

A Novel Sensor–Bridge-to-Microcontroller Interface

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Abstract – Sensor bridges are usually interfaced to microcontrollers by supplying the bridge with a voltage or current and digitizing the resulting voltage or current after being amplified and low-pass filtered. This paper proposes an alternative method to interface a sensor bridge to a microcontroller that does not need any active component between the bridge and the microcontroller. The bridge is considered a network with three inputs and one output. The resistance of each input to the output depends on the measurand. Using each input in turn to charge a capacitor connected to the bridge output yields three different time intervals. For a full bridge (a sensor at each arm), the ratio between the difference between two time intervals and the third time interval yields the fractional resistance change. Two-point calibration reduces zero and gain errors attributable to the electrical parameters of the ports of the microcontroller. The absolute error for a 15 psi (103.4 kPa) pressure sensor with 5000 Ω arms and a full-scale output of 125 mV is below 0.05 % of full scale, which is better than 1 LSB for an 11 bit ADC.

Keywords – Sensor bridge, microcontroller interfaces, pressure sensor, piezoresistive sensor, two-point calibration.

I. INTRODUCTION

Sensor bridges are very useful signal conditioners because they can cancel interference such as temperature. Furthermore, bridges with two or four active arms have increased sensitivity and are more linear than bridges with a single active arm. Piezoresistive strain gages, for example, are usually arranged in Wheatstone bridges in pressure sensors and load cells [1].

The common method to interface a sensor bridge to a microcontroller is by amplifying the output voltage or current when the bridge is supplied by either a voltage or current, and applying the resulting voltage to an analog-to-digital converter ADC (Fig. 1). In order to achieve a high accuracy, the amplifier, antialiasing filter, and ADC must have minimal errors, which requires expensive components. If several sensor bridges share a single ADC, the added multiplexer must have small errors too. Applications requiring a resolution below 10 bits can use commodity analog components but the several integrated circuits needed take printed circuit board area, increase power consumption, and reduce reliability. Because most of the cost of common interfaces is often attributable to the ADC, some low-cost interfaces rely on embedding the

information in a time interval rather than in an analog voltage or current subsequently digitized by an ADC.

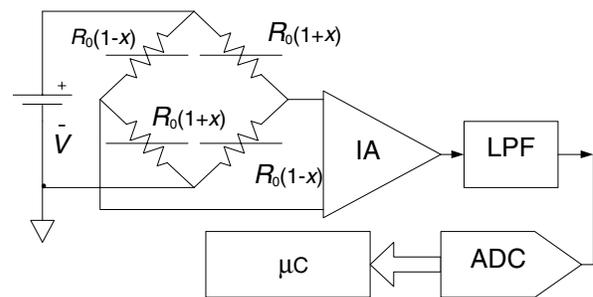


Fig. 1. Classic approach to interface a sensor bridge to a microcontroller: the voltage output is amplified and digitized by an ADC.

Fig. 2, for example, shows a circuit that does not need any ADC [2]. The RC network, op amp and comparator (internal or external to the microcontroller) perform the analog-to-digital conversion. The bridge is supplied by a constant voltage. The analog multiplexer switches the two bridge outputs to a voltage buffer in order to charge a capacitor C_1 through R_1 . The voltage buffer isolates R_1 from the multiplexer and bridge resistance. When the voltage across C_1 becomes larger than that across C_0 ($V_r/2$), the comparator is triggered low, which drives the RA3 port from high to low and, consequently, discharges C_1 through R_2 . Once the voltage across C_1 decreases below that across C_0 , the comparator is triggered high, RA3 is set high, and the cycle repeats.

The time between transitions is proportional to the bridge output voltage. A counter measures the time it takes to perform a given number of transitions (say 1024), which are tracked by another counter. After reaching the predetermined number of transitions, the microcontroller switches the multiplexer to the other bridge output terminal. The elapsed time needed for the same number of transitions to happen is counted, and the subtraction of the respective counting times for each bridge output yields the conversion result.

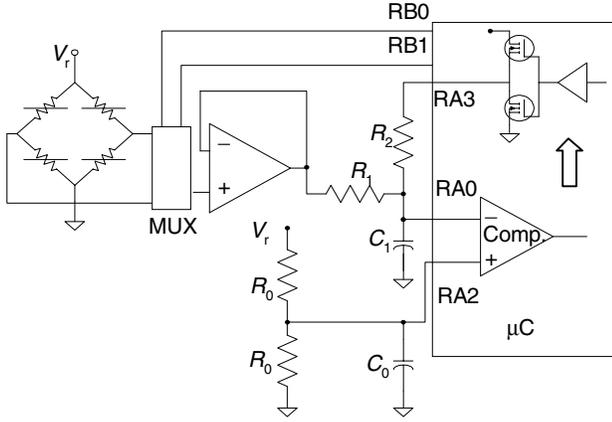


Fig. 2. Sensor-bridge-to-microcontroller interface with inherent A-to-D conversion [2]

In Fig. 1 and Fig. 2, the bridge behaves as a two-port device: voltage or current is supplied to one port and voltage or current is measured at the other port, either directly (Fig. 1) or through the integration time of an RC network (Fig.2). This paper proposes a rather different approach: the sensor bridge is considered a resistor network with three inputs and a single output (Fig. 3). The resistance from each input to the output depends on the measurand. Using each input in turn to charge a capacitor connected to the output, as previously discussed in [3], and combining the results yields a digital output. No active components are needed between the bridge and the microcontroller. A two-point calibration technique reduces errors attributable to the electrical parameters of the ports of the microcontroller that affect the charging process.

II. PROPOSED CIRCUIT AND ANALYSIS

Fig. 3 shows the proposed circuit for a full bridge (four active arms). First, port O1 is set at high level and ports O2 and O3 are set at high-impedance state. Therefore, C is charged through the resistor network formed by R_2 in parallel with the series combination of R_1 , R_4 and R_3 . When the voltage across C reaches the threshold level at port I (V_{IH}), the controller's program switches port I to low (V_{OL}) and C discharges through a current-limiting resistor R_p . Next, port O2 is set at high level and the remaining ports are set at high impedance state. C charges now through the parallel combination of R_1 in series with R_2 , and R_4 in series with R_3 . When port I senses a "1" (V_{IH}), the capacitor is discharged through R_p . Finally, the procedure is repeated for port O3, charging C through the network formed by R_3 in parallel with the series combination of R_4 , R_1 , and R_2 . Fig. 4 shows the resulting voltage waveform at port I. The time needed to charge C depends on C and on

the respective equivalent resistance seen from ports O1, O2 and O3 to C.

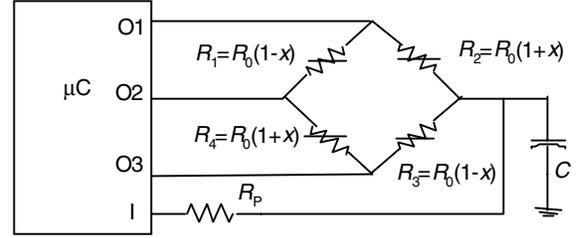


Fig. 3. Direct sensor-bridge-to-microcontroller interface (Patent applied for)

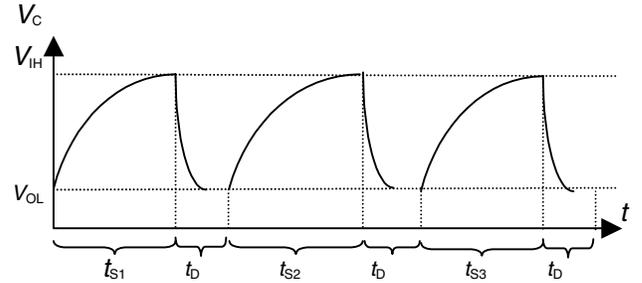


Fig. 4. Voltage waveform at port I in Fig. 3. t_{S1} , t_{S2} and t_{S3} are the respective times to charge C through R_{S1} , R_{S2} and R_{S3} . The discharge time t_D through R_p is always the same.

The respective charging times for each bridge input are

$$t_{S1} = R_{S1} C \ln \left| \frac{V_{OH} - V_{IH}}{V_{OH} - V_{OL}} \right| \quad (1)$$

$$t_{S2} = R_{S2} C \ln \left| \frac{V_{OH} - V_{IH}}{V_{OH} - V_{OL}} \right| \quad (2)$$

$$t_{S3} = R_{S3} C \ln \left| \frac{V_{OH} - V_{IH}}{V_{OH} - V_{OL}} \right| \quad (3)$$

where

$$R_{S1} = \frac{R_0(1+x)[R_0(1-x) + R_0(1+x) + R_0(1-x)]}{4R_0} = \frac{R_0(3+2x-x^2)}{4} \quad (4)$$

$$R_{S2} = R_0 \quad (5)$$

$$R_{S3} = \frac{R_0(1-x)[R_0(1+x) + R_0(1-x) + R_0(1+x)]}{4R_0}$$

$$= \frac{R_0(3-2x-x^2)}{4} \quad (6)$$

Therefore, computing the ratio between the difference in charging time through ports O1 and O3 and the charging time through port O2 yields

$$\frac{t_{S1} - t_{S3}}{t_{S2}} = \frac{R_{S1}C \ln \left| \frac{V_{OH} - V_{IH}}{V_{OH} - V_{OL}} \right| - R_{S3}C \ln \left| \frac{V_{OH} - V_{IH}}{V_{OH} - V_{OL}} \right|}{R_{S2}C \ln \left| \frac{V_{OH} - V_{IH}}{V_{OH} - V_{OL}} \right|}$$

$$= \frac{\frac{R_0(3+2x-x^2)}{4} - \frac{R_0(3-2x-x^2)}{4}}{R_0} = x \quad (7)$$

That is, a first-approach analysis yields a linear output. Nevertheless, we can expect that uncertainty in output and input threshold voltages, nonzero output resistance, finite input resistance, and leakage currents at the ports of the microcontroller cause zero, gain, and nonlinearity errors [3].

III. EXPERIMENTAL RESULTS AND DISCUSSION

We have built the circuit in Fig. 3 using the PIC16C71 microcontroller and the pressure sensor NPC-410-015-D-3L (Lucas Varity), which has $R_0 = 5000 \Omega$ (typ.) and full-scale output (FSO) 125 mV for $p = 15$ psi (103.4 kPa). The current through the piezoresistors is 1.5 mA, which means that the theoretical fractional resistance change x is from 0 to about 0.017 (disregarding offset and sensitivity errors in the pressure sensor). C has been chosen 4 μ F in order to have charging times of about 10 ms, and $R_p = 220 \Omega$. Voltage levels at the microcontroller ports have been measured to be $V_{OH} = 5$ V, $V_{IH} = 3.24$ V, and $V_{OL} = 0.002$ V.

The actual charging time has been measured by using the microcontroller to generate three pulses lasting, respectively, t_{S1} , t_{S2} , and t_{S3} . That is, when charging C through the first bridge input, the microcontroller sets an output port (not shown in Fig. 3) high when starting to charge and sets it low upon reaching V_{IL} at port I. The same procedure is performed for each bridge input but on a different output port. The resulting time intervals equal t_{S1} , t_{S2} , and t_{S3} in Fig. 4, and are measured with a 100 MHz universal counter (HP5315A/B), which achieves a resolution of 10 ns by averaging 100,000 time intervals. Consequently, dynamic changes in the measurand cannot be tracked when using this time interval measurement method.

Fig. 5 shows the fractional resistance change calculated from the sensor sensitivity and applied pressure, versus the fractional resistance change calculated from (7).

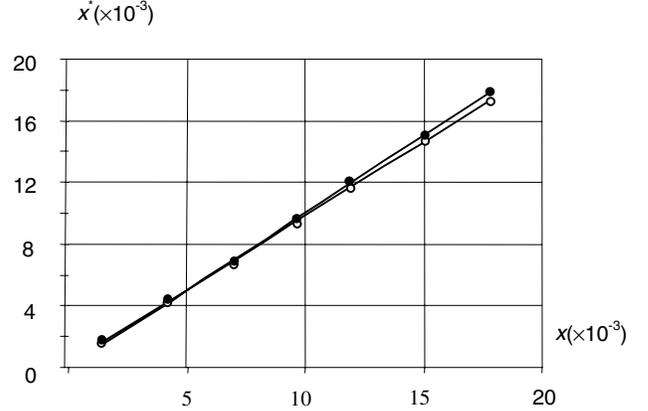


Fig. 5. Fractional resistance change calculated from (7) (dots) versus actual change (circles)

The best straight line fit to the experimental data is

$$x' = 0.9583x + 2.4 \times 10^{-4} \quad (8)$$

which shows that there are zero and gain errors, attributable to offset errors and uncertainty in the sensitivity of the sensor, and also to the nonideal electrical characteristics of the microcontroller ports. In particular, each port has a non negligible output resistance that adds to that of the bridge when charging C through that particular port. Also, ports in high-impedance state have a finite input resistance and leakage current that interfere which the charging process.

Zero and gain errors can be cancelled by calibrating at two-points, for example unloaded sensor and full-scale input (FSI). The final result is then

$$x' = \frac{(x - x_1^*)(x_2 - x_1)}{x_2^* - x_1^*} + x_1 \quad (9)$$

where x_1^* and x_2^* are the estimated fractional resistance changes measured by applying (7) for, respectively, zero load and FSI, and x_1 and x_2 are the corresponding fractional resistance changes measured with a high-resolution ohmmeter. Fig. 6 shows the absolute error for x when applying this procedure in our experimental set up. The maximal absolute error expressed as a percentage of the full-scale input (FSI = x_{\max}),

$$\frac{e}{x_{\max}} = \frac{|x' - x|}{x_{\max}} \quad (10)$$

is below 0.05 %, which is better than 1 LSB for an 11 bit ADC.

This interfacing technique cannot be applied to low-resistance sensor bridges, such as those constituted by metal-foil strain gages, because the microcontroller cannot supply the initial current surge needed to charge C through them. It cannot be applied either to IC sensors that integrate electronic circuits additional to the strain gages, such as temperature stabilizers or linearizing networks, because the equivalent circuit for those sensors is different from that in Fig. 3. Rather, this technique suits low-cost, high-resistance sensor bridges with direct access to each bridge arm.

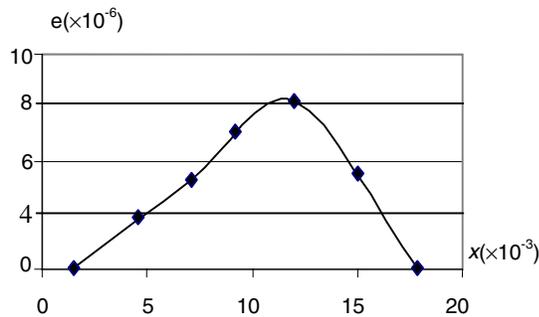


Fig. 6. Absolute error obtained when applying a two-point calibration to the estimates from (7).

IV. CONCLUSION

The classic sensor-bridge-to-microcontroller interface uses an ADC whose input is the amplified voltage (or current) from the bridge operated as a two-port device (Fig.1). An RC modulator can perform the analog-to-digital conversion to

reduce cost, but still needs a multiplexer and a voltage buffer (Fig. 2).

The novel interface described in Fig. 3 does not need any active component other than the microcontroller. The bridge is considered a resistor network with three inputs and one output. The inputs are connected to respective microcontroller ports and the output is connected to a capacitor. The information about the measurand is derived from the time elapsed since successively setting each bridge input high until the voltage across a capacitor reaches the “1” threshold of the microcontroller input. Calculating the time ratio in (7) yields a result independent of the capacitor. If the resolution needed in time interval measurements is achieved by averaging, dynamic changes in the measurand faster than the averaging time cannot be tracked. A two-point calibration reduces errors due to the nonideal electrical characteristics of the microcontroller ports. For a 5000Ω pressure sensor with 15 psi FSI and 125 mV FSO, the interface proposed yields a maximal absolute error below 0.05 % of the FSI.

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REFERENCES

- [1] R. Pallàs-Areny and J. G. Webster, *Sensors and Signal Conditioning*, 2nd ed. New York: John Wiley & Sons, 2001.
- [2] B. Baker, “Building a 10-bit bridge sensing circuit using the PIC16CXX and MCP601 operational amplifier.” Application Note AN717. Chandler (AZ): Microchip Technology, 1999.
- [3] A. Custodio, R. Pallàs-Areny, and R. Bragós. Error analysis and reduction for a simple sensor-microcontroller interface. *Proc. 17th IEEE Instrumentation and Measurement Conference*, 1-4 May 2000, pp. 277-280.