A Microcontroller Sensor Interface Suitable for Resistive Sensors with Large Lead Resistance

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Abstract— **A direct resistive sensor interface to a micro-controller reported earlier, works well only if the sensor element is very close to the micro-controller pins. If the sensor element is at a distance from the micro-controller then the lead resistance due to connecting wires between resistive sensor element and the micro-controller introduces appreciable errors in the output. A modified scheme of direct sensor interface to micro-controller is presented here. In the proposed scheme, the effect of lead resistances is compensated and thus the proposed direct resistive sensor interface to a micro-controller works well even if the sensor is kept at distance and connected through long connecting wires. Since the lead wire resistance is compensated, automatic temperature compensation (temperature effect of lead wires) is obtained. The results obtained from simulation and experimental results recorded from a prototype of the proposed scheme establishes the effectiveness of the proposed method in eliminating the effect of lead resistance in the output. Worst-case error noted in the simulation output was < ± 0.23 % and the worst-case error of the prototype unit was found to be < ± 0.33 %.**

Keywords- Lead resistance compensation; Resistive sensors; Micro-controller sensor interface; Direct sensor interface.

I. INTRODUCTION

Resistive type sensors are available in single element, differential and bridge forms [1]. As the name indicates, single element sensor has one sensing element, whose resistance changes as a function of the physical quantity being measured. They are commonly used for sensing temperature, light, gas and humidity. Examples are RTDs (Resistance Temperature Detectors), thermistors, LDRs (Light Dependent Resistors), strain gauges, various gas sensors, piezo-resistive type sensors etc. [1], [2]. To be processed by the modern instrumentation system digital outputs are preferred from the measurement circuit of these sensors. Conventional measurement schemes use analog signal conditioning circuit cascaded to an analog-to-digital converter (ADC) for obtaining digital output from the sensors. Quasi digital systems that convert resistance to frequency, pulse-width or time period are available but they suffer from the drawback of requirement of another interface to covert the quasi-digital output to digital [3], [4]. Direct digital converters based on dual-slope ADC are reported, wherein the structure of a dual-slope ADC is altered to make the sensor elements to become an integral part of the ADC. Such schemes provide a digital output dispensing with analog signal conditioning circuits [4], [5]. Even though these converters provide good accuracy, they are complex compared to direct interface of sensor element to micro-controller reported in [7], [8], for resistive and capacitive sensors.

Error introduced by a lead resistance R_{LD} in the operation of a sensor resistance R_x depends on the ratio R_{LD}/R_x. Here R_x, the resistance of the sensor element can be expressed as:

$$R_x = R_0(1 + kx), \tag{1}$$

Where k is the transformation constant of the sensor, R_0 is the nominal resistance of the sensing element when the measurand being sensed, namely x, is zero. Typical value of lead resistance of a wire (copper wire, 30 SWG) at 25 °C is 344 mΩ/m [2]. Lead wires are manufactured with a tolerance of about 10 %, resulting in the nominal resistances of the two wires connecting the two ends of the resistive sensor element to the microcontroller may not be equal. The temperature coefficient of copper is 0.00385 Ω/Ω/°C and for a 10 °C change in the operating temperature the change in the resistance of the lead wires will be 13 mΩ/m. Large errors will result, especially when long lead wires are used with low valued resistive sensors possessing low sensitivity. For example, PT100, a popular resistive temperature device (RTD) possesses a nominal resistance of 100Ω and sensitivity of 0.00385 Ω/Ω/°C. If such a sensor is used, even a few meters of connecting wire will introduce large errors due to not only lead resistances but also due to variations in the lead resistances as a result of temperature variations.

In the direct resistive sensor interface to micro-controller systems presented earlier, if the sensor is remotely located, the measurement will be significantly affected due to lead wire resistance and its variation owing to change in the atmospheric temperature [7], [8]. Use of three wire and four wire connection strategies enable precise measurement of low resistance by compensating the lead resistance but such systems require additional leads running from measurement unit to sensor side and will be efficient only when the supply and return leads have equal resistance values [9]. Methods that provide lead wire compensation presented earlier are all analog signal conditioning schemes and require an additional analog to digital converter to interface them to a micro-controller [10] - [12]. More over the schemes presented in [10] and [11] are more complex systems compared to the scheme proposed here as they use current sources and sample and hold circuits.

In this paper a simple, direct micro-controller interface scheme to connect and measure using a resistive element is presented. In the proposed scheme the resistive sensor element is directly connected to the port pins of a micro-controller, but with additional diodes and switches. The switches are suitably operated by the micro-controller so that lead resistance as well as any variation in lead resistance due to change in temperature are compensated. Thus the scheme presented here eliminates errors introduced, even by long lead wires.

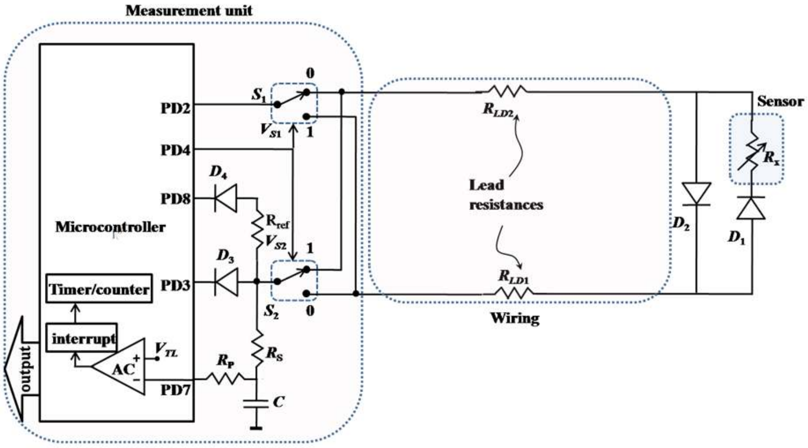

Fig. 1. Block diagram of the proposed method. The measurement unit with micro-controller, connecting wires with lead resistances and the sensor, are indicated.

II. Micro-controller Based Sensor Interface for Sensors with Lead Resistance

A block diagram of the proposed scheme is shown in Fig. 1. The measurement unit has a micro-controller, two SPDT switches S_1 and S_2, two diodes D_3 and D_4, a capacitor C and two resistors R_s and R_{ref}. The sensor R_x is connected to S_1 and S_2 as in Fig. 1. R_{LD1} and R_{LD2} indicate the resistances of the lead wires between the sensor and the measurement (micro-controller) unit. At the sensor side, two diodes D_1 and D_2 are introduced as shown in Fig. 1. The purpose of diodes D_1 and D_2 are to allow for two different measurements, wherein the first measurement includes the sensor and lead resistance and the second measurement is only the lead resistance. In place of diodes, D_1 and D_2, low ON resistance analog switches can also be used, but switches will need control signals and power supply for which, additional control wires have to run from the measurement unit to sensor, to control such switches.

The measurement process involves charging and discharging of capacitor C, alternatively, for four times as illustrated in Fig. 2. Whenever C needs to be charged, pin PD7 of the micro-controller is set at digital HIGH (say, voltage V_{DD}) and the remaining pins PD2, PD3, and PD8 are set to operate in the high impedance state. The switch control pin PD4 can be set to HIGH, LOW or high impedance state as it will not affect the charging operation as the pins used for discharging are in high impedance state. For this condition, capacitor C is charges towards V_{DD}, through R_p. R_p is introduced to improve the rejection of power supply noise / interference as reported in [7].

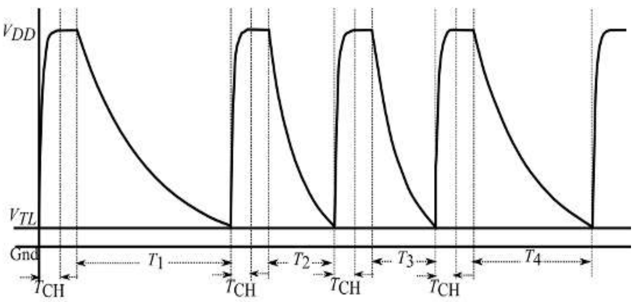

Fig. 2. Charging and discharging sequence
T_{CH} shows duration for charging while
T_1, T_2, T_3 and T_4 indicate various discharging intervals

As mentioned above, a discharging operation follows a charging process. During discharging, the time taken to reach certain voltage (V_{TL}) is measured. During the first discharging process pins PD3, PD7 and PD8 are set in high impedance state and pin PD2 alone is set at digital '0'. Simultaneously, switches S_1 and S_2 are set to position '0'. In this situation, the total resistance, R_{T1} of the discharge path-1 which includes diode D_1 is

$$R_{T1} = R_x + \left(R_s + R_{ON1} + R_{LD1} + R_{LD2} + R_{ON2} + R_{pin}\right) \qquad (2)$$

where R_s, is an additional resistor connected to ensure that the discharging current is smaller than the maximum output current (I_{max}) that is acceptable for a port pin even when R_x is very small [7], R_{ON1} and R_{ON2} are the ON state resistances of the switches S_1 and S_2, R_{LD1} and R_{LD2} are the lead resistances of the wires to the sensor, from micro-controller. R_{pin} is the internal resistance of the micro-controller pin. The diode D_1will be forward biased and diode D_2 will be reverse biased and the current i_1(t) flowing through R_{T1} will be

$$i_1(t) = \frac{(V_{DD} - V_{DON})}{R_{T1}} e^{-t/R_{T1}C} \qquad (3)$$

where V_{DON} is the ON state forward voltage drop of the diode D_1. The voltage, v_{RT1}(t) across R_{T1} can be expressed as

$$v_{R_{T1}}(t) = i_1(t)R_{T1} = (V_{DD} - V_{DON})e^{-t/R_{T1}C} \qquad (4)$$

and the capacitor voltage v_c(t) can be expressed as in (5).

$$v_c(t) = V_{DON} + v_{R_{T1}}(t) \qquad (5)$$

By substituting v_{RT1} (t) from (4) into (5), v_c(t) can be modified as in (6).

$$v_c(t) = V_{DON} + (V_{DD} - V_{DON})e^{-t/R_{T1}C} \qquad (6)$$

The capacitor voltage, $v_c(t)$ at the time of the start of discharge ($t = 0$) will be

$$v_c(t) = V_{DD} \tag{7}$$

The discharging process is continued till the capacitor voltage drops down to a threshold voltage, V_{TL} and let 'T_1' be the time taken to complete this process. At $t = T_1$, $v_c(T_1) = V_{TL}$ and V_{TL} can be expressed as in (8).

$$V_{TL} = V_{DON} + (V_{DD} - V_{DON})e^{-T_1/R_{T1}C} \tag{8}$$

The time T_1, taken by the capacitor C to discharge from V_{DD} to V_{TL} through R_{T1} can be calculated as in (9).

$$T_1 = R_{T1}C\ln\frac{(V_{DD} - V_{DON})}{(V_{TL} - V_{DON})} \tag{9}$$

For a system, values of C, V_{DD}, V_{TL} and V_{DON} can be assumed to be constants then T_1 is proportional to the total resistance R_{T1} of path-1.The internal Timer/Counter unit of the micro-controller will be started when the capacitor starts discharging and will be stopped when $v_c(t) = V_{TL}$. The time taken by the capacitor to discharge is now available in terms of counts, a digital number say N_1. The equations (3) to (9) holds good for the second, third and fourth discharging periods also except for the total resistance, R_T involved in the different paths and V_{DON} of the respective diodes D_2, D_3 and D_4. Fig. 2 depicts that the time taken by the capacitor to charge in all the four cases is same and the time taken for discharging depends on the total resistance of the discharging path.

To obtain the time taken by the capacitor to discharge through lead wire resistance alone, a second discharging operation is performed. The status of the micro-controller pins are maintained same for the second discharge operation but the positions of switches S_1 and S_2 are changed to '1'. This change in switch position changes the path for the current through capacitor C. Diode D_2 is forward biased and diode D_1 is reverse biased and thus path of discharge current does not include the sensor resistance. The total resistance R_{T2} of the discharge path-2, can be expressed as in (10).

$$R_{T2} = R_s + R_{ON1} + R_{LD1} + R_{LD2} + R_{ON2} + R_{pin} \tag{10}$$

The time taken by the capacitor to discharge through R_{T2} to reach V_{TL} is T_2 and the count obtained from the counter corresponding to T_2 is considered as N_2.

The internal resistance R_{pin} of the micro-controller contributes an offset error in the measurement of resistance. To correct for that offset error, the counts corresponding to the time taken, by the capacitor to discharge from V_{DD} to V_{TL} through resistance of the micro-controller pin, R_{pin} and the additional resistance R_s, is needed. In order to perform this, pins PD2, PD7 and PD8 are set in high impedance state and the pin PD3 is set to digital '0'. The positions of the switches S_1 and S_2 have no effect during this discharge operation. The total resistance R_{T3} of the discharge path-3 can be written as in (11).

$$R_{T3} = R_s + R_{pin} \tag{11}$$

T_3, the time taken by the voltage across the capacitor to discharge to V_{TL}, can be obtained in terms of count N_3 from the internal Timer/counter unit.

The final discharging operation is intended to measure time corresponding to the reference resistor, R_{ref}. In this case, the digital I/O pins PD2, PD3 and PD7 are kept at high impedance state and the pin PD8 is kept at ground by setting it as output pin providing digital '0'. The total resistance R_{T4} of this discharge path-4, can be written as in (12). The switch positions play no role in this discharging stage.

$$R_{T4} = R_{ref} + (R_s + R_{pin}) \tag{12}$$

The counts obtained for this measurement is denoted as N_4.

The expression for T_1 is given in (9) whereas T_2, T_3 and T_4 can be obtained by replacing R_{T1} in (9) with R_{T2}, R_{T3} and R_{T4}, respectively. If we perform a ratio-metric operation of the four discharging time periods T_1, T_2, T_3 and T_4 as in (13), we get output as the ratio of sensor resistance R_x to R_{ref}, which is independent of the lead resistors R_{LD1} and R_{LD2}.

$$\frac{T_1 - T_2}{T_4 - T_3} = \frac{R_{T1} - R_{T2}}{R_{T4} - R_{T3}} = \frac{R_x}{R_{ref}} \tag{13}$$

Since the counts corresponding to the discharging time periods T_1, T_2, T_3 and T_4, are available, we can re-write (13) in terms of the counter outputs, as in (14), which is a ratio of R_x to R_{ref} in digital domain.

$$\frac{R_x}{R_{ref}} = \frac{N_1 - N_2}{N_4 - N_3} \tag{14}$$

Equation (14) is not affected by lead resistance. If lead resistance compensation is not considered as in [7], then the measurements obtained would be N_1, N_3 and N_4, using which R_x to R_{ref} is calculated as in (15).

$$\frac{R_x}{R_{ref}} = \frac{T_1 - T_3}{T_4 - T_3} = \frac{N_1 - N_3}{N_4 - N_3} \tag{15}$$

III. SIMULATION STUDIES

The functionality of the proposed method has been verified by simulating the circuit using circuit simulation tool, LTSpice. To simulate the micro-controller part, control logic with a few switches, pulse signals and logic gates were used. Two different simulations were performed; in the first one the lead resistance values, R_{LD1} and R_{LD2} were set as 10Ω, the nominal resistance R_0 of the sensor was set as 1.0 kΩ and the sensor resistance was incremented in steps of 10Ω up to 1100Ω. In the second simulation, the sensor resistance was again set as 1.0 kΩ (the nominal resistance) and the lead resistance R_{LD1} and R_{LD2} values were varied in steps of 1Ω in the range of 0 Ω to 10 Ω and the corresponding variations in discharging time periods were noted. The ratio R_x to R_{ref} was then computed using (13) (Lead Resistance Compensation - LRC) and (15) (No Lead Resistance Compensation- NLRC). The relative error was calculated for each case using the results obtained from the first simulation and plotted. Fig. 3 shows the output characteristics and error curves before and after compensating

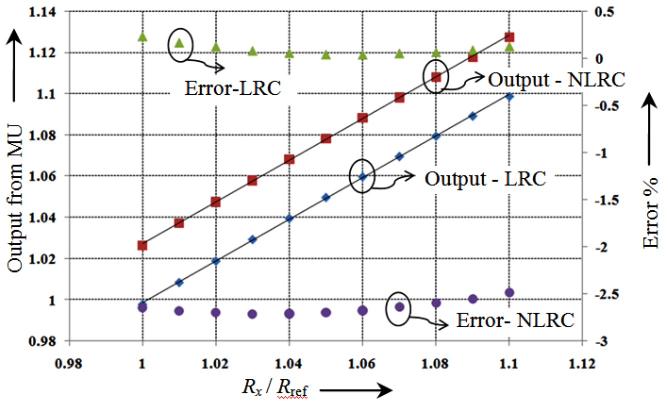

Fig. 3. Results obtained from the simulation studies with R_{LD1}=R_{LD2}=10Ω
MU – Measurement Unit
LRC- Lead Resistance Compensation
NLRC- No Lead Resistance Compensation

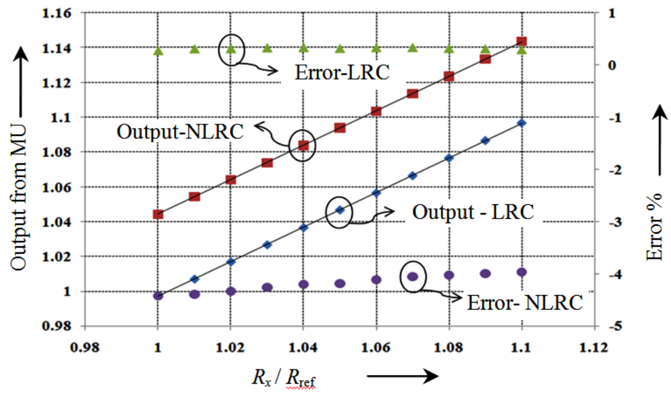

Fig. 4. Results obtained from the prototype with R_{LD1}=R_{LD2}=10Ω
MU – Measurement Unit
LRC- Lead Resistance Compensation
NLRC- No Lead Resistance Compensation

the lead resistance using the method proposed here. The worst case error was <±2.7% in case of no compensation for lead resistance and <± 0.23% after compensation. This shows the efficacy of the proposed method.

IV. Experimental Results

A prototype unit was developed and tested to check practical working of the proposed scheme when a sensor with lead wire resistance is employed. The resistor R_P used for charging the capacitor was selected as 75 Ω and the capacitor C was selected as 2.2 µF. These values were selected as per the recommendations in [7]. The additional resistor R_s and R_{ref} were selected as 1 kΩ. Four 1N4007 diodes with matching (measured) V_{DON} values were selected to serve as D_1, D_2, D_3 and D_4. There is a possibility of small mismatch in diode voltages but the error due to mismatch will be negligible as reported in [11]. To keep any offset error that may be introduced by the switch ON resistance, an IC with very low on state resistance is preferred. IC MAX 4602 has quad SPST switches having ON resistance of 2.5 Ω. Two SPST switches were connected in parallel to form an SPDT switch. While the control voltage of one of the switches was fed directly, the remaining switch was controlled with an inverted version of the control voltage (inversion was obtained using one of the six NOT gates of IC SN 7404).

An Arduino Uno board containing an ATMEGA 328 micro-controller is used in the prototype to implement the necessary control logic. The analog comparator unit inside the micro-controller was used to compare the capacitor voltage with the threshold voltage (V_{TL}). The voltage v_c(t) across the capacitor was connected to the negative input terminal of the comparator named as AIN1 and the analog comparator band gap select bit in the analog comparator control and status register was set so that a fixed band gap reference voltage of 1.1 V replaces is fed to the positive input AIN0 of the comparator [13], [14]. When the capacitor voltage drops below 1.1 V the comparator triggers the analog comparator interrupt and initiates the necessary action. The internal Timer/ Counter unit was used to perform the necessary counting operation, every time the capacitor was made to discharge. The Arduino board was interfaced to a personal computer (PC) through the USB port and the measured count values were read by the USB interface and displayed on the PC.

The sensor resistance R_x and the lead wire resistances R_{LD1} and R_{LD2} were emulated by using standard variable resistance boxes form Otto Wolff, Germany having a resolution of 1.0 Ω and an accuracy of ±0.01 %. The nominal resistance of the sensor was set as 1.0 kΩ, lead resistances R_{LD1} and R_{LD2} were set as 10Ω each. The counter output for the four discharging periods were obtained for sensor resistances in the range of 1000 Ω to 1100 Ω, varied in steps of 10 Ω. Using the count values obtained R_x/R_{ref} was calculated using (14). It was also compared with conventional method for direct sensor interfacing, (R_x/R_{ref} obtained using (15)). The output obtained from the measurement unit for both the cases were plotted in a graph and was found to be linearly varying with respect to R_x. The relative errors were calculated and error characteristics were drawn. Fig. 4 shows the output and error graphs plotted using the results obtained from the prototype. The worst case error obtained from the prototype unit was found to be <±4.42 % for results obtained without lead resistance compensation and it reduced to < ±0.33 % after compensation. Fig. 5 shows the snapshot of the waveform across the capacitor C for a typical value of R_x = 1100 Ω and R_{LD1} = R_{LD2} = 25 Ω. A photograph of the experimental setup with the prototype unit is

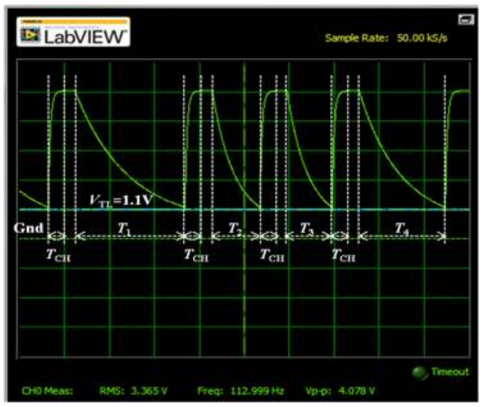

Fig. 5. Snapshot of capacitor waveform $v_c(t)$ for a typical value of R_x=1100 Ω and R_{LD1}= R_{LD2}=25Ω

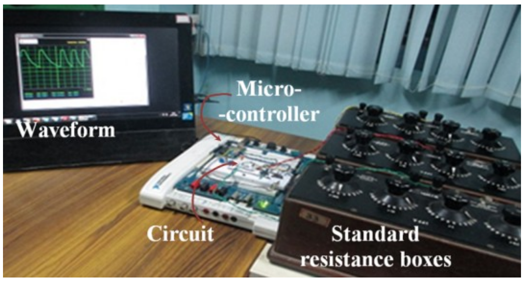

Fig. 6. Experimental setup to test the proposed scheme

shown in Fig. 6.

To study the effect of variation in lead resistance due to temperature, another measurement was performed, where the sensor resistance R_x was kept constant at 1.0 kΩ and lead resistances R_{LD1} and R_{LD2} were incremented in steps of 1 Ω in the range of 0 Ω to 10 Ω. The corresponding R_x / R_{ref} calculated using (14) as well as the conventional method (15) is given in Table I.

TABLE I. RESULTS WITH VARIATION IN LEAD RESISTANCE

Sl. No.	$R_{LD1} = R_{LD2}$ [Ω]	Output from MU (R_x / R_{ref})	
		Without compensation	Proposed method
1.	0	1.0239	0.9944
2.	1	1.0252	0.9945
3.	2	1.0277	0.9946
4.	3	1.0299	0.9946
5.	4	1.032	0.9947
6.	5	1.0334	0.9948
7.	6	1.0362	0.9949
8.	7	1.0376	0.995
9.	8	1.0399	0.9951
10.	9	1.0435	0.9952
11.	10	1.0447	0.9953

In Table I, the values of R_x/R_{ref} corresponding to serial number 1 for the case of $R_{LD1} = R_{LD2} = 0$ are not found to be equal. The reason behind it, is the effect of R_{ON1} and R_{ON2}, the ON-state resistance of the switches S_1 and S_2, which gets eliminated in the proposed method but in the existing method this additional resistance due to switch is not cancelled automatically. Also the microcontroller port pin through which the voltage across the capacitor discharges to ground in the discharging operations 1 and 2 are same which is different from 3 and 4. The microcontroller port pin resistances in actual case may have a mismatch of about few tenths of ohms as reported in [7]. The results show that the proposed method has very less sensitivity to change in the lead resistance, enabling interfacing of resistive sensors directly to micro-controller even if they are separated by a long distance cable.

V. CONCLUSION

A new scheme for compensating the effect of lead resistance in direct resistive sensor to micro-controller interface is presented in this paper. The proposed scheme makes the direct resistive sensor to micro-controller interface system suitable for resistive sensors with large lead resistance. A prototype of the proposed system has been developed and tested. The efficacy of the proposed scheme has been established by the results obtained from simulation studies as well as from the prototype unit.

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