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# A Low-Cost Voltage-to-Current Calibration Technique for Multiple-Sensor Systems

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**Abstract**—Systems with multiple sensors pose a problem of heterogeneity, i.e., different sensors have different outputs subject to the same excitation. To tackle this problem, this paper presents a calibration technique for multiple-sensor applications. An array of voltage-to-current converters, followed by a summing inverter, is employed to aggregate the responses of the system, which originated from heterogeneous sensors. The calibration method aims to normalize the output from each independent sensor, so that heterogeneity of the system, like positional error, could be reduced. The performance of the calibration technique had been tested by a prototype with multiple sensors, and the results were found to be satisfactory, which indicates that a reduction from 2% to 0.2% in positional error can be achieved. The proposed method can be implemented by adding only a minimal of passive components, which is suitable for cost-sensitive mass-production-type products.

**Index Terms**—Calibration, heterogeneity, multiple sensors, piezoresistive, voltage to current.

## I. INTRODUCTION

MULTIPLE-SENSOR applications are ubiquitous in real-life applications, e.g., large-scale weighing systems for trucks. In such applications, it is impractical to employ a sole sensor to achieve accurate measurement. In other words, multiple sensors are placed in different locations on such a large platform. One problem to be tackled in such configuration is that homogeneous sensors with the same output subject to the same excitation can rarely be obtained. Consequently, problems due to the heterogeneity of sensors are not uncommon in such applications.

Taking a weighing scale as an example again, if the object under measure is offset from the central position, weight reading would not be accurate, because each sensor is subject to unbalanced force; hence, the expected response would be offset as well. This heterogeneous nature leads to positional error, i.e., different readings are obtained if the load is placed on different locations on a large platform. Table I(a) is an example of such positional error when a load is placed at different locations on a large platform of a weighing scale. It can be observed from Table I(a) that such error could be more than 2% if nothing is done to calibrate the system, although this is based only on one set of readings, which is taken from the prototype system for testing in this paper. Nevertheless, the typical upper bound

is about 2% for this specific product. Taking the values in Table I(a) as an example, if the scale is calibrated at the center position but the object to be measured is placed or located at one of the corners, the measurement error could be as high as 2.16%. In addition, if consecutive measurements are taken around the corner, users may find that the readings are not consistent and that the repeatability could be as worse as 1.73%. Even for consumer electronics applications, these errors are not tolerable.

The origin of the aforementioned problem comes from various sources but could generally be regarded as the heterogeneity nature of the sensors [1]. This will result in a difference in the output voltage between the no-load and full-load situations, as illustrated in Table I(b). The most common source of error is the intrinsic offset error that is present in different sensors [2]. Variance in mechanical construction further enlarges this error. Second, the temperature effect of each sensor could contribute to this error as well [3]. In line with this, some procedures have to be adopted prior to actual application of such systems to eliminate errors due to the heterogeneous nature of different sensors [4], [5]. Usually, three approaches are employed to calibrate the systems with multiple sensors. They are listed here in ascending order of the associated costs for calibration.

- 1) Matching: Measure the output of each sensor, and then, group the sensors with the same output subject to the same excitation [6].
- 2) Calibration: A procedure is employed to calibrate the multiple sensors with additional components [2].
- 3) Networked measuring system: Each unit is equipped with an independent controller, so that calibration and measurement can independently be carried out. This is of particular interest if the monitoring station is physically separated from the other measuring stations. During measurement, each unit is connected in a network configuration, and individual results are sent to a central unit, which is responsible in coming up with the aggregate result [7].

Obviously, all approaches will incur additional costs, but this is inevitable. The major concern is devising a methodology to make the additional costs as low as possible. The first approach (i.e., matching) would normally involve the least additional cost, because each sensor is individually handled, and the matching process is usually done offline. This, however, also means that additional errors added to the system during assembly would be an obstacle for achieving good accuracy. In this paper, the second approach is adopted for multiple-sensor applications. However, by using a voltage-to-current converter, followed by a summing inverter, additional components are

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TABLE I  
 HETEROGENEITY OF MULTIPLE SENSORS. (a) PERCENTAGE ERROR WHEN A LOAD IS PLACED AT DIFFERENT LOCATIONS ON A PLATFORM.  
 (b) DIFFERENCE IN OUTPUT VOLTAGE WHEN A LOAD IS PLACED AT DIFFERENT LOCATIONS ON A PLATFORM

Position	Percentage Error with respect to the centre position
Front Left	1.43
Front Right	1.86
Rear Left	2.16
Rear Right	0.43

(a)

Position	Difference in output voltage between no load and full load, $\Delta V_o$ (mV)
Front Left	22.5
Front Right	22.4
Rear Left	26.6
Rear Right	23.2

(b)

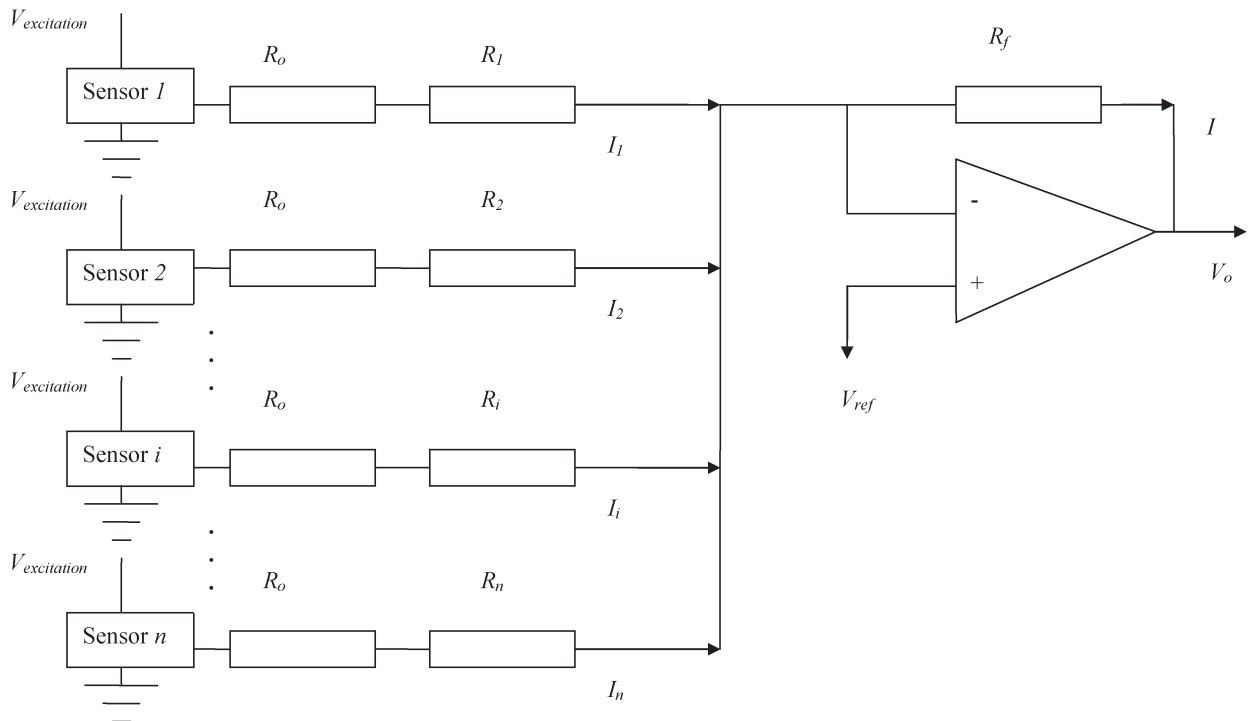


Fig. 1. Simplified diagram of the proposed multiple- or distributed-sensor system.

kept minimal; hence, virtually not many components are added to the system. In addition, the calibration procedure can be done with the aid of computer automation; hence, the associated labor cost is also very low. More importantly, the system is calibrated at a product level, which means that the error due to the tolerance added during assembly could be reduced to a minimal level. The details are discussed here.

## II. DESCRIPTION OF THE CALIBRATION TECHNIQUE

The proposed technique aims to calibrate an array of multiple piezoresistive sensors, which produce voltage change subject to excitation. For example, if the system is a large-scale weighing system, the sensors would induce voltage change due to variation in the resistance of the sensing elements subject to excitation [8]. Fig. 1 shows the simplified circuit diagram of the multiple-sensor system for discussion. Each sensor is connected

to a constant voltage  $V_{excitation}$  from a common constant voltage source that provides excitation for each sensor. The sensors in this proposed system and the prototype to be discussed later are piezoresistive sensors with internal resistance on the order of 1 k $\Omega$ . When the sensors are loaded, each of them will produce a differential voltage because of a change in the internal resistance. Although half-bridge sensors are employed in the prototype, the proposed method is suitable for any similar piezoresistive sensors with a single-end output, which provide a change in voltage output subject to loading.

Sensors 1– $n$  in the diagram represent the array of sensors. Each sensor  $i$ ,  $i = 1, \dots, n$ , produces output voltage  $V_i$ , which is a representation of the measured parameter. All outputs are connected to a voltage-to-current converter, followed by a summing circuit configuration. The output of each sensor will inject a current  $I_i$  subject to an excitation load to the voltage-to-current converter through bias resistor  $R_o$  and the calibrated

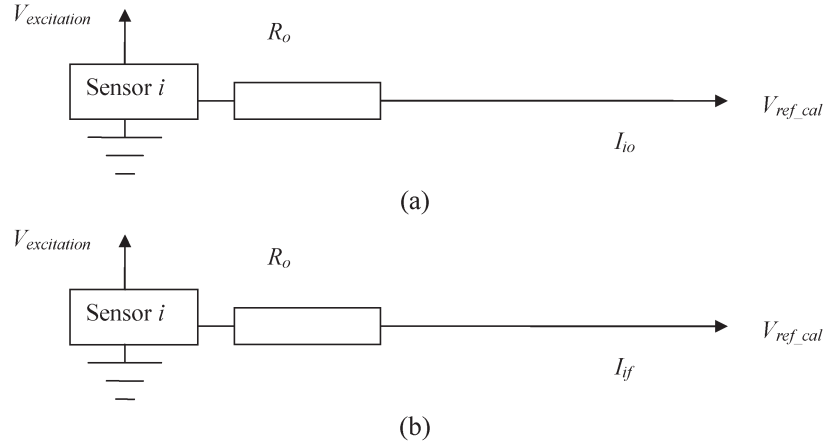


Fig. 2. Simplified diagram for calibrating sensor  $i$ . (a) At no loading. (b) At full loading.

resistor  $R_i$  of sensor  $i$ . (This resistor is determined from the calibration procedures.) In other words, each sensor can be considered as a current source, and the difference between the loaded and no-load currents is a direct representation of the excitation due to the measured parameter. Due to the high input impedance of the operational amplifier, the aggregate injected current from the sensors will pass through feedback resistor  $R_f$ . In other words, the total current flow through the feedback resistor is just the summation of these current sources. In the prototype system,  $V_{excitation}$  is normally in the range of 1.5–3 V for commercial applications with batteries.  $R_o$  is on the order of 10 k $\Omega$  (e.g., 30–60 k $\Omega$ ), so that it is relatively large, compared with the resistance of the sensors, and relatively low, compared with the internal resistance of the operational amplifier. In addition,  $R_i$  is normally on the order of 100  $\Omega$  (sometimes on the order of 1 k $\Omega$ ).

Mathematically, output voltage  $V_o$  is given by

$$V_o = V_{ref} - I \cdot R_f \quad (1)$$

$$I = \sum_i I_i = \sum_i \frac{V_i - V_{ref}}{R_o + R_i}. \quad (2)$$

When the sensors are excited, the difference in output voltage is given by

$$\Delta V_o = -\Delta I \cdot R_f \quad (3)$$

$$\Delta I = \sum_i \Delta I_i = \sum_i \frac{\Delta V_i}{R_o + R_i}. \quad (4)$$

The major problem in multiple-sensor applications is that  $\Delta V_i$  is not the same for different sensors subject to the same excitation load [refer to Table I(b)]. This leads to different  $\Delta I_i$ 's for different sensors with the same excitation load. From (4), it is obvious that  $\Delta I_i$  can be normalized/compensated by choosing a proper value of  $R_i$  for different sensors.

The objective of the calibration scheme is to equalize  $\Delta I_i$  for all  $i$ 's, i.e.,  $\Delta I_i = \Delta I_j$  if  $i \neq j$ , with the same excitation. The calibration procedure is summarized here.

- 1) Disconnect the sensor array from the voltage-to-current converter, i.e., break the connection between  $R_o$  and  $R_i$  for sensor  $i$ , which is shown in Fig. 2 for example. This

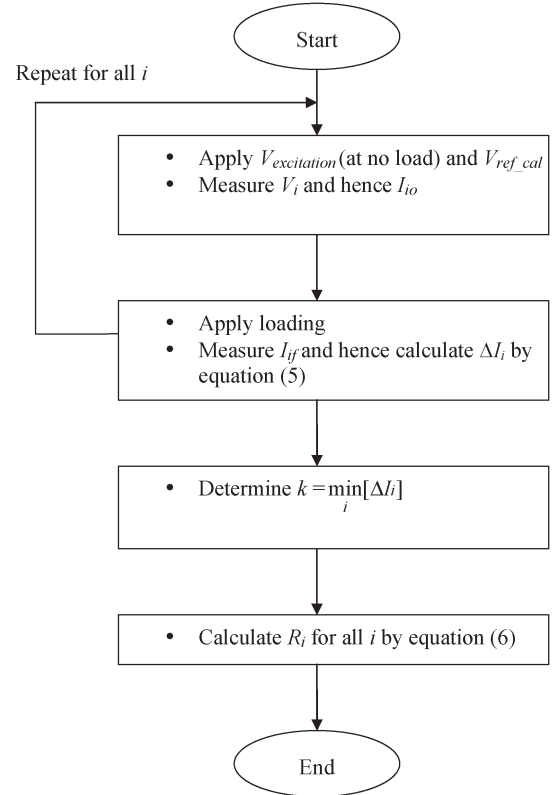


Fig. 3. Flowchart of the proposed calibration.

can easily be done, because  $R_i$  is not placed on the printed circuit board (PCB) until its value is found after calibration. In other words, no actual operation is needed if a space for  $R_i$  is reserved on the PCB.

- 2) Measure the current at no load  $I_{io}$  by connecting the open node to a voltage reference  $V_{ref\_cal}$  [please refer to Fig. 2(a)]. This is done by measuring the voltage drop across  $R_o$  and its resistance, and  $I_{io}$  is thus calculated. In this connection, the tolerance of  $R_o$  (and also the resistance from the wire, PCB, etc.) is negligible. The only error is the accuracy of the measuring device. However, the same measuring device is employed for different sensors; hence, the said error becomes a common-mode error,

TABLE II  
NUMERICAL EXAMPLE

Sensors	Front Left	Front Right	Rear Left	Rear Right
Measured voltage reference $V_{ref\_cal}$ (mV)	378.73	378.10	362.29	377.54
Voltage difference due to excitation, $\Delta V_o$ (mV)	25.52	24.83	25.35	24.94
Measured Reference Resistance, $R_o$ (kohm)	30.16	30.24	31.88	30.22
Current increase due to excitation, $\Delta I_i$ (uA)	0.8461	0.8210	0.7952	0.8254
Minimum $\Delta I_i$ , $k$ , (uA)	0.7952	0.7952	0.7952	0.7952
Resistor needed, $R_i$ (ohm)	1,931	982	0	1,146

which should be compensated in the inverting summing circuit.

- Apply loading to each sensor with a known source (such as standard weights set in an automatic fixture, which can mechanically add the load on the platform), and then, measure the current at that load  $I_{if}$  [please refer to Fig. 2(b)]. Then, calculate  $\Delta I_i$ , which is given by

$$\Delta I_i = I_{io} - I_{if}. \quad (5)$$

- Find the minimum value of  $\Delta I_i$  for all  $i$ 's. Assume  $k = \min_i[\Delta I_i]$ .
- Since  $\Delta I_i$  is given by  $\Delta I_i = (\Delta V_i/R_o + R_i)$ ,  $R_i$  can be found by rearranging the following:

$$R_i = \frac{\Delta V_i}{\Delta I_i} - R_o. \quad (6)$$

- Substituting  $\Delta I_i = k$  in (6) gives a calibrated value of  $R_i$  to normalize  $\Delta I_i$  for different sensors  $i$  since  $\Delta V_i$  and  $k$  are measurable, and  $R_o$  is known in advance.
- Add  $R_i$  to the PCB to finish the calibration process. (Remark: If the system needs to be recalibrated for some reason,  $R_i$  has to be removed from the PCB before repeating steps 1–6.)

### III. IMPLEMENTATION RESULTS AND DISCUSSIONS

The proposed calibration procedures are implemented with LabVIEW 6.1 of the National Instruments Corporation, and the 16-bit analog-to-digital conversion card PCI-6036E [9]. The maximum acquisition rate of such card is 200 ksample/s. One thousand samples are averaged to give a measured value for reducing the error due to noise. The software is easily implemented with the help of the easy-to-use graphical interface from LabVIEW. A flowchart of the software is attached (Fig. 3) for further reference.

As mentioned in Section I, a weighing scale with multiple sensors would be suffering from the positioning problem. Therefore, a weighing scale with multiple piezoresistive sensors is prototyped to test the proposed calibration technique. The sensors are distributed under a large platform, and they sense the force acting on the platform in a distributed manner.

By using the calibration software, the total time to calibrate the system is only 5 s to find out the required calibrated resistors (i.e.,  $R_i$ ). Table II shows the numerical values of the system under study.

Theoretically, the calibration algorithm can completely eliminate heterogeneity. However, one limitation affecting the accuracy is the availability of standard resistor values. Ideally, once a resistor value is calculated, the exact equivalent resistor network can be built to obtain a precise resistance that is desirable. However, this is impractical in real-life applications. Therefore, after the calibration procedures, the closet standard resistor values are chosen to simplify the procedures.

Before the system was calibrated (i.e., all  $R_i$ 's are set to zero by shorting the pads on the PCB through a jig), the prototype was tested with a standard weight, which is the maximum rating of the specification that the device can withstand. Results indicated that the maximum positional error when the standard weight was placed at different locations on the platform was as high as, in general, 2% of the loading [please refer to Table I(a)]. After the device was calibrated, the positional error decreases to 0.2% of the loading at different positions. This is our best result, even if the limitation of standard resistors was considered. After minor modification necessary for production environment, the weighing scale has been mass produced by employing the calibration technique.

### IV. CONCLUSION

A calibration technique for systems with multiple sensors has been proposed in this paper. A prototype system with multiple piezoresistive sensors has been tested by using the proposed calibration procedures, and the results were found to be satisfactory in reducing the heterogeneity of the system. Although the algorithm is tested with a force sensing system with piezoelectric sensors, the technique can be generalized to any multiple-sensor systems. The calibration technique uses a minimal of external components and is excellent for low-cost applications.

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