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Design and Implementation of Bending Force Sensor Featuring Printed Circuit Board

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***Abstract*—This paper proposes a bending force sensor that integrates the sensing member, signal amplification, and analog-to-digital conversion all on a single printed circuit board. A specially designed raster copper pattern is directly fabricated on this printed circuit board, replacing the traditional process of adhering a strain gauge foil to the substrate. The adhesion-free advantage reduces human error and increases the accuracy of this bending force sensor, making it suitable for mass production and cost-effective. The experiment results show that the linearity and full scale of the proposed bending force sensor are 99.3% and 20 N, respectively.**

Keywords—printed circuit board, strain gauge, bending force sensor.

I. Introduction

Robotic arms are widely applied in automation technology in various industries including industrial manufacturing, commercial agriculture, medical rescue, entertainment services, military security, and even space exploration. Due to their extensive application and involvement in numerous dangerous, specialized, and irreversible operations, precise control of this technology is extremely critical. Therefore, assessing whether the robotic arm is operating within an appropriate range is a very important issue.

Taking force and torque sensors as examples of robotic arms, they play crucial roles in accurately controlling the motion path, force and correcting actions [1]. Due to the current limitations in fully controlling robotic arms and automation, research and development of mechanical sensors such as force sensors, torque sensors [2], three-axis sensors, six-axis sensors [3], etc., are increasingly being promoted.

All of these sensors consist of strain gauges, which include Wheatstone bridges [4, 5], and are outputted to signal amplifiers. The relationship among the three is based on the use of strain gauges to measure the change in resistance of metal wires and to measure strain. Then, the principle of unbalance in Wheatstone bridges is applied, resulting in a small voltage output. This output is then processed into the required voltage through a signal amplifier, enabling us to perform tasks such as measurements, monitoring, and feedback control, and then let us determine the current values of force, torque, and other related physical quantities.

However, the key to the poor accuracy of traditional sensors lies in the manufacturing process of adhering foil strain gauges. First, in traditional sensors, users need to use a special glue, such as cyanoacrylate, to attach strain gauges to the substrate [6, 7]. If too much glue is used, the deformation of the substrate surface and strain gauge may not be consistent. On the other hand, if too little glue is used, the strain gauge may not be fixed entirely to the substrate surface and may even fall off, affecting other nearby components. Secondly, perfect alignment is also required when adhering the strain gauges since the positioning of the strain gauges depends on the direction of force. Thirdly, the accuracy of the strain gauge also depends on the bonding technique, such as whether the surface is smoothed and thoroughly cleaned during bonding, and whether a protective coating is applied after bonding. The purpose of the protective coating is to reduce the exposure of the strain gauge to external factors such as dust, moisture, chemicals, or mechanical forces. If any of the aforementioned errors occur, it will make the factory-labeled gauge factor (GF) inaccurate, requiring recalibration or even the replacement of the strain gauge, resulting in additional costs without a corresponding improvement in accuracy. To address these problems, we propose a force sensor that does not require adhesive, as described below.

In order to solve the adhesion issue of foil strain gauges, this study aims to utilize the characteristics of copper foil to integrate the Wheatstone bridge and signal amplifier on a single circuit board, reducing the interference caused by signal transmission in the manufacturing process. The study also leverages the ease of integrating electronic components on printed circuit boards to increase design flexibility and reduce human errors, while also taking advantage of the capability for mass production to achieve the desired outcome.

The remaining structure of this paper is as follows: Section II introduces the structure and working principles of traditional strain gauges and describes the detailed system design of the PCB-based bending force sensor. Section III uses Solidworks software to simulate and analyze the bending process. Section IV presents the experimental results. Section V highlights the advantages and disadvantages of the system design, explores potential sources of error, and presents the conclusion of this article.

II. SYSTEM DESIGH

A. Material and Working Principles

Many traditional force sensors consist of spring elements and strain gauges. Elastomers are typically made of steel or aluminum [9], which means they deform under load but return to their resting position within their elastic limit. Therefore, we choose aluminum alloy A5052 as the material for the PCB [10] because of its better thermal conductivity and also because it is easy to mine and extract, making it a cost-effective alternative to heat sinks. Strain gauges are electrical conductors, and deformations can be obtained from them. When the elastomer is stretched, the electronic conductors are also stretched, and vice versa when compressed. In this scenario, the deformations of the strain gauges result in changes in resistance. We use this phenomenon to indirectly measure external forces [11] based on Ohm's law. Shown as

$$R = \rho \frac{l}{A} \tag{1}$$

where R is the object's resistance, ρ is the object's resistivity, l is the object's length, and A is the object's cross-sectional area. The deformation of the strain gauge generates an output voltage signal, and through a signal amplifier, we can obtain the numerical value of the bending force at that moment, analogous to Hooke's law, whereby the physical quantity of displacement can be converted into a unit of force, by relying on experiments to derive the magnitude and units of the elastic coefficient. In contrast to traditional strain gauges, we only need to focus on designing for functionality, and after development is complete, we can use the standard PCB etching process to link up the entire process from designing to manufacturing [12], which not only reduces manufacturing costs but also easily adds many other features.

B. Electronic Circuits and Components

This design proposes a force sensor based on printed circuit board. The final device equips a Wheatstone bridge, which can counteract the effects of temperature changes, suppress lateral force interference, and conveniently resolve compensation issues, strain gauge patterns with dimensions 15*100 mm and a signal processing chip (HX711, Avia Semiconductor [13]), which includes an internal voltage regulator, on-chip clock oscillators, a programmable gain amplifier, and a 24-bit resolution ADC, and it has the advantages of high integration, fast response speed (80 Hz), and strong anti-interference.

C. Sensor Design

Fig. 1 shows the bending force sensor based on printed circuit board, Fig. 2 illustrates its size and hole position, and Fig. 3 and 4 show its enlarged details. The line width and spacing are 4 mils (101.6 µm). The planar density of the copper layer is 1/3 oz/ft^2, so the corresponding thickness is 11.7 µm. In order to achieve high resistance, the circuit is made as thin, narrow, and long as possible within the limited area, and changes in the overall length can be determined more easily under the condition that the volume of the copper foil pattern remains unchanged. The implemented resistance is 100 Ω, compatible with the Wheatstone bridge excitation current embedded in the signal processing chip.

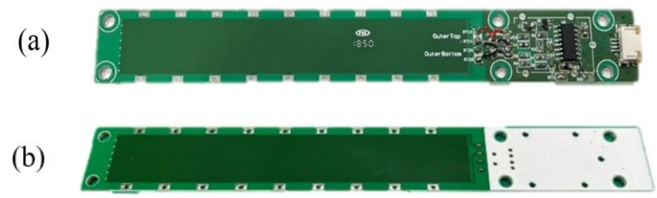

Fig. 1. The PCB-based bending force sensor physical photos: (a) top layer, (b) bottom layer.

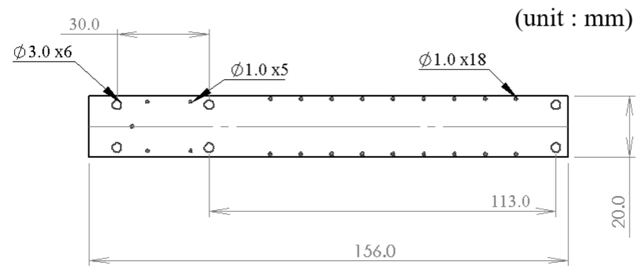

Fig. 2. The PCB size mark and hole map.

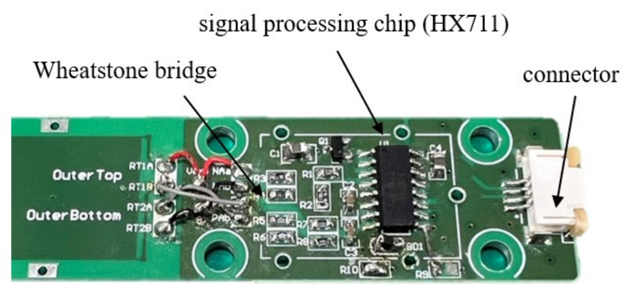

Fig. 3. The PCB-based bending force sensor physical enlarged detail diagram.

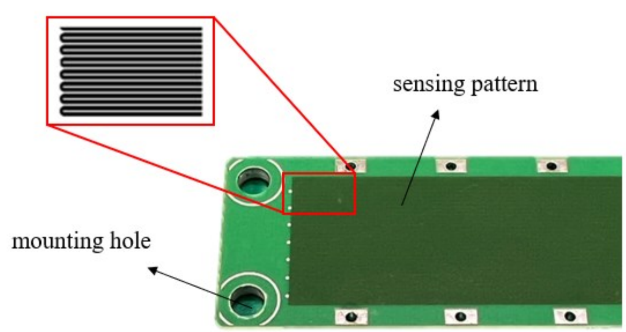

Fig. 4. The PCB-based bending force sensor enlarged detail diagram. The specifications for the copper foil pattern of the bending force sensor are: trace width = 4 mil, trace spacing = 4 mil, planar density of the copper layer = 1/3 oz per ft^2, length = 100 mm.

In terms of circuit design, we integrate the force sensing pattern, Wheatstone bridge, and signal amplifier into the circuit diagram shown in Fig. 5. The actual system setup is shown in Fig. 6, with the fixed part located near the electronic components and the loading part on the side of the strain gauge pattern. The PCB force sensor is installed on the measuring platform for direct measurement, and the measurement results are outputted by a flexible cable, decoded by the Arduino Uno, and then passed on to the PC for recording. The overall flowchart is shown in Fig. 7.

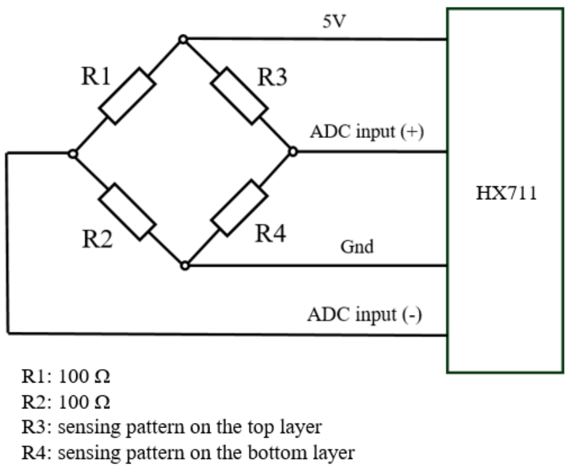

Fig. 5. The schematic diagram of the PCB-based bending force sensor.

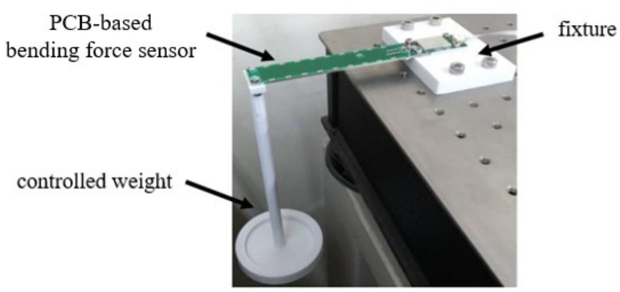

Fig. 6. The system design of the PCB-based bending force sensor.

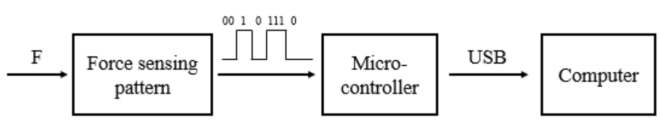

Fig. 7. Diagram of the flowchart for PCB-based force sensor measurement.

III. Experiment Simulation

As the measurement target of this design is bending force, the system is designed as a cantilever beam. Therefore, we use Solidworks software to simulate the stress distribution beforehand and find that when a fixed force is applied, the strain distribution on the upper layer of the PCB gradually increases from the fixed end to the stress action end. This can prove that when a positive pressure is applied, the length of the upper layer pattern of the PCB will be stretched under a fixed volume, and the opposite is true for the compression state of the lower layer. The simulation result is shown in Fig. 8.

However, because force application may cause stress concentration around the holes and lock positions, affecting the variation of PCB patterns, we design to separate the PCB pattern from other holes and electronic components. Using Solidworks software to analyze, the results shown in Fig. 9 demonstrate that the stress distribution around the hole or lock positions does not interfere with each other. Therefore, stress concentration around the pattern itself will not cause any effect.

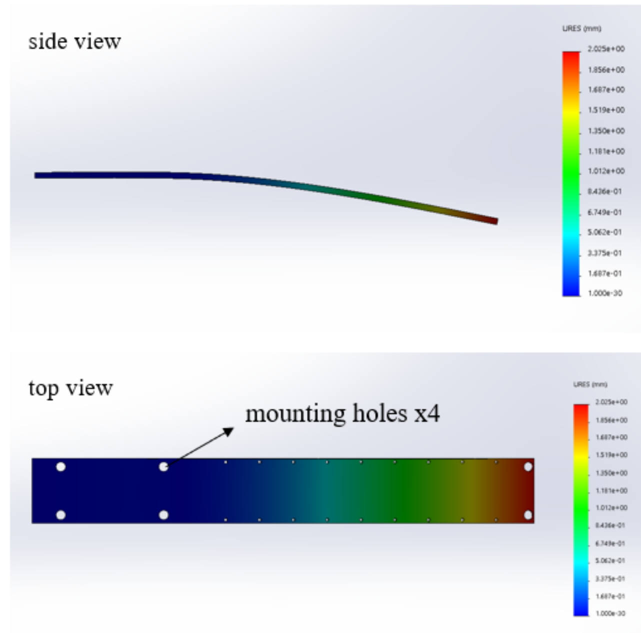

Fig. 8. Strain distribution of cantilever beam.

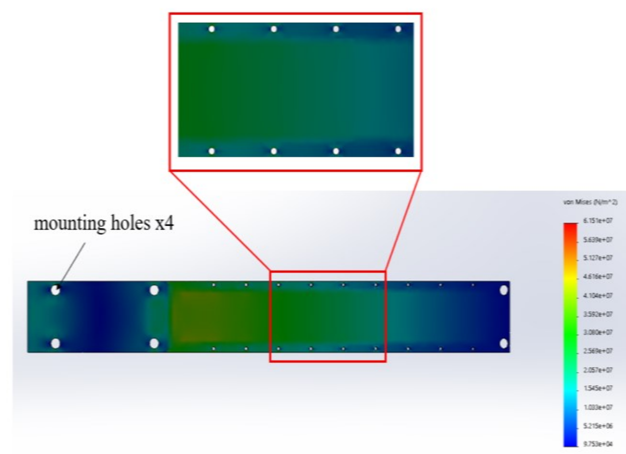

Fig. 9.Stress distribution of cantilever beam of the top layer.

IV. The Experiment Result

First, let's discuss the gauge factor (GF) of a strain gauge, which measures the sensitivity to strain. It is defined as the ratio of the relative change in electrical resistance R to the mechanical strain, expressed as [14]

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\varepsilon} \tag{2}$$

where ΔR is the change in resistance of the strain gauge due to axial and transverse strains, and R is the unstrained resistance of the strain gauge. ε represents strain, which is equal to ΔL/L, where ΔL is the absolute change in length and L is the original length. To obtain ΔR/R, we incrementally add 200 g weights up to 2000 g in the experiment, as shown in Fig. 10.

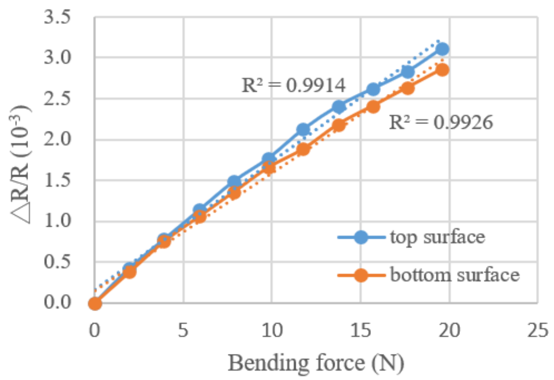

Fig. 10. The change of force and resistivity on the surface above the PCB-based bending force sensor.

However, for the fixed end to the stress application end, the strain and stress are proportional. Therefore, we take half of the total strain value as the effective strain, as shown in Fig 11. In fact, the actual resistance we measure was 141 Ω, which is higher than the calculated resistance of 106 Ω. It is speculated that the slight difference between the experiment and the simulation is mainly caused by issues in the PCB fabrication process, such as under-exposure and over-etching. Additionally, when we observe the traces under an optical microscope (Axioskop 40, ZEISS), we find that the trace width is not exactly uniform and is wider than our the expected width of 101.6 μm, with a deviation of approximately 10% for each trace, as shown in Fig. 12. To solve for the GF equation, we compare and obtain the resistance change rate and strain values from both experiment and calculation. The GF value obtained from both methods is approximately equal to a numerical value of 3.

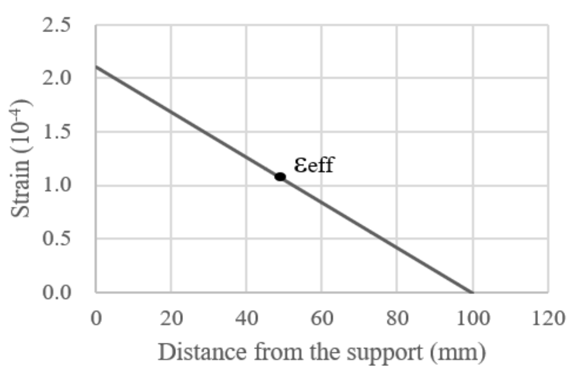

Fig. 11. Effective strain at 200 grams.

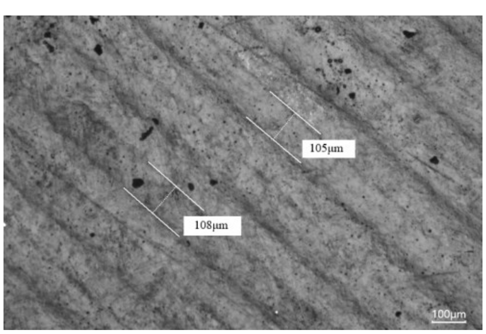

Fig. 12. The microscopic photograph of the trace on the sensing pattern of the PCB-based bending force sensor.

To verify the accuracy of the measurement data, signal conversion is used to verify the measured resistance variation, as shown in Fig. 13. When the PCB bending force sensor is subjected to a bending force (F), the resistance value of the bending force sensor pattern changes (ΔR), as shown in Fig. 14. The Wheatstone bridge outputs a voltage signal (V), which is then amplified 128 times and converted into a digital signal (count) when it is sent to the signal processing chip. The PCB-based bending force sensor is connected to a microcontroller (Arduino Uno) to parse the data and transmit the final force values to a personal computer. Fig. 15 shows the ADC output data displayed on the computer, which displays weights from 0 to 20 N. The output rate is 80 samples per second, which is determined by the signal processing chip equipped on the force sensor. Ultimately, we can conclude that the length difference can be converted into resistance difference, which can be amplified and output by the signal, thereby determining the current bending force.

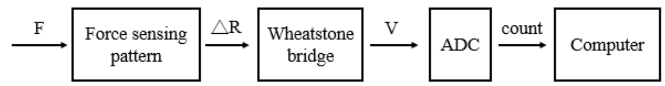

Fig. 13. Flowchart of signal conversion.

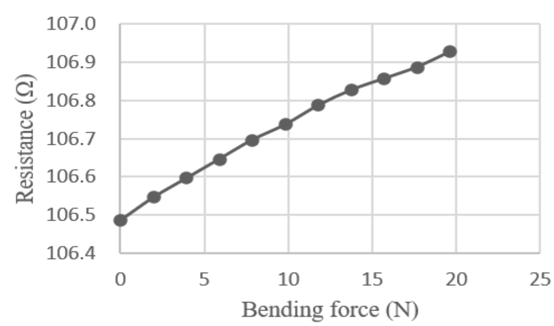

Fig. 14. Resistance value that changes based on the magnitude of stress.

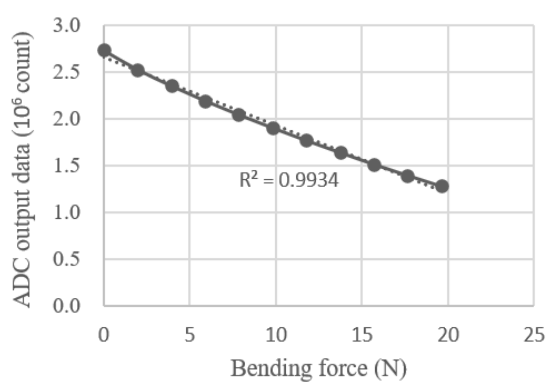

Fig. 15. The change of force and ADC output data.

V. CONCULSION

In previous studies, traditional strain gauges have been widely used, but this article finds that the integration of PCB etching technology can improve the bonding defects of previous strain gauges. The proposed bending force sensor is fabricated entirely through standard PCB etching process without the need for attaching any strain gauges. This idea has been proven to be feasible and successfully implemented. The experimental results demonstrate that this bending force sensor has linearity, full scale, and bandwidth are 99.3 %, 20 N, and 0-80 Hz, respectively, which indicates its high precision and suitability for mass production as a bending force sensor.

In future applications, PCB etching technology can be utilized to miniaturize designs, making it suitable for automation and robotic arms. Additionally, the use of multi-layer PCB processing technology can stack various electrical layers to form a circuit board, making it suitable for various load analysis and inspection in different directions. Perhaps, combine with torque sensors and other related mechanical sensors, the scope of applications will become even wider, and the range of applications will become even more diverse.

REFERENCES

[1] Pérez Ubeda R, Gutiérrez Rubert S. C, Zotovic Stanisic R and Perles Ivars A,"Design and Manufacturing of an Ultra-Low-Cost Custom Torque Sensor for Robotics," MDPI. Sensor, vol. 18, pp. 1786-1804, 2018.

[2] T. Liu, C. Li, Y. Inoue and K. Shibata,"Reaction Force/Torque Sensing in a Master-Slave Robot System without Mechanical Sensors," Sensors, vol. 10, pp. 7134-7145, 2010.

[3] M. K Kang, S. Lee and J. H Kim,"Shape optimization of a mechanically decoupled six-axis force/torque sensor," Sensor and Actuators, vol. 209, pp. 41-51, 2014.

[4] J. Thaysen, A. Boisen, O. Hansen, S. Bouwstra,"Atomic force microscopy probe with piezoresistive read-out and a highly symmetrical Wheatstone bridge arrangement," Sensor and Actuators, vol. 83, pp. 47-53, 2000.

[5] C. Wheatstone,"An account of several new instruments and processes for determining the constants of a voltaic circuit," Phil. Trans. R. Soc. Lond., vol. 133, pp. 303-327, 1843.

[6] Omega, "Transducer Quality Strain Gauges for Shear or Torque Applications", [Online]. Available: https://www.omega.co.uk/pptst/SGT_SHEAR_GAGES.html.

[7] Kyowa,"How strain gages work," http://www.kyowa-ei.com/eng/index.html.

[8] J. Zhu, J Fengbc and Z Guo,"Mechanical properties of commercial copper current-collector foils," RSC Advances., vol. 4, pp. 57671-57678, 2014.

[9] B. Noble, S. J. Harris, K. Dinsdale,"The elastic modulus of aluminum-lithium alloys," Materials, vol. 17, pp. 461-468, 1982.

[10] Abhijeet Bhowmik and Dilip Mishra, "A Comprehensive Study of an Aluminum Alloy AL-5052," Advance Physics Letter, vol. 3, 2016.

[11] K. Hoffmann,"An Introduction to Measurements using Strain Gauges," Hottinger Baldwin Messtechnik GmbH, Darmstadt, 1989.

[12] PCBCART,"PCB Manufacturing Process – A Step by-Step Guide," https://www.pcbcart.com/article/content/PCB-manufacturing-process.html.

[13] Avia Semiconductor,"24-Bit Analog-to-Digital Converter (ADC) for Weigh Scales," http://www.aviaic.com/.

[14] Thomas G. Beckwith, N. Lewis Buck, Roy D. Marangoni (1982). Mechanical Measurements (Third ed.). Reading, MA: Addison-Wesley Publishing Co. p. 360. ISBN 0-201-00036-9.