable, and low-power optical sensor system design for RGB, oxygen sensing, or plasma monitoring.

In item 11) of the Appendix, a time-grating capacitive displacement sensor that can relax the manufacturing precision required, while assuring accurate displacement measurement, is proposed. This is achieved by utilizing the overlapping area integral method, the smoothing effect of the electric field, etc. The prototype developed is based on PCB manufacturing technology with a manufacturing accuracy of 10 μm, and achieves an accuracy of 0.38 μm over a 220-mm range after calibration.

In item 12) of the Appendix, the outcome of an experimental study conducted on heat transport in microscale gas gaps is presented. In this study, the thermal conductance of four gas gaps from 220 nm to 21 μm was measured. The outcome provides information on the effect of size, which will be valuable for MEMS devices that have such gas gaps.

In item 13) of the Appendix, an improvement in the conventional lock-in method, which is widely used for various measurement applications, is discussed, along with results and inferences obtained from the simulation and experimental studies conducted. This paper focuses on the need for an online estimator for lock-in amplifier-based system measurements. The convergence of the estimates is discussed, followed by possible applications.

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APPENDIX
RELATED WORK

1) L. V. Allmen *et al.*, "Aircraft strain WSN powered by heat storage harvesting," *IEEE Trans. Ind. Electron.* vol. 64, no. 9, pp. 7284–7292, Sep. 2017.
2) L. Wang and Z. Zhang, "Automatic detection of wind turbine blade surface cracks based on UAV-taken images," *IEEE Trans. Ind. Electron.* vol. 64, no. 9, pp. 7293–7303, Sep. 2017.
3) T. Kim *et al.*, "Piezoelectric floating element shear stress sensor for the wind tunnel flow measurement," *IEEE Trans. Ind. Electron.* vol. 64, no. 9, pp. 7304–7312, Sep. 2017.
4) Y. Hu, S. Zhang, Y. Yan, L. Wang, X. Qian, and L. Yang, "A smart electrostatic sensor for online condition monitoring of power transmission belts," *IEEE Trans. Ind. Electron.* vol. 64, no. 9, pp. 7313–7322, Sep. 2017.
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9) W. Su and M. M. Tentzeris, "Smart test strips: Next-generation inkjet-printed wireless comprehensive liquid sensing platforms," *IEEE Trans. Ind. Electron.* vol. 64, no. 9, pp. 7359–7367, Sep. 2017.
10) G. Li *et al.*, "Multiple-wavelength detection in SOI lateral PIN diodes with backside reflectors," *IEEE Trans. Ind. Electron.* vol. 64, no. 9, pp. 7368–7376, Sep. 2017.
11) K. Peng, Z. Yu, X. Liu, Z. Chen, and H. Pu, "Features of capacitive displacement sensing that provide high-accuracy measurements with reduced manufacturing precision," *IEEE Trans. Ind. Electron.* vol. 64, no. 9, pp. 7377–7386, Sep. 2017.
12) Z. Huang, J. Wang, S. Bai, J. Guan, F. Zhang, and Z. Tang, "Size effect of heat transport in microscale gas gap," *IEEE Trans. Ind. Electron.* vol. 64, no. 9, pp. 7387–7391, Sep. 2017.
13) J. Leis and D. Buttsworth, "Determining the convergence of synchronous measurements for embedded industrial applications," *IEEE Trans. Ind. Electron.* vol. 64, no. 9, pp. 7392–7398, Sep. 2017.

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