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A Stainless Steel Electrode Phantom to Study the Forward Problem of Electrical Impedance Tomography (EIT)

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Abstract: A stainless steel electrode phantom is developed to study the Forward Problem of Electrical Impedance Tomography. A sixteen-electrode array is placed inside the phantom tank filled with KCL solution. A low magnitude sinusoidal current is injected at the phantom boundary and the boundary potentials are measured using adjacent current injection protocol. A forward solver is developed using Finite Element Method and the differential potentials are numerically calculated by solving the governing equation of EIT. Measured potential is compared with the differential potential calculated for known current and solution conductivity for detecting and eliminating the source of error in the voltage signal for better image reconstruction. *Copyright © 2009 IFSA.*

Keywords: Electrical impedance tomography, Phantom, Forward problem, Finite element method, Common mode electrode

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1. Introduction

Electrical Impedance Tomography (EIT) is an image reconstruction technique in which the electrical conductivity of a conducting domain is reconstructed from the surface potential developed by injecting a current signal at the object boundary (Fig. 1). Electrical impedance tomography has been extensively researched in clinical diagnosis [1], biomedical engineering [2] and biotechnology [3] for its several advantages [4], [5], [6] over other computed tomographic techniques. Due to poor signal to noise ratio and poor spatial resolution [7] the medical EIT systems is not yet accepted as the regular medical imager.

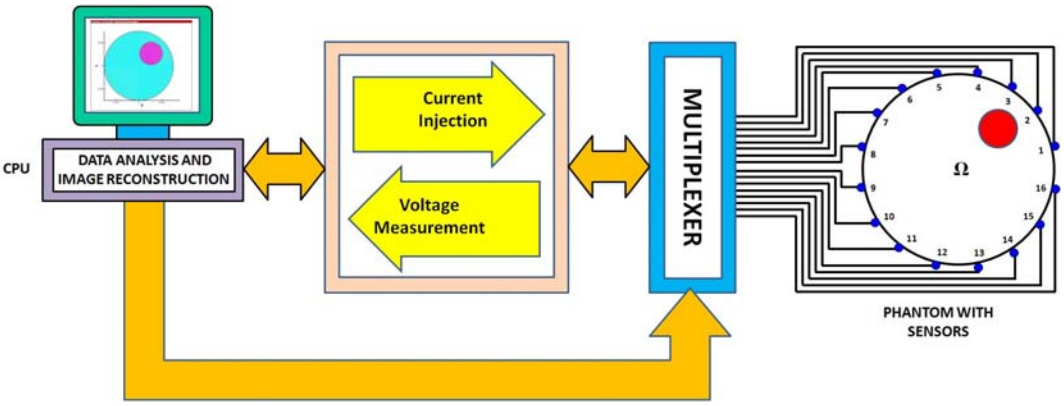


Fig. 1. A Modern EIT System Architecture.

The reconstructed image quality in impedance tomography greatly depends on the performance of Forward Solver (FS) and the measurement errors which is influenced by the phantom geometry, electronic behavior of the current injector, data acquisition module and signal conditioners. Before reconstructing the conductivity from the measured potentials it is advantageous to eliminate the measurement error produced by the phantom geometry and EIT-hardware for better image reconstruction. Hence it is very important to study and analyze a practical EIT-phantom and associate electronics (EIT-electronic hardware) prior to the image reconstruction for eliminating the measurement errors. In this direction a 16-electrode phantom is developed and the Forward Problem (FP) of a 2-D EIT is studied with a FEM based forward solver. Potential data is collected at the phantom boundary by injecting a sinusoidal current using adjacent (or neighboring) current injection method (Fig. 2) and the differential potentials are numerically estimated using the forward solver developed. Comparing measured voltage with the calculated data it is attempted to find the sources of error associated with the electronic hardware, phantom geometry and the electrode array structure to improve data quality.

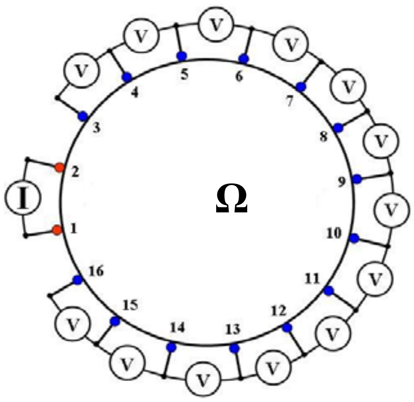


Fig. 2. Adjacent or Neighboring Method of Electrode Switching Protocol in EIT.

2. Materials and Methods

2.1. EIT

Electrical Impedance Tomography is a non linear Inverse Problem (IP) in which the electrical conductivity distribution across a closed domain (Ω) of interest inside a volume conductor is reconstructed from the surface potentials measured at the domain boundary (∂Ω) by injecting a low frequency (10 kHz to 1 MHz) [4] and low magnitude, constant current through an array of 16×2^n (n= 0, 1, 2, 4…) electrodes surrounding the domain to be imaged. A low frequency constant current is injected to the object boundary and the surface potential developed is collected by an efficient data acquisition system (Fig. 1). The voltage data collected by the data acquisition system is processed in PC using an image reconstruction algorithm consisting of forward and inverse solvers.

2.1.1. Governing Equation

Electrical potential (φ) produced by a low frequency sinusoidal current applied to a homogeneous and isotropic medium with low magnetic permeability (biological tissue) and without any internal current source can be represented as [8]:

$$\nabla\cdot\sigma\nabla\phi=0 \tag{1}$$

This nonlinear partial differential equation representing the electro-dynamics of EIT is known as the Governing Equation of EIT [8] and has an infinite number of solutions. Boundary conditions required to restrict these solutions can be applied to specify the value of certain parameters on the surface. These may be either the potential at the surface (Dirichlet conditions), the current density crossing the boundary (Neumann conditions), or mixed conditions.

2.1.2. Forward Problem (FP)

A relation between the measured potentials and the domain conductivity can be obtained [9] from the equation (1) using FEM as:

$$[\Phi]=[K][\sigma], \tag{2}$$

where [σ] is a vector of conductivity values, [Φ] is the vector of voltage measurements and [K] is the transformation matrix relating φ to σ. If K and σ are known, equation (2) can be solved numerically to calculate the nodal potentials of the domain for the known current injection. It is known as the “forward problem”.

2.1.3. Inverse Problem (IP)

From the equation (2) we get,

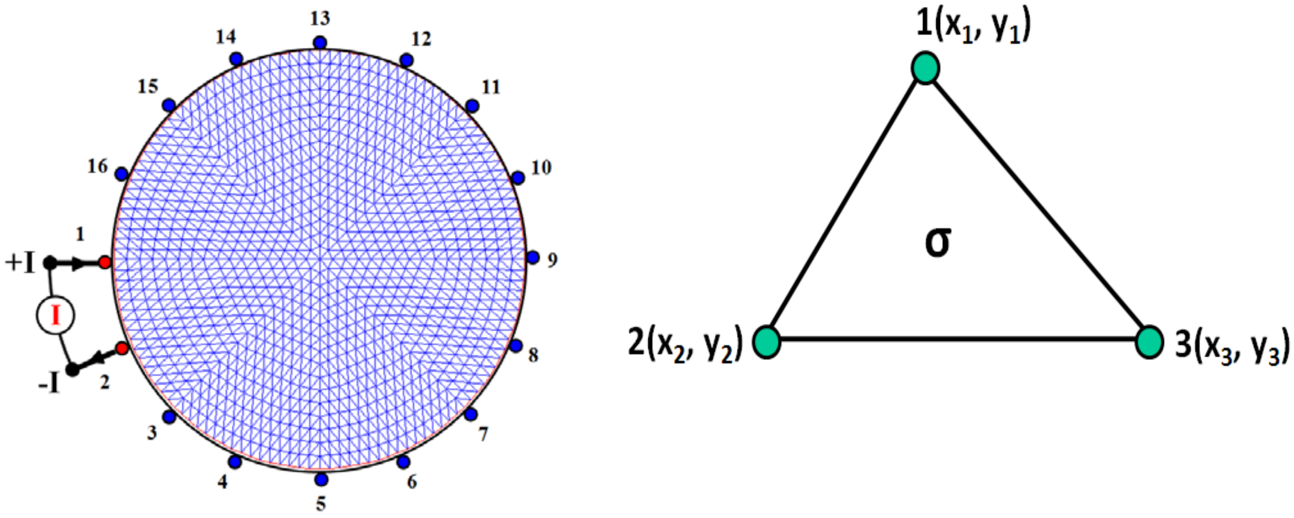
$$\sigma = K^{-1}\Phi \tag{3}$$

That means if transformation matrix K and the surface potentials Φ are known then the conductivity can be reconstructed. This is known as the “inverse problem”.

2.2. Forward Solver

Forward Problem is the basis of EIT and it is essentially to be solved to calculate the boundary potential for estimating the conductivity update (Δσ) for each iteration in Inverse Problem. Solving the FP, for an EIT system, the instrumentation error can be detected to eliminate the noise in the voltage signal for better image quality. An EIT-forward solver is developed in MatLab 7.0 using Finite

Element Method (FEM) which has several advantages [10], [11] over other numerical techniques. Due to its ability to model arbitrary geometries and various boundary conditions, the Finite Element Method [12] is the most common method currently used for the numerical solution of EIT problems [11]. The finite element formulation for EIT [11] first discretizes the medium under analysis into a finite number of elements collectively called a finite element mesh (Fig. 3a). Within each element the field variable is approximated by shape functions (interpolation functions) that are defined only within the individual element (Fig. 3b) in terms of the values of the field variables at specified points on the element called nodes. Method of Weighted Residuals (MWR) [12] is the most versatile approach used to formulate the finite element problems [11]. Forward Solver is used to solve the governing equation for calculating the surface potential (V_{ds}) and compared with the measured data (V_{dm}).



(a) (b)

Fig. 3. (a) Current injection to the discretized domain having 2048 elements and 1089 nodes, (b) A single triangular element.

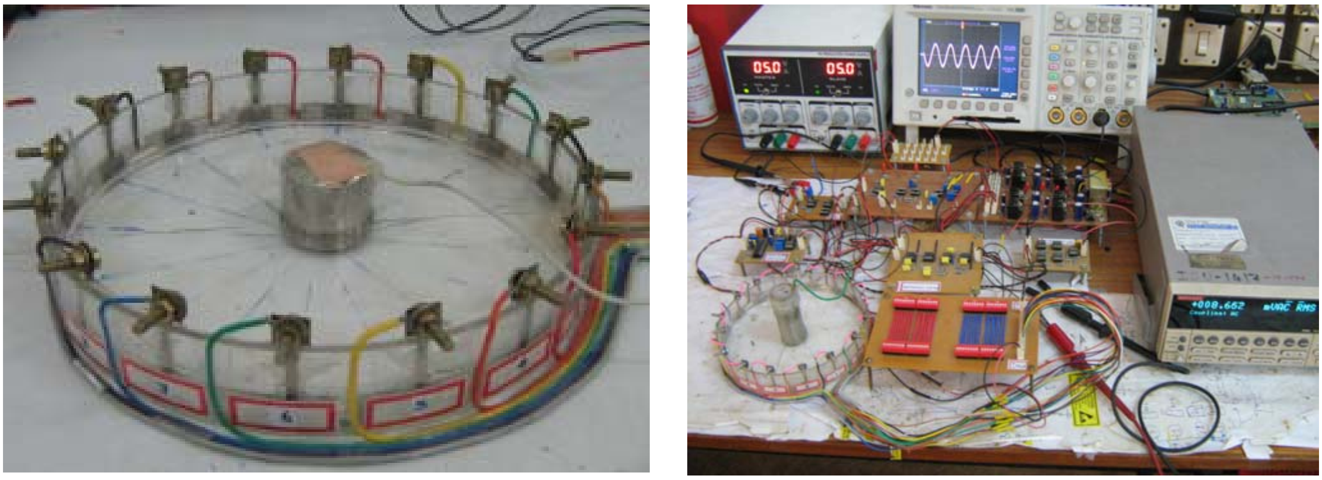
2.3. Instrumentation

A variable frequency (100 Hz – 10 MHz) Voltage Controlled Oscillator (VCO) is developed using MAX038 IC (Maxim, Inc.) [13] to feed a modified Howland current generator developed using AD811 IC (Analog Devices, Inc.) [14]. A simple electrode switching module is developed using single pole single throw (SPST) slide actuated DIP switches [15] based multiplexers. AD811 is a high speed video Op-Amp having very high bandwidth and capability of delivering 1mA current through the maximum load of 3.2 kΩ. A wideband current feedback operational amplifier, the AD811 is optimized for broadcast-quality video systems. The −3 dB bandwidth of 120 MHz at a gain of +2 and the differential gain and phase of 0.01 % and 0.01° (RL = 150 Ω) make the AD811 an excellent choice for all video systems.

2.4. EIT-Phantom

Biological phantoms are a mimic model of the body parts or limbs resembling the similar properties of body parts of the patients or any other practical objects to be imaged. Biological phantoms [30] are required to test analyze and calibrate an EIT system prior to use it in the practical field of application. In this context an EIT phantom is developed (Fig. 4a) for studying the forward problem of wideband

EIT. A cylindrical shallow glass crystallizing dish (diameter - 150 mm height – 25 mm) is used for phantom tank and an array of 16 square stainless steel electrodes is pasted on the inner wall of the glass tank using water proof high strength adhesive glue (Bondtite, Resinova Chemie Ltd., India). Electrodes are identically cut from a 0.1 mm thick type 304 Stainless Steel (SS) sheet and machined them to give all the electrodes approximately equal surface area (10 mm × 10 mm). Electrodes are connected with the multiplexer board through the low resistive flexible multi-strand copper wires fastened with the electrodes by stainless steel screws. All the lead wires are of equal lengths for getting an identical impedance path for each electrode to reduce the mismatch in electrode impedances. A Central Ground Electrode (CGE) or Common Mode Electrode (CME) is placed at the phantom centre and connected to the ground point of the EIT hardwires to reduce the common mode error [16] of the electronic circuits. The phantom tank is filled up with a bathing solution [16] prepared with a 0.05 % (w/v) solution of KCl. Forward problem is solved with a known current injection and a given conductivity of the homogeneous medium. Hence to calculate the potentials at the phantom boundary, the bathing solution conductivity is essentially to be known. A liquid conductivity measurement setup is developed with a rectangular (20 mm × 20 mm × 50 mm) glass container and two stainless steel square electrodes with a surface area of 20 mm × 20 mm. The conductivity measurement setup is filled with the KCl solution and the electrical impedance and phase angle is measured with a current signal of 1mA, 10 kHz–1 MHz using a LCR meter (Model - QuadTech 7600, QuadTech, Inc., USA) and the conductivity is calculated using standard formula. 1 mA 50 kHz sinusoidal current is injected to the phantom and the differential potentials developed are measured (Fig. 4b) using neighboring method of electrode switching protocol. The voltage signal developed on the voltage electrodes is passed through an instrumentation amplifier and narrow band pass filter and then it is acquired by a programmable Multimeter (Model - Keithley 2002, Keithley Instruments, Inc., USA) as well as Digital Storage Oscilloscope (Model - Tektronix: TDS3014B, Tektronix Inc.). Measured potential (V_{dm}) is compared with the calculated data (V_{ds}) obtained from the FS data correction.



(a) (b)

Fig. 4. (a) Practical Biological Phantom developed by us; (b) EIT Data Collection set up.

3. Results and Discussions

Differential potential measured by injecting sinusoidal current is compared with the calculated data obtained. The differential potential is calculated with the phantom data provided by Ider *et al* [17] using our forward solver. The deviation between the potential data generated through our forward solver and that provided by Ider *et al* is only 0.08 % to 0.80 % (Fig. 5). It is observed that CME reduces the common mode error providing a common mode feedback [18] to the EIT electronics. Differential potential is reduced up to 80 mV at the voltage electrode pair opposite to the current electrodes (Fig. 6) by incorporating a CME with a diameter of 0.5 mm. It is noticed that the differential potential is further reduced by increasing the CME diameter. A CME with 25 mm diameter reduces the V_{dm} by 70 mV and hence gives more acceptable potential data (Fig. 7). The voltages across the voltage electrodes near the current electrodes are around 27.2 mV higher than that of V_{ds} due to the high current density. The offset potential is measured for each current projection and then it potential is subtracted from the corresponding V_{dm} data. Thus a more analogous data (Fig. 8) is achieved. It is found the optimum diameter of the CME for our EIT system as 2.5 cm - 3 cm. It is also noticed that the V_{dm} varies significantly (result not shown) varies with the water column above and below the electrode array level.

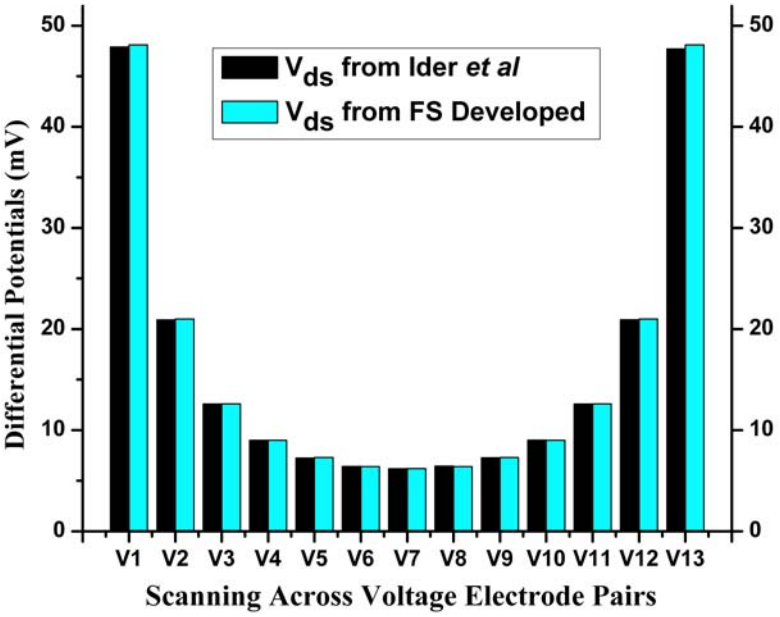


Fig. 5. V_{ds} Curve Compared with Ider *et al* Data.

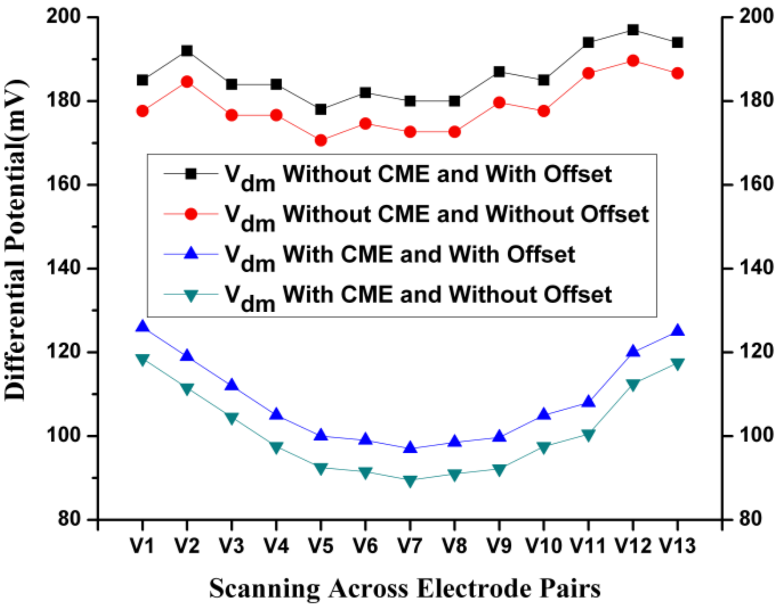


Fig. 6. Voltage correction by incorporating CME with a diameter of 0.5 mm.

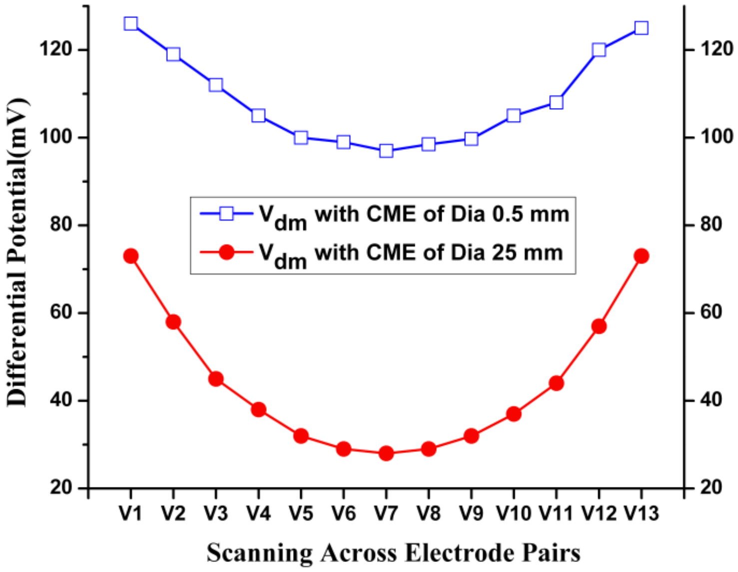


Fig. 7. Voltage correction by improving the CME structure.

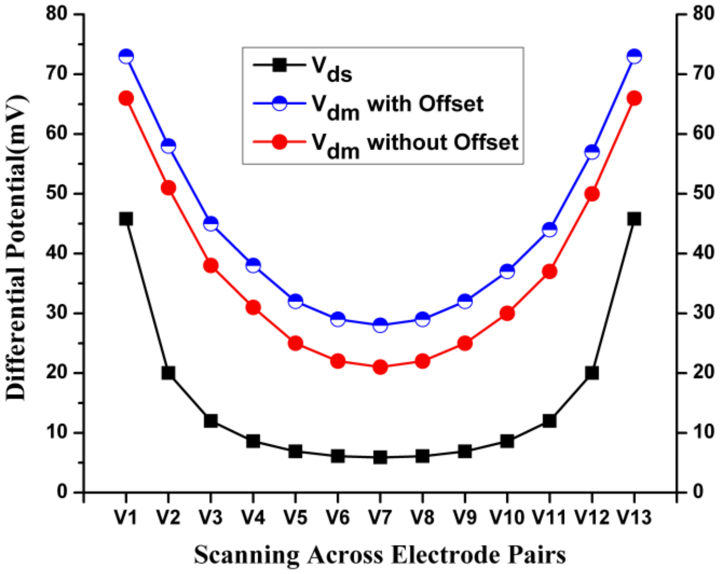


Fig. 8. V_{dm} data correction by offset subtraction.

4. Conclusions

2D EIT assumes that the current conduction is being confined in a plane which is not true for a real volume conductor and hence the geometry of the practical phantom and its sensor array play a significant role in image reconstruction. Hence the image reconstruction accuracy and image resolution in 2D-EIT extensively depends on the phantom design parameters like Phantom height, electrode number, electrode materials, electrode geometry, electrode width, electrode array position etc. In this paper it is intended to investigate the phantom responses for different electrode geometry and electrode array position in bathing solution column. An EIT phantom and simple experimentation are developed and studied with the forward solver to calibrate the EIT system for eliminating the measurement error for better image quality. It is observed that the surface potential can be easily corrected by offset correction and incorporating a suitable CME.

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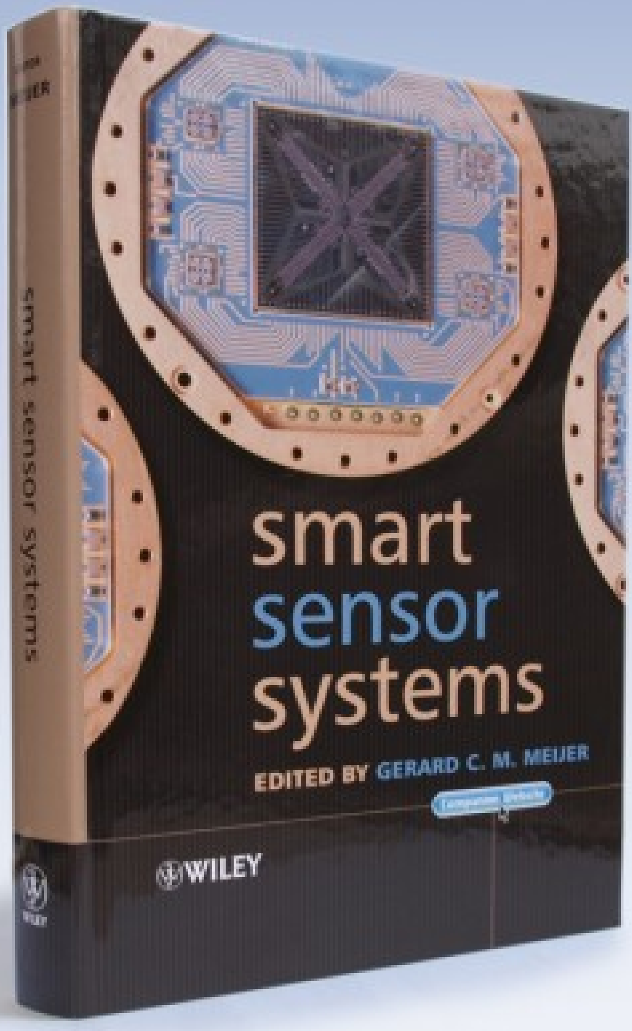
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