Research on Adhesion State Sensing Method for a Gecko-Inspired Multiscale Adhesive Structure

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Abstract— This study addresses the lack of real-time state perception in existing gecko-inspired adhesive structures. Inspired by the hierarchical "lamella-setae" architecture of gecko toes, a multiscale adhesive structure was developed, integrating a millimeter-scale boot-shaped elastic component with a micrometer-scale mushroom-type adhesive array. Finite element analysis based on a cohesive zone model was employed to analyze stress distribution during adhesion-detachment processes, identifying the optimal region for embedding a thin-film pressure sensor. Experimental results demonstrate that the sensing signal accurately responds to variations in normal preload and shear displacement, effectively identifying adhesion, slip, and detachment states. A gripper utilizing this technology achieved stable grasping on smooth glass, real-time state perception ("pick-and-place", "drop", "pick failure"), and controllable switching between "strong adhesion" and "easy detachment". This research provides a crucial step towards adaptive and reliable robotic manipulation in unstructured environments.

Keywords—gecko-inspired adhesive; controllable adhesion; multiscale structure; adhesion sensing

I. INTRODUCTION

Geckos exhibit remarkable climbing capabilities due to their multi-level "lamella-setae" structure and precise adhesion control mechanisms, primarily relying on van der Waals forces [1]-[3]. Their ability to switch between strong adhesion and easy detachment by adjusting toe posture [4][5] provides significant inspiration for robotic grasping applications. Research on bio-inspired dry adhesives has progressed substantially, from early developments of high-aspect-ratio micropillars [6] and mushroom-shaped arrays [7] to more recent asymmetric structures such as tilted [8] and wedge-shaped arrays [9] for directional adhesion control. Despite these advances, most studies have focused primarily on the micro-scale, often overlooking the macro-mechanical control analogous to the function of gecko lamellae. Furthermore, while the integration of sensing materials such as conductive polymers [10] or carbon nanotubes [11] has enabled normal force perception, the synergistic sensing of both normal and shear states within a controllable, multiscale system remains challenging. This work bridges this gap by presenting a comprehensive approach—from bio-inspired

design and simulation to sensor integration and experimental validation—enabling controllable adhesion with integrated state perception for reliable robotic manipulation.

II. BIO-INSPIRED DESIGN & FABRICATION

Inspired by the gecko toe structure (Fig. 1a), our adhesive design combines a compliant, millimeter-scale boot-shaped component for macro-scale adaptation and motion control with a dense array of micrometer-scale mushroom-shaped pillars providing high adhesion strength (Fig. 1b). This architecture enables controllable "strong adhesion" through shear motion and "easy detachment" via reverse shear [12][13].
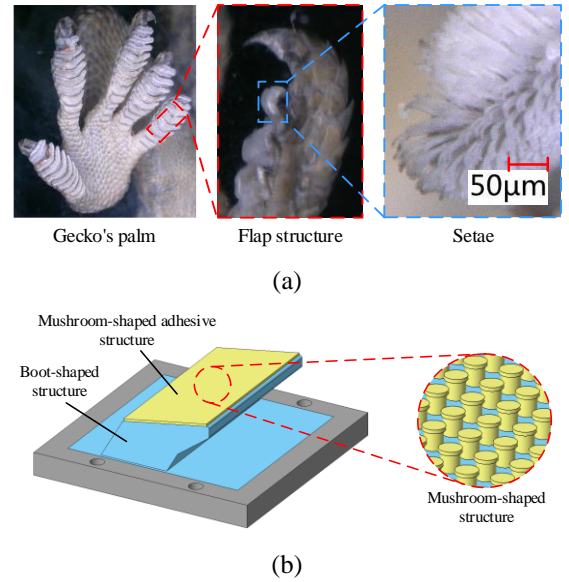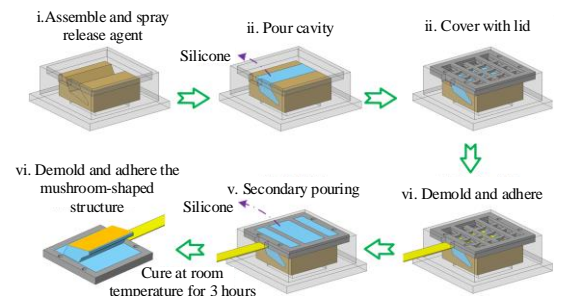

(a)

(b)

Fig. 1. (a) Gecko toe lamella-setae hierarchy. (b) Design of the bio-inspired multiscale adhesive structure.

The fabrication process incorporates a flexible thin-film piezoresistive pressure sensor [14] within the structure (Fig. 2a). The sensor is embedded into the silicone backing layer during the casting process (Fig. 2b), enabling monitoring of internal stress states critical for adhesion perception.

(a)

Thin-film pressure sensor

Mating surface

Boot-shaped structure

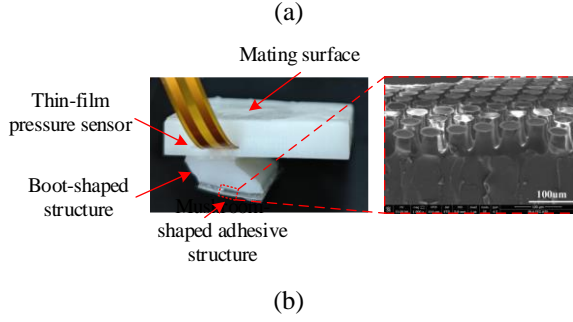Mushroom-shaped adhesive structure

100μm

(b)

Fig. 2. (a) Fabrication schematic with integrated sensor. (b) Physical image of the sensor-integrated adhesive structure.

III. SIMULATION ANALYSIS & SENSING STRATEGY

A finite element model (Abaqus, CPS4R elements, Ogden material model) incorporating a cohesive zone model [15] was established to analyze stress distribution during adhesion and detachment cycles (Fig. 3). The simulation accurately replicates the preloading, shearing, and peeling phases, illustrating the evolution of contact area and internal stresses.
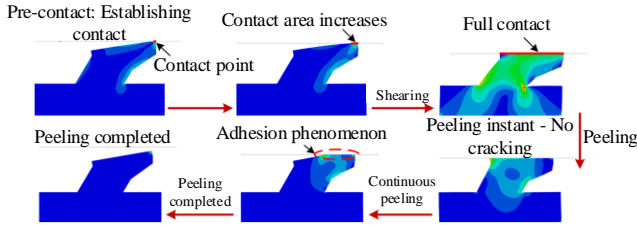

Fig. 3. Simulated adhesion and peeling processes of the adhesive structure.

Analysis of normal stress distribution across six predefined regions (Fig. 4) identified the inner backing area (Region 4) as the optimal sensor placement location. This region exhibits a pronounced and characteristic transition from compressive stress (during preload and shear phases) to tensile stress (during peeling initiation), providing a clear and discriminative signal for state identification (Fig. 5).
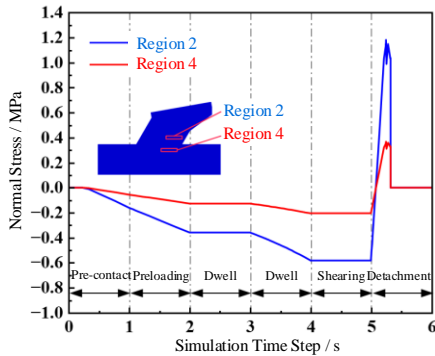

Fig. 4. Normal stress curves across different regions of the adhesive structure.
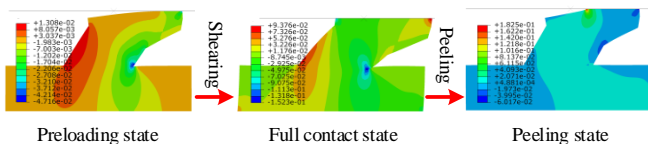

Preloading state → Shearing → Full contact state → Peeling → Peeling state

Fig. 5. Variation of normal stress in the selected sensing region (Region 4) during adhesion-detachment.

IV. EXPERIMENTAL RESULTS

An experimental test platform was constructed to validate the sensing performance. The voltage signal output from the embedded sensor demonstrated strong correlation with directly measured interfacial forces.

Figure 6a illustrates the signal characteristics during a successful adhesion cycle: the signal increases proportionally with applied preload, exhibits a sharp rise during shear displacement, and shows a distinct transition during the peeling phase. Figure 6b demonstrates the detection capability for slip events: a sudden drop and subsequent recovery in the sensor signal clearly indicates momentary adhesion loss followed by successful re-attachment, enabling effective discrimination between stable adhesion and unstable states.
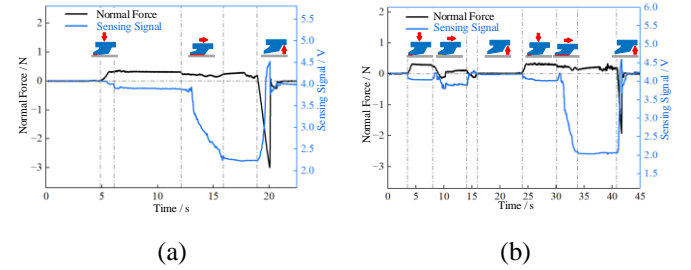

(a)   (b)

Fig. 6. (a) Normal force and sensing signal during preloading, shearing, and peeling. (b) Signals during preloading, shearing, slipping, and re-adhesion processes.

The developed structure was successfully integrated into an opposing-grip adhesive gripper. The integrated sensing system enabled real-time distinction between fundamental manipulation scenarios—"pick-and-place", "drop", and "pick failure"—based on characteristic signal signatures during object engagement and lifting phases.

V. CONCLUSION

This study developed and validated a gecko-inspired multiscale adhesive structure with integrated state perception capability. Computational analysis using FEA identified the optimal sensor placement strategy based on stress distribution patterns. Experimental results confirmed the sensor's ability to reliably detect key states including preload magnitude, shear displacement, slip events, and detachment initiation. The technology, demonstrated through a functional gripper prototype, provides a significant advancement towards achieving adaptive and reliable robotic manipulation in unstructured environments using bio-inspired adhesive technologies.

REFERENCES

[1] Kellar Autumn, Yiching A. Liang, S. Tonia Hsieh, et al. Adhesive force of a single gecko foot-hair [J]. Nature, 2000, 405(6787): 681-685.

[2] Boxin Zhao, Noshir Pesika, Kenny Rosenberg, et al. Adhesion and friction force coupling of gecko setal arrays: implications for structured adhesive surfaces [J]. Langmuir, 2008, 24(4): 1517-1524.

[3]   Rodolfo Ruibal, Valerie Ernst. The structure of the digital setae of lizards [J]. Journal of Morphology, 1965, 117(3): 271-293.

[4]   Kellar Autumn, Anne M. Peattie. Mechanisms of adhesion in geckos [J]. Integrative and Comparative Biology, 2002, 42(6): 1081-1090.

[5]   Y. Tian, D. Tao, N. Pesika et al., "Flexible control and coupling of adhesion and friction of gecko setal array during sliding," Tribology Online, vol. 10, no. 2, pp. 106–114, 2015.

[6]   Yu Tian, Dashuai Tao, Noshir Pesika, et al. Flexible control and coupling of adhesion and friction of gecko setal array during sliding [J]. Tribology Online, 2015, 10(2): 106-114.

[7]   A.K. Geim, S. V Dubonos, I. V Grigorieva, et al. Microfabricated adhesive mimicking gecko foot-hair [J]. Nature Materials, 2003, 2(7): 461-463.

[8]   Gorb S, Varenberg M, Peressadko A, et al. Biomimetic mushroom-shaped fibrillar adhesive microstructure [J]. Journal of the Royal Society Interface, 2007, 4(13): 271-275.

[9]   Burak Aksak, Michael P. Murphy, Metin Sitti. Adhesion of biologically inspired vertical and angled polymer microfiber arrays [J]. Langmuir, 2007, 23(6): 3322-3332.

[10] Daniel Santos, Matthew Spenko, Aaron Parness, et al. Directional adhesion for climbing: theoretical and practical considerations [J]. Journal of Adhesion Science and Technology, 2007, 21(12): 1317-1341.

[11] J Krahn, C Menon. Dry adhesives with sensing features [J]. Smart materials and structures, 2013, 22(8): 085010.

[12] Betul Yurdumakan, Nachiket R. Raravikar, Pulickel M. Ajayan, et al. Synthetic gecko foot-hairs from multiwalled carbon nanotubes [J]. Chemical Communications, 2005, 30: 3799-3801.

[13] Michael P. Murphy, Burak Aksak, Metin Sitti. Gecko-inspired directional and controllable adhesion [J]. Small, 2009, 5(2): 170-175.

[14] Aaron Parness, Daniel Soto, Noe Esparza, et al. A microfabricated wedge-shaped adhesive array displaying gecko-like dynamic adhesion, directionality and long lifetime [J]. Journal of the Royal Society Interface, 2009, 6(41): 1223-1232.

[15] Tong Zhang, Zhaoyang Li, Kun Li, et al. Flexible Pressure Sensors with Wide Linearity Range and High Sensitivity Based on Selective Laser Sintering 3D Printing [J]. Advanced Materials Technologies, 2019, 4(12): 1900679.