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A Low-cost Fabrication Approach to Embody Flexible and Lightweight Strain Sensing on Flapping Wings

Sunyi Wang, Martijn den Hoed, Salua Hamaza

***Abstract*— Aerial flyers in nature utilize strain sensing to monitor forces in real time, crucial for navigating through wind disturbances and obstacles in flight. While micro air vehicles (MAVs) typically utilize vision and airflow sensing [1], [2], the potential of strain sensing remains relatively unexplored, despite the abundance of available solutions crafted via advanced microfabrication techniques. After surveying available techniques in the literature, we introduce a streamlined fabrication process for rapid prototyping of strain gauges that requires a minimal set of low-cost tools, suitable for roboticists with limited microfabrication experience or resources. To showcase the effectiveness of our method, two kinds of strain gauges (with ginkgo-leaf-inspired patterns and conventional meander patterns) are integrated on a pair of flapping wings to monitor the wing deformation during flapping cycles. We aim to inspire researchers in aerial robotics to incorporate this lightweight and affordable strain-sensing technology to enhance flight navigation and control, opening new avenues for lightweight autonomy and intelligence.**

I. INTRODUCTION

Strain gauges are widely used in different engineering applications, and are gaining more attention in the field of robotics thanks to the advancement in microfabrication. In aerial robotics, bio-inspiration has shown that distributed strain sensors provide gyroscopic-like sensing on a flapping wing [3]–[5]. However, for innovative platforms like flapping wing MAVs (FWMAVs), comprehending and utilizing the wing deformation information in flight control remains challenging. Among current solutions, simulation methods with reasonably simplified assumptions are still heavy in computation, and hardware alternatives often lack durable, accessible, and easy-to-integrate instrumentation.

Various advancements in microfabrication fields provide lightweight strain gauge prototypes with materials such as graphene [6], piezoresistive [7], conductive hydrogel [8], and carbon-based nanomaterials [9]. However, they often involve more sophisticated processing environments that are less accessible or are not directly suitable for aerial robotics applications.

Therefore, embedding force-sensitive sensors on flapping wings remains a novel research direction. Several attempts have been made to utilize force-related sensory information to further understand and improve flapping wing platforms. Sensors that can detect vibration [10] or pressure [11] directly on the wing have been developed to monitor the flapping motion. With strain sensors, researchers are also able to perform flapping flight posture recognition with an IMU [12] or detect disturbances such as wind gusts [13].

A distributed strain sensor solution that can be easily accessible to aerial roboticists for fabrication and that is soft, lightweight, and durable for free flight onboard a FWMAV is yet to be found. In this article, we provide a Kapton polyimide- and copper-tape-based solution that is suitable for prototyping strain gauges and can be fully integrated as part of the flapping wing.

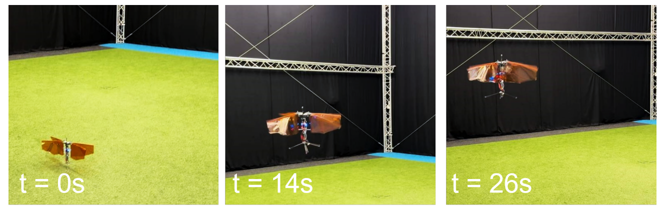

Fig. 1: Free flights of the Flapper Drone with embodied strain sensing on the Kapton polyimide-film wings.

II. STRAIN GAUGE DESIGN

A. Design constraints and goals

The design and fabrication aspects are limited by both the available laser source's characteristics (both power and beam diameter for minimal achievable trace width) and the desired application platform for intended wing deformation investigations, in our case, the 102 g (min. take-off weight) Flapper Drone [1] subjected to different wing loads.

For a FWMAV to reach the desired thrust-to-weight ratio while maintaining sufficient maneuverability, the size and material of the wing pairs are crucial. In particular, the material choice of the wings often needs to ensure an optimal balance of elasticity and rigidity. This way, the wings undergo a suitable amount of deformation under loads while still maintaining good responsiveness and structural integrity, and can provide sufficient lift enhancement through the clap and fling mechanism.

To mimic a force-sensitive wing inspired by nature, we are faced with the stringent requirements of having a soft and lightweight strain gauge that ideally 1) is intrinsically part of the wing, 2) brings minimal changes to the wing stiffness, 3) can survive hundreds or even thousands of *mN* inertial forces from the flapping motion 4) requires simple and minimal electrical components. In the end, the goal is to select a material that can both be the wing fabrication

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[1] https://flapper-drones.com/wp/nimbleplus/

material such that flight can still be sustained and able to house the fabricated strain gauge seamlessly.

B. Analytical calculation

Strain is defined as the relative change in length of a component when subjected to tensile or compressive stress. Thin film resistors are ideal for measuring strain, as they offer sufficient elongation or compression under force, allowing the variation in resistance to reflect changes in strain. Copper is commonly used for estimating resistor dimensions due to its widespread availability and ease of sourcing, such as using 0.06 *mm* copper adhesive tape in our case. Additionally, copper can be easily soldered for interfacing with cables and other electronic components. It's worth noting that the size constraints of the Flapper Drone's wings also impact the size of the resistor. According to Eq. 1 where ρ is resistivity, L is length, A is the cross-sectional area of the material,

$$R = \rho L/A \tag{1}$$

and with the size of the wing in mind, we are dealing with small resistance values in the range of approximately 1 to 5 Ω for a strain gauge that uses 20 to 30 traces of 0.3*mm* width, with a length of 50 to 150 *mm* per trace. Here, the trace width is predominantly affected by the laser beam's diameter, the laser gantry, and the chemical processes during the microfabrication. In our case, we have found that a minimal trace width of 0.3*mm* is reliable in fabrication.

III. Strain Gauge Fabrication

A. Selection of materials and fabrication methods

The selection of materials that are suitable for both flight and embedded strain gauges is intertwined with the fabrication process. For an in-house workflow emphasizing minimal tooling, rapid iteration, and cost efficiency, photo etching copper adhesive tape on polyimide film (Kapton tape) emerges as a reliable method. Compared to alternatives requiring more chemicals, equipment, or pricier materials, this approach offers sufficient accuracy with minimal effort. While laser-induced graphene (LIG) is another potential method, preserving or enhancing the quality of porous graphene poses challenges [12], [14], especially for highly deformable wing surfaces. During flapping, LIG-based sensors easily delaminate, leading to conductivity loss.

Given the elasticity of the original 1 *mm* foam wing of the Flapper Drone and to maintain a similar thrust-to-weight ratio, we narrow down our choice of wing material to 2,3 and 4 mil (50, 75, and 100 μm) Kapton polyimide films. They are easily sourceable from the flexible electronics industry, can be made into wing pairs with high precision through laser cutting, and are easy to integrate with the copper resistor fabrication process.

To quickly determine which thickness of the polyimide film is the candidate material for both forming the flapping wings and being the suitable material for strain gauge fabrication, we test flight manually the MAV with all three thicknesses of Kapton films. We discover that all three of them could sustain manual flight well. An impression of

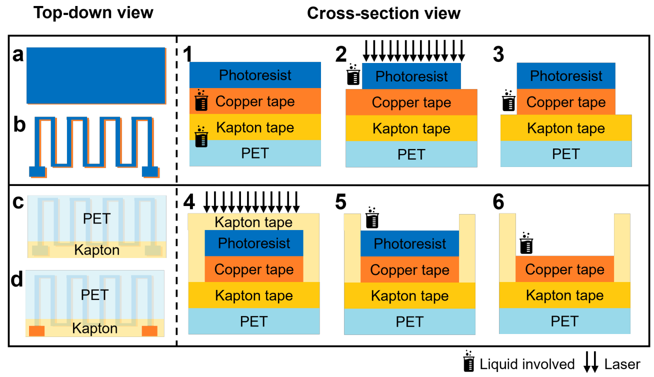

Fig. 2: An overview of the fabrication workflow. From top-down view a to b: the desired strain gauge trace patterns are etched out through Step one to three; From top-down view c to d: the protection layer (PET film) for the sensor and the copper solder pads are made through Step four to six. For simplicity, the top-down view only contains the top two layers of the stack.

the free flight testing is shown in Fig 1. In the end, we decide to proceed with the 50 μm Kapton film, such that the bioinspired nature of soft and elastic wings is maintained as much as possible.

B. Fabrication workflow

The strain gauge fabrication workflow is iteratively developed, with inspiration taken from industrial Flex PCB production. A 120 μm PET base layer is covered with a strip of 30 μm Kapton tape, and cleaned in a bath of 5% NaOH solution. Subsequently, a layer of 60 μm copper tape is applied, and the stack is again cleaned with the caustic solution. A layer of dry-film negative photoresist is applied next, making use of a heated laminator, resulting in a stack illustrated in Fig. 2a.

A consumer-grade 405 *nm* diode laser (SCULPFUN S9) is used to expose the sensor pattern on the photoresist, at 600 mm/s, 20 lines/*mm*, 70 mW. The photoresist is developed in a solution of 0.6% NaOH. Afterward, the remaining photoresist is exposed under a strong UV light to increase robustness. The uncovered copper layer is etched away in a ferric chloride bath, such that only the exposed pattern remains, shown in Fig. 2b.

Next, a PET film coverlay is laminated over the etched area to overcome adhesive interference from the copper tape residue. Unlike the adhesive-backed copper tape, PET film doesn't hinder Kapton tape adhesion. Its adhesive-free nature and slight melting during lamination enhance bonding. Kapton tape replaces PET film in areas requiring copper solder pads for better adhesion. This distinction of film use is shown in Fig. 2c through the tinted light blue and yellow color. At the location of the copper pads, Kapton is burned away by the same laser, at 600mm/s, 20 lines/*mm*, 500mW. The now exposed pads are still covered by photoresist, which is further dissolved in a solution of 5% NaOH, resulting in the final sensor, as shown in Fig. 2d.

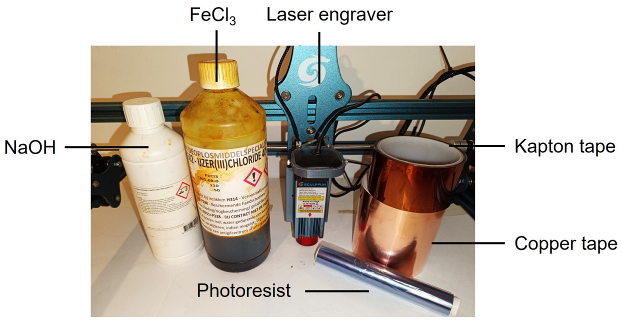

Fig. 3: A collection of the major tools, materials and chemicals involved in the fabrication process.

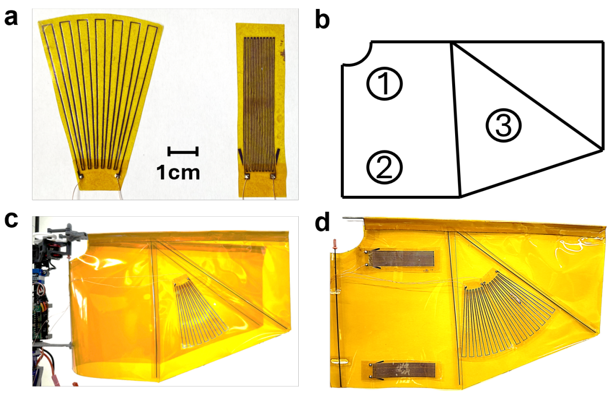

Fig. 4: Examples of fabricated sensors and tested placement locations on the Flapper Drone. a: two designs of the strain gauges (ginkgo-leaf inspired pattern and conventional pattern); b: locations where strain gauges are placed on the wing and measurements are conducted; c: an example of test location ③ where the ginkgo-leaf inspired sensor is placed; d: a demonstration that our strain gauges can be easily applied and re-applied for testing at different locations.

IV. Results and Discussion

A. Fabrication examples

Two designs of strain gauges are fabricated, see Fig. 4a. The first is inspired by ginkgo leaves, where extra stretchable and deformable results have been achieved for the monitoring of tensile stress [15]. The second is the conventional strain gauge design with straight meandered lines in a compact space. The bottom Kapton film is adhesive, and after the backing PET film is peeling off, the sensor can be further applied to any surface area of interest (in our case, the three locations shown in Fig.4b. Note that the first design is not tested in location 2 due to lack of space at the trailing edge). Strands of 0.18 *mm* thin copper wires are soldered to the copper solder pads for further measurements on the FWMAV. More examples of how strain gauges can be easily embedded on the wing are demonstrated in Figs. 4c & 4d.

B. Measurements

Typical strain gauges utilize readout methods that incorporate 1) operational amplifiers, 2) constant current drivers, and 3) Wheatstone bridges with analog-to-digital converters for more accurate and readable signals. Here, as a simple proof of concept, our only measurement goal is to have measurable resistance changes (through measurable voltage changes) when the strain gauge is embedded in the wing and subjected to flapping motion.

Therefore, we select Texas Instruments ADS1220, which is a precision, 24-bit, analog-to-digital converter (ADC) tailed for measuring small sensor signals at the resolution of 0.0003 mV. We connect our strain gauge with a 100 Ω resistor in series, with a 5V DC input to form a voltage divider circuit, where the ADS1220 ADC directly reads out the voltage across the strain gauge. For simplicity, error sources such as input voltage quality, wire parasitic resistance and resistor tolerance are not mitigated for the current study. And as our test environment's room temperature is regulated around 20 °C, we do not consider the temperature influence here on the resistance value. After the strain gauge is applied to the wing at each test location, we conduct a 30-second data logging to acquire the initial resistance R_0 of the sensor where it is only subjected to the wing's morphology at the resting state, and acquire the one standard deviation values to help assess the voltage readings later when subjected to flapping. Then, we conduct the flapping around 1-1.5 Hz with 20% throttle input on a transmitter. The voltage across the strain gauge is sampled around 45 Hz. A fourth-order Butterworth filter is applied, with a cutoff frequency at 4Hz. Each group of tests is repeated 3 times and logged for 5 seconds. The results are shown in Fig. 5 and Fig. 6, where we can see both sensors have good repeatability even after they are being peeled off and re-applied to a new location, although each time we need to re-measure the initial resistance. The cyclic data pattern caused by flapping is also visible. For both sensors, the higher amplitude oscillations at the leading edge location near the wing root indicate a higher strain change, i.e. more significant wing deformation, which corresponds well to the biological insights [16]. The ginkgo leaf inspired shape is particularly interesting for future design thanks to its stretchability and wider coverage that provides a more measurable wing deformation amount. Last, this high resolution and small form factor ADC is also of future readout design interest as aerial robotics applications could benefit from lightweight, low-power data acquisition hardware with sufficient accuracy.

C. Discussions

From the perspective of microfabrication, improving layer adhesion between copper and photoresist dry film remains a key challenge in fabrication due to particle contamination. Enhanced wash and clean routines could boost copper layer adhesion and pattern etch quality.

For faster iterations and ease of handling, smaller standalone strain gauges prove more reliable, allowing for easy application onto the wing and multiple reapplications without damage. Attempts to directly fabricate larger strain gauges onto the Kapton film, serving as the wing itself, face challenges such as air bubble formation and trace discontinuities during manual processing.

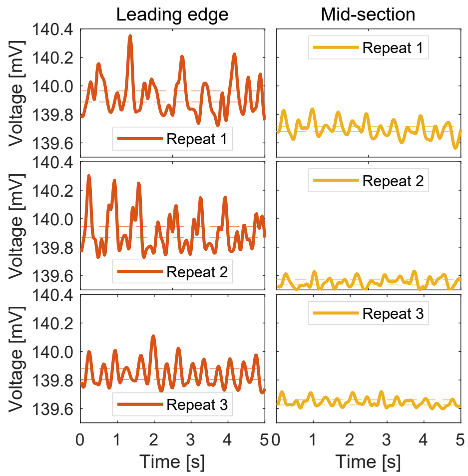

Fig. 5: Voltage changes across the ginkgo-leaf inspired strain gauge. Dashed lines are the envelope of $\pm\sigma$ calculated from initial sensor calibration without any flapping.

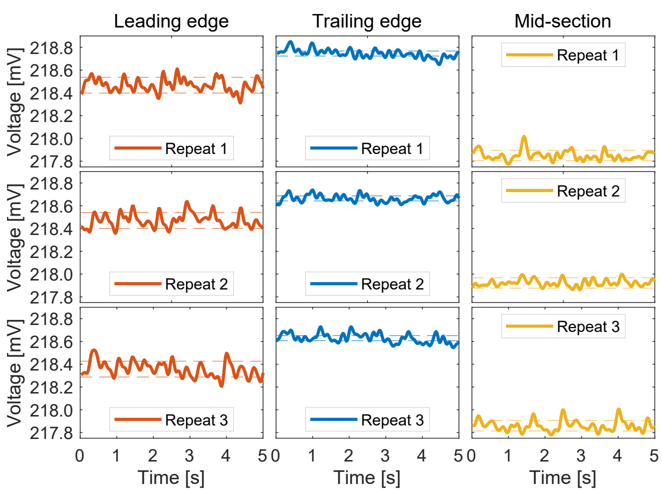

Fig. 6: Voltage changes across the conventional strain gauge. Dashed lines are the envelope of $\pm\sigma$ calculated from initial sensor calibration without any flapping.

While thin copper traces exhibit robust functionality, laser-induced graphene counterparts fail upon minimal bending. Ensuring the layer quality and long-term reliability of strain gauges is critical for enduring numerous flapping cycles on the FWMAV platform. In general, with our simple fabrication flow and set-up, factors such as laser characteristics(beam diameter, laser fluence, speed), thin film qualities (layer thickness, adhesion, temperature resistance, solderability) and hands-on handling easiness all contribute to having a reliable and functional strain gauge embedded wing.

V. Conclusions

This article presents a simple and cost-effective fabrication process to produce flexible strain gauges designed for integration on flapping wing drones. These sensors not only serve as a versatile tools for investigating strain's role in FWMAV flight control – including sensor number, placement, and sensitivity – but also hold potential for various soft robotics applications, such as tactile sensing. Future avenues for exploration include advancing towards more integrated wing designs that incorporate both structural and sensing functionalities. For instance, controlling the local stiffness of the wing by varying strain gauge patterns.

Originally designed for flapping wing applications, this low-cost method offers the community a simple tool for rapid prototyping strain gauges. This approach can also be adapted for other embedded force-related sensing applications in soft aerial robotics, avoiding the need for more complex or expensive methods during initial prototyping stages.

Availability Statements

The authors are willing to share the exact products and the detailed fabrication flowchart upon reasonable request.

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