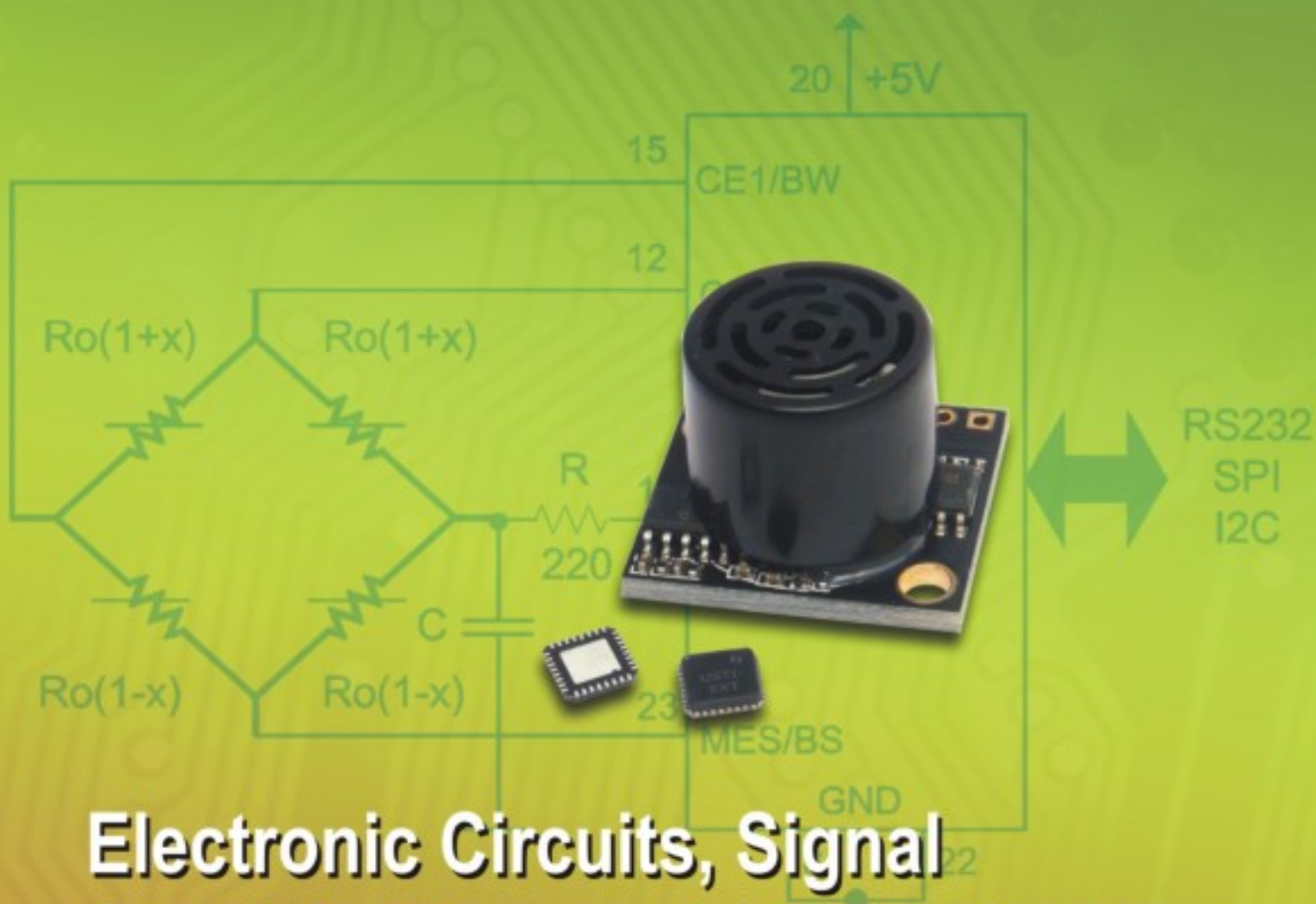


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Handbook of Laboratory Measurements and Instrumentation

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Low Concentration Sodium Chloride Salinity Detection System

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Abstract: An AC Andersons bridge coupled with a low matching impedance solenoid coil is employed to detect and measure low concentration of sodium chloride aqueous solutions (ppm) is designed and constructed. The sensory system is independent of the excited driving frequency. The finite element method simulation of the sensor element is simulated and modeled with approximately 1.23 million 3D tetrahedron meshes with CST EM studio. The constructed induction sensor is sensitive and able to observe Millipore Milli-Q low resistivity (18.2 MOhm-cm) ultrapure water and various concentration of lab prepared sodium chloride solutions. The observed sodium chloride system sensitivity is $-1.5228 \times 10^{-4} \ln\{\text{NaCl}(\text{ppm})\}$ with high correlation constant of $R = 0.9835$.

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Keywords: Aqueous NaCl, Induction sensor, Andersons' bridge, Non-invasive, ppm.

1. Introduction

Interest in accurate determination of sodium chloride radicals in aqueous form [1, 2], specifically in the low concentration range of parts-per-million (ppm) range is crucial for biological application [3, 4] for instance by way of impedance spectroscopy technique using Langmuir-Blodgett theory [5], direct hydrogels permeation and kinetics desorption methods [6]. The level of sodium chloride concentration beyond the standard threshold in hypertension patients for extensive period will lead to DNA damage [7] and health complications [8]. Non-invasive electromagnetic sensing methods [9] and in-situ chronoamperometry method coupled with a Cottrell-related equation [10] have been investigated. These systems are off sites [9], tedious to operate [11, 12, 13] and easily contaminated [13]. Biomedical device and sensor researchers have worked on sodium and/or chloride ions detection but at higher concentration level (> 1000 ppm or 1 ppt) in both in vitro and in vivo situations, such as the

embedded evanescent waveguides spectrometry [11] and optical fiber based sensor [11, 12, 13] which needs constant optical re-alignment.

A frequency independent induction sensor utilizing a balanced AC Andersons Bridge for low concentration of sodium chloride solutions, in tens of ppm limits is reported in this article. The induction sensor presented is constructed with a low impedance solenoid coil as the sensing arm of a four elements Anderson's full bridge electronics circuit. The Andersons AC Bridge is chosen because of its inherent frequency independent characteristics similar to Owens' Bridge detection system [14]. The sodium chloride induction sensory system constructed is non-contact and non-invasive as the sensing methodology does not require the skin of the patients to be punctured such as in the regular medical checkup or blood work. By deploying this highly sensitive induction sensor device, it will ensure that no fluid is exchanged throughout the measuring process [15]. Fast, accurate, and real time sodium chloride concentration sensing is favorably sought to reduce abnormal or excessive sodium chloride related complication [8, 16] and mortality rate [17]. It will also promote normalcy on quality of lifestyle for hypertension disease patients [18, 19]. The proposed sodium chloride induction sensor could be employed for the standardized minus the clinical in-vivo blood sample taking for periodic monitoring.

2. Device Design and Realization

The theoretical electromagnetic flux of the induction sensor responses to the different sodium chloride concentrations via the sensing arm are modeled and simulated using CST 2011 EM Studio. The total mesh size is approximately 1.23M 3D tetrahedron elements. The model is as shown in Fig. 1. This CST model is analyzed under distributed computing method on Dell T7500 Precision 64-bit workstation; with 32 GB capacities installed with Nvidia Tesla a C2070 GPU. The CST time domain parametric solver is used. The electromagnetic simulation is as shown in Fig. 2.

The sodium chloride detection system consists of an AC Andersons Bridge and a solenoid as the sensing element. AC Andersons Full Bridge, shown in Fig. 3, is selected as part of the induction sensor electronics due to its inherent input frequency independent characteristic. The AC Andersons Bridge is initially DC balanced to nullify any external environmental fluctuation such as source current fluctuation, voltage frequency variation, etc.

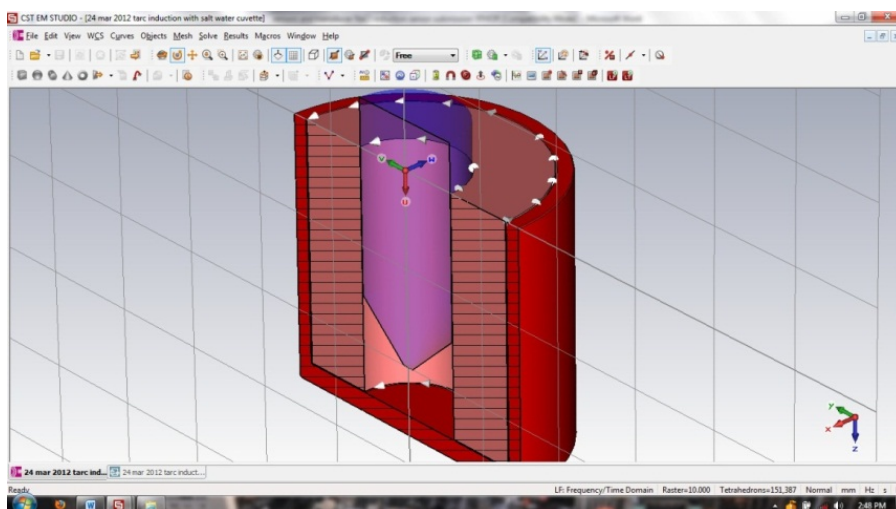


Fig. 1. CST model of the induction sensor with aqueous sodium chloride polymer cuvette.

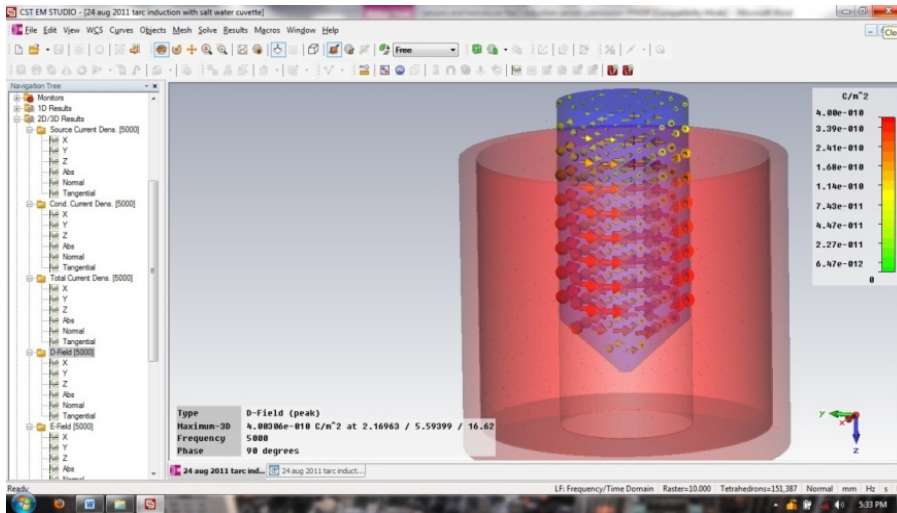


Fig. 2. CST EM field model of the induction sensor with the aqueous sodium chloride cuvette inserted.

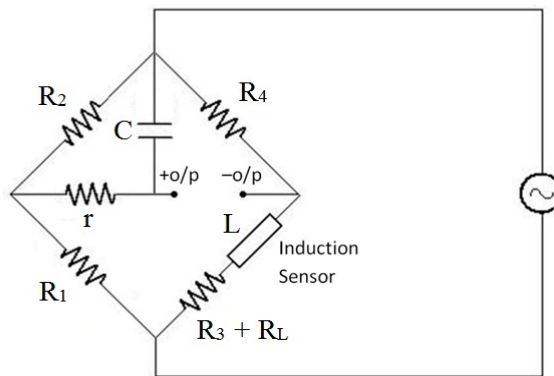


Fig. 3. Andersons full bridge schematic layout.

The full Anderson bridge circuit in Fig. 3 is further simplified by means of using analog circuit network analysis [20] to convert the π -network to T-network to exploit it for theoretical bridge balancing and for low concentration sensing.

From a DC balanced Andersons Bridge, as shown in Fig. 4, the relationship between the reactance and impedance is as formulated in Equation 1.

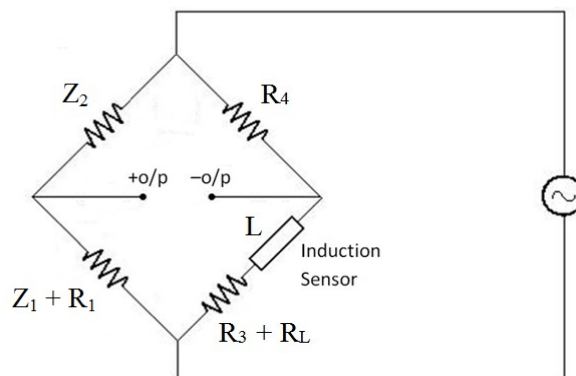


Fig. 4. Reduced Andersons full bridge schematic layout.

$$\frac{Z_2}{Z_1 + R_1} = \frac{R_4}{R_3 + R_2 + X_L}, \quad (1)$$

where, Z_1 , and Z_2 are the effective impedances, R_1 , R_3 and R_4 are the resistances of the Andersons Bridge, and X_C , X_L are the impedances of induction sensor coil respectively.

$$\begin{aligned} Z_1 &= \frac{rR_2}{r + R_2 + X_C} \\ Z_2 &= \frac{R_2X_C}{r + R_2 + X_C} \\ X_C &= \frac{1}{2\pi fC} \\ X_L &= 2\pi fL \end{aligned} \quad (2)$$

The existence of sodium chloride ions, even in low ppm concentration, would induce a change in the sensing arm self-induction field. These perturbations due to the ionic sodium chloride radicals will in turn unbalance the initially balanced AC Andersons Bridge (Equation 3).

$$R_2[(R_3 + R_L) + (2\pi fL)R_2] = (2\pi fC)R_4\{r[(R_1 + R_2) + R_1R_2]\} + R_1R_4. \quad (3)$$

While the AC Andersons Bridge is balanced, both the DC and AC terms (capacitors and inductor reactance components) are equal and are cancelled out, leaving the sample inductance to be determined experimentally (Equation 4). It can be inferred from Equation 4 that, the resultant bridge output is independent of input source frequency across the bridge.

$$\begin{aligned} \frac{R_4}{R_2} &= \frac{R_3 + R_L}{R_1} \\ \frac{L}{C} &= \frac{R_4}{R_2} \{R_1R_2 + r(R_1 + R_2)\} \end{aligned} \quad (4)$$

The experimental setup schematic is as shown in Fig. 5. The 200 mV, 4.0 kHz sinusoidal AC driving frequency is provided by the Tektronix arbitrary function generator, AFG3021. The balanced bridge sensing arm output is connected to a digital EG&G DSP7260 lock-in amplifier that utilizes the phase detection method to further reduces the electronic noises and improves the inferred ppm concentration measurements readout.

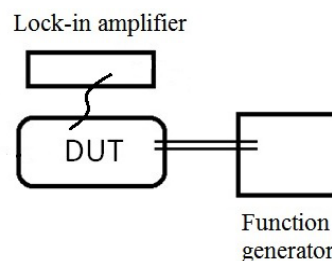


Fig. 5. Schematic of the induction sensor experimental setup.

The solenoid coil used is an open iron frame ISO9000 linear solenoids. This TAU-0630 induction coil can function optimally at a relative humidity of between 45 % and 85 %. The maximum operation temperature is 65 °C, which is ample for possible in-vivo or in-vitro biological detection. In addition, the solenoid copper coil has a 100 MOhm insulation resistance.

Aqueous sodium chloride solutions of different ppm concentration are prepared with Millipore Milli-Q ultrapure (Type I) integral water. The Milli-Q water used has a resistivity of 18.2 MOhm-cm. The total organic carbon (TOC) of the ultrapure water used is controlled below 5 ppb ($\mu\text{g/L}$), in order to reduce stray induction observation. Several batches of sodium chloride aqueous concentration ranging from 1 ppm to 120 ppm are prepared using Hamburg Chemical NaCl stock # 135660. A milliliters chemical cuvette [14] is made out of polymer with constant low permeability, 6.0 mm diameter is used to hold the aqueous sodium chloride solutions. Precise sodium chloride in powder form is weighted with the help of a balance scale (Sartorius model # ED224S). The weighted powder is then mixed with the ultrapure Milli-Q water. These sodium chloride solutions are next pipetted into the polymer cuvette for experimental measurements [14].

3. Results

The induction sensor readings are measured and recorded into an excel spreadsheet with the help of a custom designed National Instruments LabView 2011 program. The program front panel is designed as shown in Fig. 6. Each readings recorded is an average of exactly 3000 measurements. The readings are obtained in real-time via the digital lock-in amplifier with line-in bandpass filter.

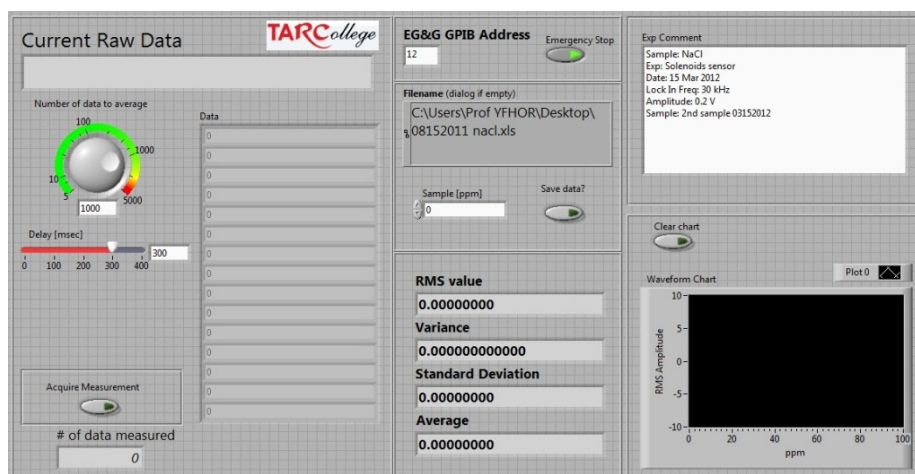


Fig. 6. Induction sensor real-time LabView 2011 front panel.

The input sinusoidal voltage is 200.0 mV. The independent of external driving frequencies trend of the Andersons Bridge remove all the frequency dependency related errors and intolerances in the data acquisition process and is important when employing the proposed induction sensor to monitor and detect small sodium chloride concentration in the range of ppm. It will significantly reduce the error in monitoring the sodium chloride under prolonged testing cycle.

The corresponding induction sensor output as a function of the different sodium chloride concentrations is as plotted in Fig. 7. The data is normalized with respect to the 0 ppm Milli-Q high purity calibration standard. The input driving frequency is set at 4.0 kHz. A natural logarithm theoretically simulated curve is also presented and used to map the induction sensor responses to the sodium chloride ppm variations. The experimental induction sensor sensitivity is $-1.5228 \times 10^{-4} \ln\{\text{NaCl (ppm)}\}$ with a very high correlation $R^2 = 0.9673$. This induction sensor sensitivity is more than adequate to detect the controlled normal and high sodium chloride concentration aqueous solutions, such as blood salinity content (>1500 mg per day for hypertension, diabetes mellitus type II, or above 51 years old) [21].

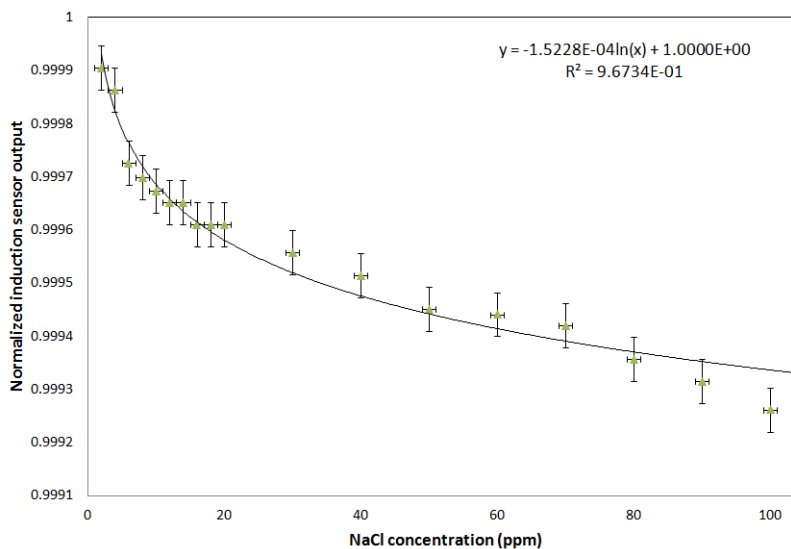


Fig. 7. Normalized induction sensor output as a function of sodium chloride concentration in ppm.

4. Conclusion

An input frequency independent electromagnetic flux induction sensor system utilizing a low matching impedance solenoid coil is designed and realized. Simulation of the electromagnetic field measured by the solenoid coil sensing arm with respect to the various aqueous sodium chloride solutions are modeled in 3D using CST EM Studio 2011. A full AC Andersons bridge is used to eliminate external perturbations. The real-time analog solenoid coil response is captured by the Lock-in amplifier via a custom LabView program. The induction sensor can distinguish and measure the aqueous sodium chloride ranging from 1 ppm to 100 ppm. The sodium chloride aqueous solutions are prepared with Millipore Milli-Q ultrapure water of 18.2 MOhm·cm with TOC of 5 ppb. The induction sensing electronics circuit is independent of input source frequency. The experimental induction sensor system sensitivity is $-1.5228 \times 10^{-4} \ln\{\text{NaCl}(\text{ppm})\}$ with a very high correlation R of 0.9835.

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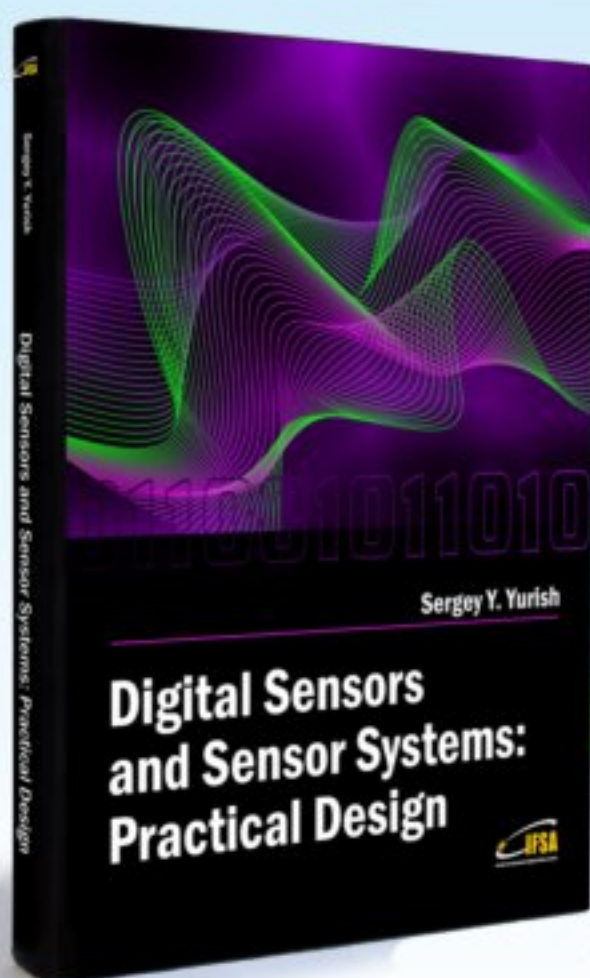
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