Sensing Skin for Detecting Wing Deformation with Embedded Soft Strain Sensors

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***Abstract*—This work presents the design and fabrication of a flexible wing skin with an array of embedded soft strain sensors for detecting the deformation of an airplane wing. The fabricated skin is composed of soft sensors and wires encapsulated by an elastomeric sheet. The soft strain sensors comprised of conductive elastomeric comb capacitors provide enough sensitivity to detect the mechanical strain changes of the wing and a process was developed to integrate these sensors into the skin. Soft electrical wires made of the same conductive elastomer were used for connecting the sensors to an external read-out circuit that was then connected to a computer for analysis. Experimental results from both single sensors and the wing skin show a clear relationship to wing deflection.**

***Keywords*—soft sensors; strain sensors; capacitive sensors; sensing skin; microfabrication; wing deformation; flight control**

I. Introduction

Small unmanned aerial systems (UAS) face flight stability and control challenges. Low moments of inertia of small air vehicles due to smaller geometries make them vulnerable to fast angular accelerations. Atmospheric disturbances have a greater effect on smaller aircraft as wind gusts can be of comparable magnitude or greater than the forward speed of small air vehicles. Due to these fast dynamic challenges and more sensitivity to atmospheric phenomena, faster reaction mechanisms need to be developed.

Feedback using gyroscopic instrumentation provides some disturbance mitigation, however alternative sensing technologies may provide a solution to larger bandwidths and therefore faster reaction to disturbances [1]. Strain sensing may provide the required high speed reaction for effective navigation through atmospheric phenomena. It has been shown that wing deflection precedes fuselage rotation [2], which indicates that material deformations on the wings of an aircraft can be used for flight control. Strain sensors can be used to measure these deformations which typically occur at higher frequencies than those of rigid body dynamics.

Recent developments in soft artificial skin sensors [3] have demonstrated various sensing modalities, for example strain, pressure, and shear force, using a change in electrical resistance or capacitance of the embedded conductors. This class of soft sensors is typically comprised of a silicone rubber or polydimethylsiloxane (PDMS) with embedded flexible and stretchable conductors such as liquid conductors and conductive PDMS (cPDMS) to maintain their high stretchability and flexibility while experiencing mechanical stimuli. Taking advantage of their inherent material softness, the sensors can be mounted easily and conformally on surfaces with more complex 3-D shapes.

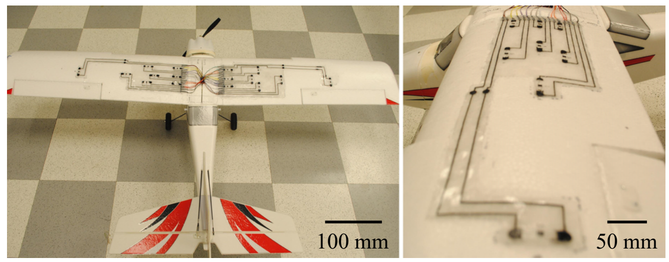

Fig. 1. (a) Images of the wing integrated with the skins and (b) close-up view of one of the skins.

In this paper, a soft wing skin with an array of embedded soft strain sensors for flight control (Fig. 1) is demonstrated. The embedded eight identical sensors having cPDMS comb electrodes allow the skin to track the wing deformation with reasonably high resolution. Taking advantage of capacitive based sensing, only one type of elastomeric conductor (cPDMS) was used for both sensing and wiring, which allowed the skin to be manufactured by simple process. In addition, due to the conformality of the skin, it was attached flush with the wing surface thereby avoiding flow perturbations.

II. Design

A. Strain sensors and their distribution

The overall design of the skin prototype (Fig. 2(a)) includes eight identical soft strain sensors and electrical wires made of cPDMS and PDMS. This design allows the skin to have both a relatively simple circuit, as well as simplified mounting on the wing without protrusions from the surface of the wing. Exploiting an interdigitated capacitor architecture, each strain sensor has high sensitivity and repeatability to uniaxial strain with 500 μstrain resolution [4]. Fig. 2(b) describes the sensing principle of the embedded sensors. Given an applied load (i.e. strain), the orthogonally aligned electrodes of the sensor are deformed along with increasing the gap between adjacent electrodes, causing a change in the capacitance of the sensor.

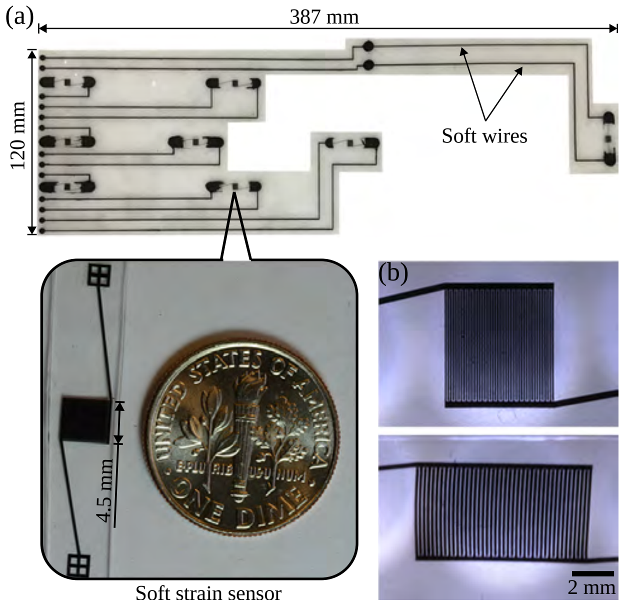

Fig. 2. (a) Image of the skin prototype and one of the embedded strain sensors (inset). (b) Close-up view of the strain sensor when it is at rest (top) and stretched (bottom).

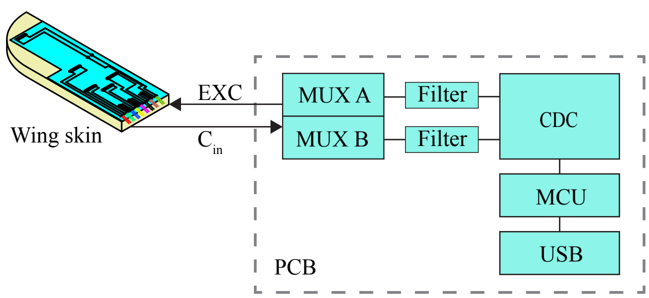

Fig. 3. Schematic of the capacitance read-out electronics.

Taking into consideration the structure, material properties, and clamped-free configuration of the wing[1], eight identical soft strain sensors were distributed along a wing area in a semi-span where high strain response is expected. This area was found closer to the root of the wing, and along an area containing spars. Sensors were kept away from aileron servo motors to avoid electromagnetic interference. Given the conditions for the feasible wing area, 7 out of 8 sensors were placed within the half semi-span closest to the fuselage and the remaining sensor was 465 mm away from the center of the fuselage. The closest three sensors were installed at a distance of 15 mm from the soft electrical pads in order to accommodate the electric connections between the soft and conventional wires.

B. Sensor read-out circuit

Fig. 3 describes the sensor read-out circuit designed for measuring the capacitance of all sensors embedded in the skin

[1]The wing used is 1500 mm long and composed of compressed polystyrene beads with three semi-spars, one of which is made of carbon-fiber (Eflite).

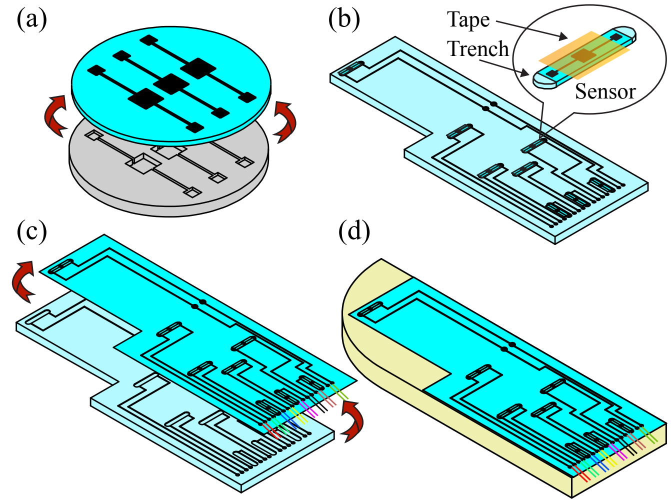

Fig. 4. Fabrication process of sensing skin: (a) Prepare strain sensors. (b) Prepare a mold, locate sensors, and refill cPDMS. (c) Coat with PDMS, connect wires by inserting their electrodes, and peel off skin. (d) Mount skin on wing by using silicone adhesive.

and the data transfer to a personal computer (PC) via an universal serial bus (USB). Using a commercial capacitance to digital converter (CDC), AD7746 (Analog Devices), the data was acquired with a high resolution (0.5 fF/24 bit). In order to scan all sensors of the skin with one CDC, commercially available 8-channel analog multiplexers (74HC4051, PHILIPS) were used with the light-medium filter [5] reducing the electromagnetic interference from avionics. The Inter-Integrated Circuit (I^2C) protocol was used for communication between the CDC and microcontroller, an ATmega328P(Atmel). Finally, Arduino code was written and used for data acquisition and control of the system.

III. Fabrication

As shown in Fig. 4, the fabrication of the skin was divided into two steps, fabricating sensors followed by fabricating the skin prototype embedded with the sensors and soft wires. The sensors were manufactured by casting cPDMS in a microfabricated mold. cPDMS paste—7 wt.% multi-walled carbon nanotube (MWCNT)—was prepared by mixing MWCNTs powder [2] and liquid PDMS (Sylgard 184, Dow Corning) blended at a 10:1 curing ratio. More details on the fabrication of the sensors can be found in the previous work [4].

The skin prototype was also fabricated by molding cPDMS and coating it with PDMS. Using a commercial laser cutter (VLS3.50, Universal Laser Systems), the mold was engraved with the contours of sensors and wires. In step (b), the prepared sensors were sited in the desired locations and covered by a cellophane tape to protect the sensing area from cPDMS. The electrical pads of the sensors were left as open for the connections between sensors and electrical wires. cPDMS paste refilled trenches and was planarized by hand using an

[2]MWCNTs powder has length of 10–30 μm and outer diameter of 10–20 nm (Cheap Tubes Inc.)

industrial screen printing squeegee (Ryonet), and then cured in an oven at 80 °C for an hour. After the cPDMS was cured, liquid PDMS was poured over the entire mold and cured in the same manner, following the insertion of the conventional wires' electrodes into the electrical pads of the skin. A silicone adhesive (Sil-Poxy, Smooth-on) was used on the wire insertion areas to improve the robustness of these connections. The excess material of fabricated skin was cut by hand using a razor blade. Finally, the fully fabricated skin prototype was bonded on the wing by using a silicone adhesive.

IV. Results and Discussion

Two preliminary experiments, the calibration of a single sensor and the skin prototype, were performed to evaluate the performance of the prototype. Both the single sensor and the skin were mounted on the wing for testing. A set of weights were placed at the tip of the wing to produce artificial wing loads. These loads have a direct correlation with wing loads during flight and are generated depending on speed and angle of attack, among other factors. Three tests were conducted for each weight and output signals from a single sensor and all sensors in the skin were recorded at a sampling rate of 90.1 Hz and 26.3 Hz, respectively.

In the calibration of a single sensor, eight weights were chosen as static loads placed at the wingtip. As shown in the inset of Fig. 5(a), a single sensor showed reasonably high sensitivity to the applied loads with a resolution of 10 grams. Moreover, both repeatability and linearity of a single sensor response were verified based on the results of three trials shown in Fig. 5(a).

For the skin prototype, a differential capacitance measurement using a reference capacitor (28 pF) was performed with respect to the initial capacitance. An average over all of the sensor measurements was obtained and correlated to each weight, as shown in Fig. 5(b). The strain response of the skin prototype was sufficiently high for flight control implementation, which may ultimately provide faster inputs to improve small UAS response to atmospheric disturbances.

V. Conclusion

The primary contribution of this work is the development of an elastomer-based wing skin for flight control on small fixed-wing aircraft. The skin was fabricated by a simple molding process, and also provided reliable sensor measurements with highly linear output signals from the embedded sensors. The preliminary experimental results verified the functionality of the skin prototype. Integrating the proposed device with avionics is a part of our immediate future work. Further simplification of current fabrication method by developing a single skin mold with both wiring and sensors is also included in our future work.

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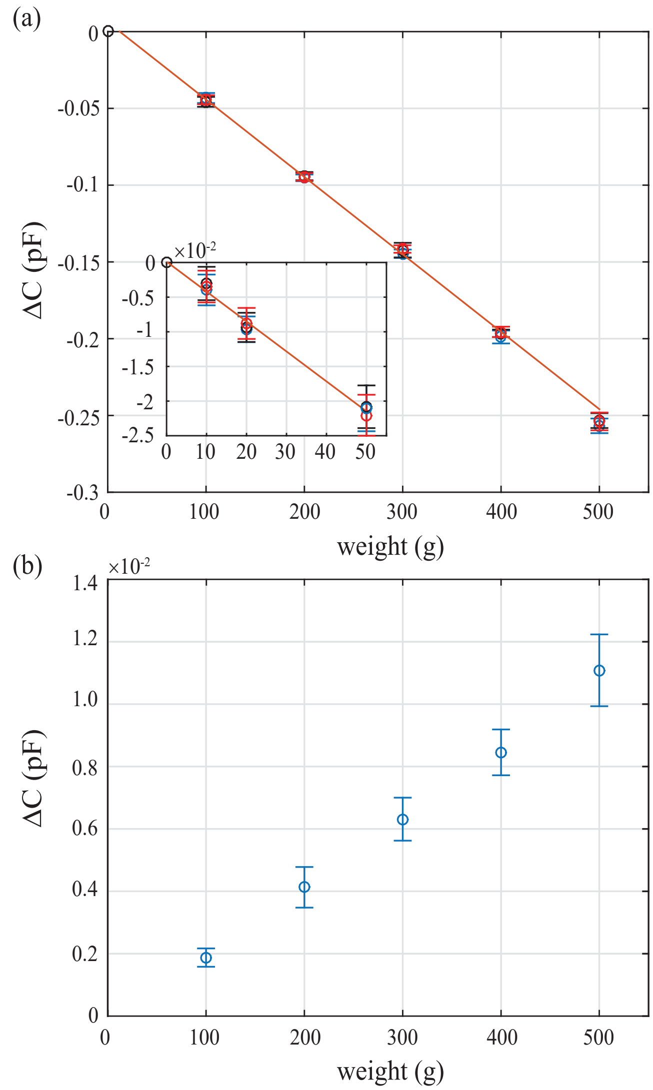

Fig. 5. Static strain response of single sensor (a) and skin prototype (b): Mark and bar stand for the mean value and the standard deviation of acquired data, respectively. Orange line denotes linear fitting.

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