Supporting Information

for

Self-Sensing Flapping Wings for MAVs Using New Compliant Strain Gauges

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1 Data Acquisition with the Arduino Platform

Data collection from the cantilevers was performed with an Arduino Uno R3, a commercially available, open-source microcontroller. It is possible to create a proportional-integral-derivative (PID) controller and to control a digital potentiometer with serial peripheral interface (SPI). The Arduino's six analog-read pins utilize 10-bit built-in analog to digital converters that read 0 to 5 V with a resolution of 4.9 mV.

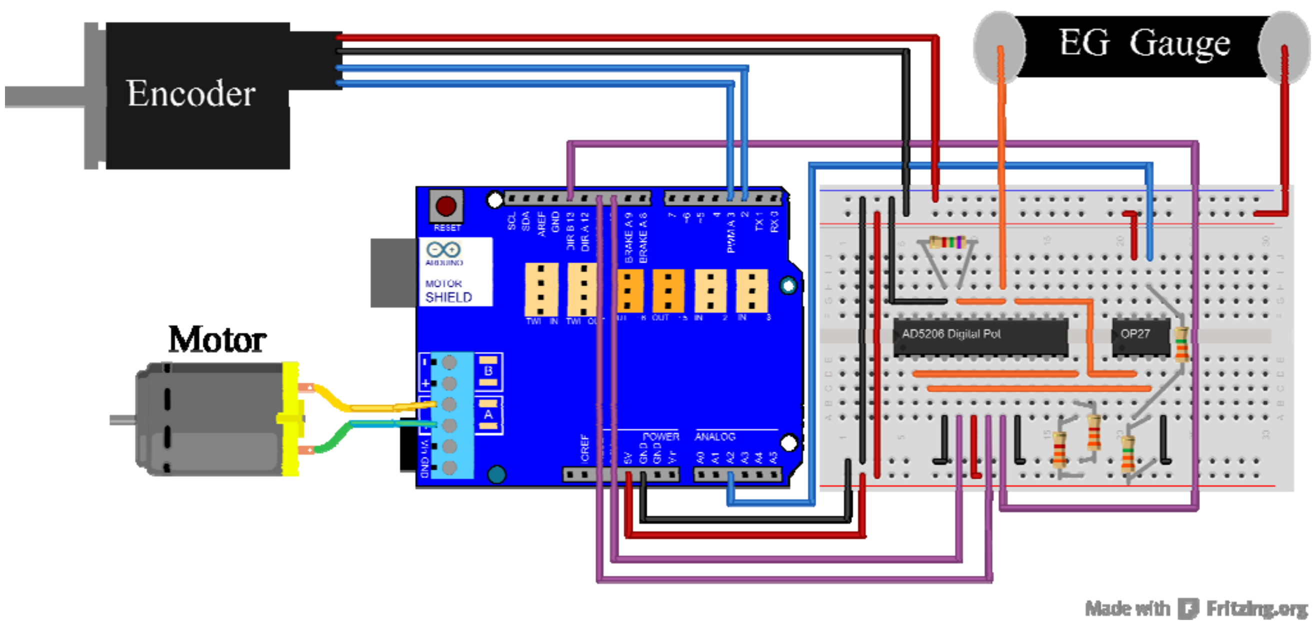

Figure 1. Wiring schematic for the data acquisition system.

The data acquisition system is shown in Figure 1. Output pins 3 and 12 of the motor shield were bent to prevent their connecting with the corresponding pins on the Arduino. Pin 5 on the shield was attached to pin 3 to control the motor speed so that the Arduino's pin 3 was free to receive encoder signals.

Likewise, pin 7 on the shield was attached to pin 12 to control the motor direction to avoid interference with the SPI interface, which used pin 12 on the Arduino.

The changes in voltage were read using a Wheatstone bridge and amplified using a differential op amp configuration (OP 27, Analog Devices), as shown in Figure 2. It was necessary to amplify the signal because the changes in voltage across the bridge were on the order of 1 mV or less in response to the 5 V applied to the bridge (V_{in}) by the Arduino.

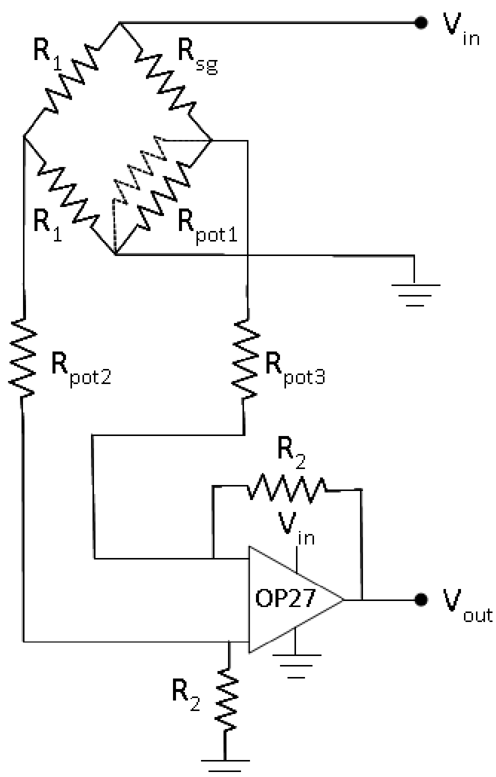

Figure 2. Data acquisition circuit comprising a Wheatstone bridge and a differential op amp configuration.

In Figure 2, R_{sg} represents the strain gauge and the three $R_{pot\#}$ represent variable resistors. A 100 kΩ digital potentiometer (AD5206) was used for each of the variable resistances, allowing for automated computing and tuning, which was done in a custom-written Matlab Program. Adjusting R_{pot1} focused the voltage between 0 and 5 V while R_{pot2} and R_{pot3} controlled the amplifier gain. A resistor (dashed line) in parallel with R_{pot1} lowered the resistance of that leg of the bridge and allowed finer control in balancing the bridge. The value of this resistor was chosen to optimize the signal from each gauge: two gauges had R_0 = 16 kΩ and one had R_0 = 11 kΩ. R_1 was 3.300 kΩ and R_2 was 3.3 MΩ. V_{out} (going into pin A2) was the voltage measured by the Arduino. The resistance of the strain gauge can be calculated using Equation (1) (where the parallel resistor is included in the value for R_{pot1}).

(1) $$R_{sg} = -R_{pot1} - \frac{R_2 R_{pot1} V_{in}}{R_{pot2}\left(V_{out} - \frac{R_2 V_{in}\left(R_2 + R_{pot2}\right)}{2R_{pot2}\left(R_2 + R_{pot3}\right)}\right)}$$

2 Effect of Humidity, Temperature, and Time

2.1 Long-Term Data Collection

An array of 16 nominally identical strain gauges with 25 wt% EG was fabricated on the same Lexan substrate. Each gauge was 40x6 mm^2 in area, created by spray-coating multiple layers through a stencil. Silver epoxy was used to make electrical contact, and two sets of wires were attached on either end of each gauge. Measurements of relative humidity (RH), temperature (Enviracaire EIO Digital Humidity/Temperature Indicator), and the resistance of each strain gauge (Fluke 175 or 179 True RMS Multimeters), using both pairs of wire leads, were conducted over a period of 109 days. These devices were not strained.

The average resistance of the gauges on the day they were made (day 0) was 1.33 kΩ, with a standard deviation of 0.46 kΩ (35%), a minimum of 0.73 kΩ, and a maximum of 2.33 kΩ. The resistance on subsequent days has been normalized to that on day 0 in Figure 3.

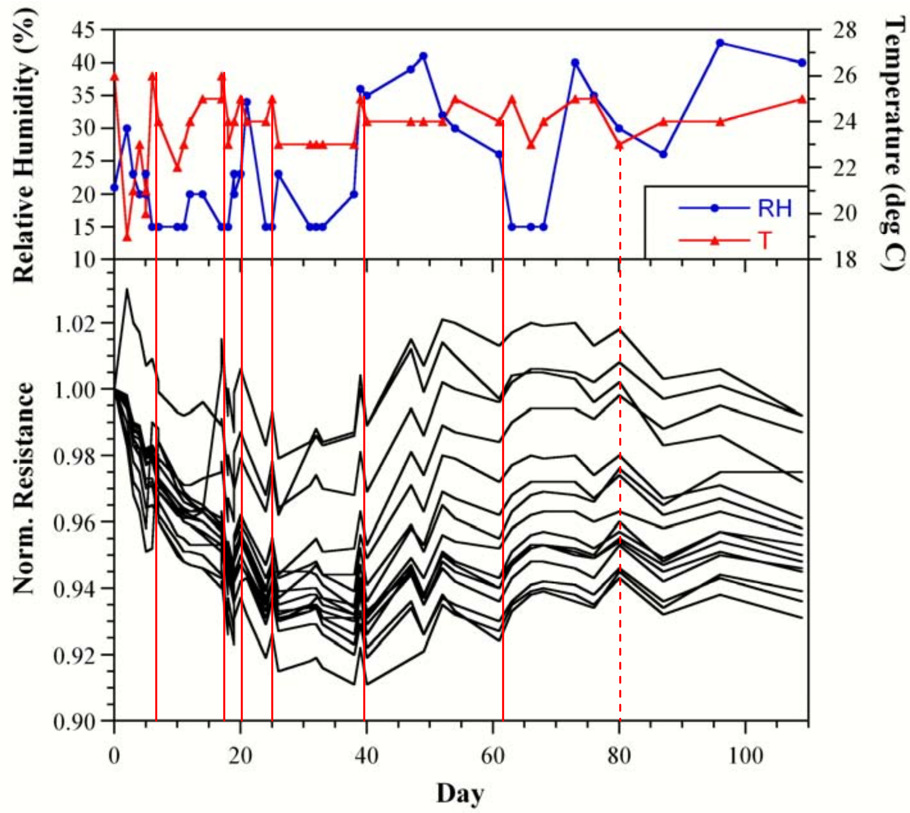

Figure 3. Humidity, temperature, and the normalized resistance of 16 strain gauges over time.

The resistance of the gauges drifted over the months, with all the gauges dropping during days 0-30, rising from 30-50, holding relatively constant from 50-80, and dropping again from 80-109. This baseline drift was not accounted for by the humidity, even taking into account the possibility of long-term water uptake (see below). While the gauges behaved similarly, however, there was still considerable variation, particularly in the decrease in R over the first 20 days; thereafter the lines remained more or less parallel.

Above the baseline changes, there were occasional small spike increases in resistance, across all the gauges, and these were in some cases correlated with temperature (as indicated by the solid red lines), although in one instance (dotted red line), R went *up* when T went *down*. There was no clear correlation with RH, nor an apparent interaction response to RH and T. Given the data in section 2.2 below, these results are puzzling.

What these time-course data do show is that for long-term strain monitoring applications, an unstrained reference gauge is required for calibration. Also, the gauges should be allowed to stabilize for some weeks; there is typically a larger extent of drift during this initial period. Given the wide variation in the behavior of these nominally identical devices, however, to provide confidence in the strain measurement the strains should lead to larger changes in R than these baseline shifts.

2.2 Humidity Chamber

The resistance of another set of strain gauges and the humidity were monitored over time (Fluke 175 or 179 True RMS Multimeters and Enviracaire EIO Digital Humidity/Temperature Indicator, respectively) as the humidity inside a chamber increased; five samples were measured, one in duplicate. The data are shown in Figure 4. The resistance increased with humidity, as would be expected due to swelling of the host matrix. The increase did not depend in a systematic way on EG loading.

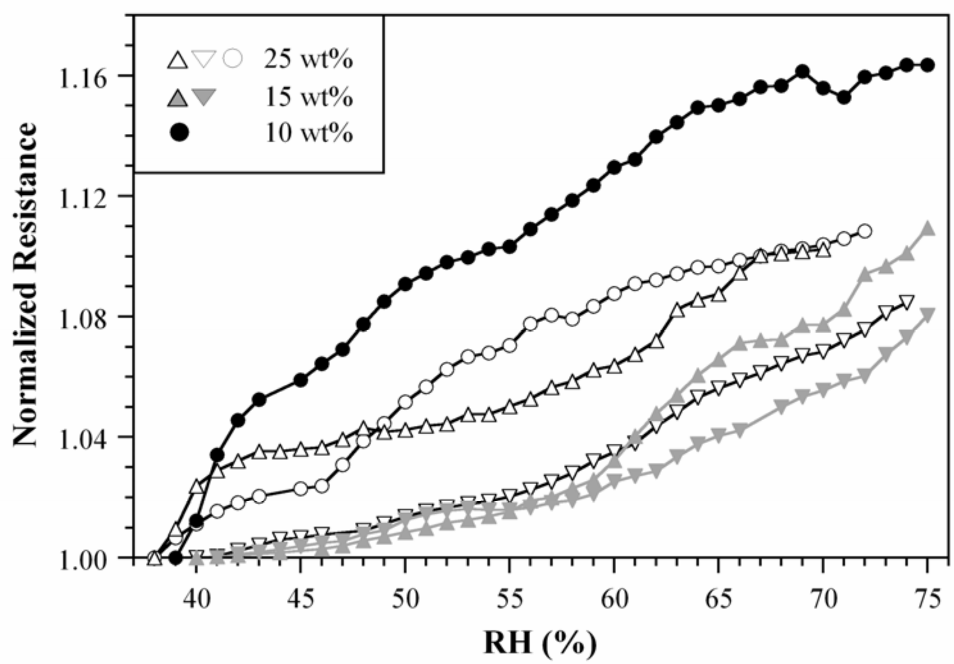

Figure 4. Resistance, normalized by the resistance at the initial point in time, as a function of relative humidity for five strain gauges; the 15 wt% readings were duplicates from a single sample taken on different days.

The 15 wt% sample was measured twice, four days apart (Figure 5). The resistance during the second measurement began at the value at which it ended after the first measurement, indicating that the adsorbed water had not left the polymer during the intervening four days at room RH. The resistance continued to increase during the second measurement, albeit with a somewhat smaller slope (Figure 4). The resistance therefore reflects the water content of the film, rather than the RH.

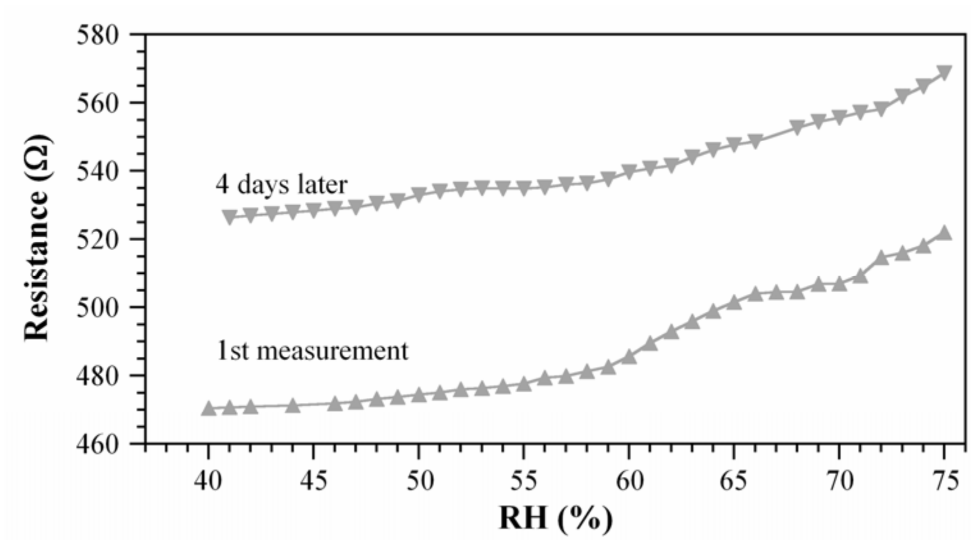

Figure 5. Resistance as a function of relative humidity for the 15 wt% sample measured on two occasions, separated by 4 days. The symbols match those in Figure 4.