

Optimization of Geometric Parameters for Passive Barbed Anchor Mechanisms

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Abstract. To address the issue of excessive power consumption in ecological and environmental monitoring devices, which prevents their long-term deployment in the field, this paper proposes a nature-inspired, zero-power-consumption passive barbed anchoring structure. To quantitatively evaluate the influence of geometric parameters on static anchorage force, this study systematically investigated, through controlled-variable experiments, the effects of barb inclination angle (ranging from 15° to 75° , with a total of five groups) and normal preload (at two levels: 50g and 100g) on static anchorage force. The experimental results show that under both preload conditions, the static anchoring force increases significantly as the barb inclination angle increases. These results indicate that when the angle between the barbs and the vertical direction increases, the microscopic mechanical interlocking effect between the barbs and the bark surface will become more pronounced. Through quantitative analysis, this study reveals the impact of the angle of the barbs on the passive fixation effect of devices, providing a reliable engineering design approach for low-power deployment of small monitoring devices in large-scale wireless sensor networks (WSNs).

Keywords: Passive barbed anchoring structure, Static anchorage force, Wireless sensor networks

1. Introduction

The continuous monitoring of microclimatic parameters is fundamental to the preventive conservation of cultural heritage sites and fragile ecological environments. Due to the fragility of historical buildings and natural habitats, the traditional fixation methods of monitoring devices are highly likely to cause irreversible damage to historical buildings or the environment during the assembly process. Therefore, the concept of non-invasiveness should be one of the key factors to be considered when deploying environmental monitoring equipment. In this context, wireless sensor networks (WSNs) do not require the laying of a large number of lines and can reduce physical damage to the monitored objects to a certain extent, thus being widely applied in the fields of cultural relic protection and environmental monitoring [1].

It is worth noting that non-invasive deployment does not merely refer to avoiding physical damage such as drilling, but also includes the visual integration of the monitoring device with the surrounding environment. Therefore, the deployment of sensors should minimize the damage to the

aesthetic appearance and functional use of the building being measured [1]. In practical applications, most of the monitoring nodes in existing wireless sensor networks adopt industrialized shells, which leads to the inability of monitoring devices to blend with the surrounding environment and causes the problem of visual intrusion. Therefore, this study focuses on the research and development of bionic environmental monitoring equipment, achieving the integration of equipment and the environment through bionic design [2].

On the other hand, the traditional fixation method of wireless sensor networks leads to a lack of flexibility. To make up for this limitation, recent studies have adopted climbing robots as environmental monitoring devices for flexible adjustment. However, the existing climbing robots, due to their fixation method, have obvious structural and energy consumption shortcomings in long-term outdoor environments. At present, such robots mainly rely on fixed methods that depend on continuous power supply, such as active clamping. Therefore, most of them face problems of complex structure and excessive energy consumption [3], and high energy consumption will significantly shorten the robot's battery life [4], fundamentally making it impossible for these robots to meet the long-term low-maintenance cost environmental monitoring operation requirements.

To sum up, at present, there is still a lack of bionic designs for environmental monitoring robots that can not only meet the requirements of long-term low-power deployment but also integrate into the environment. Bionic designs can well meet the requirements of visual fusion, while passive fixed structures can achieve long-term low-power deployment. Therefore, combining these two becomes a feasible solution to the existing problems. Previous studies have confirmed that, in the absence of tight or loose entanglement behavior, the micro-thorn structure plays a key role in the fixation of attachments [5]. In conclusion, inspired by the structural forms of animals and plants in nature, this paper proposes to use the micro-thorn structure to achieve passive fixation of environmental monitoring equipment. To systematically explore the influence of the thorn Angle on the fixation effect, this paper selects 15 Experimental research was conducted from five perspectives: 30, 45, 60, and 75, aiming to find the optimal passive fixation structure, thereby providing reliable engineering basis for the research on the passive fixation structure of environmental monitoring robots.

2. Related work

At this stage, there has been extensive research on attachment methods for climbing robots, including vacuum suction, magnetic adhesion, and cooperative mounting of unmanned aerial vehicles, among other fixation methods [6, 7]. However, it is worth noting that these fixation methods are significantly restricted by environmental conditions in practical applications. Therefore, passive attachment through the robot's own structure has become an effective solution for the low-cost and long-term stable deployment of environmental monitoring equipment.

To achieve this goal, many researchers have explored animals and plants in nature, regarding them as bionic design inspirations for passive anchoring structures, such as climbing insects and burdock seeds. Research has confirmed that in the absence of tight entanglement or loose entanglement behavior, micro spur structures are key elements for biological attachment and fixation [5]. The working principle is: When plants are subjected to downward gravity, barbs will generate extremely strong anchoring resistance; when plants slide upwards, the resistance drops to an extremely low level, presenting a passive locking effect similar to the natural pawl and ratchet structure. This research provides an important theoretical basis and design concept for the development of a fixed structure for passively fixed environmental monitoring robots.

At the application level, some researchers have already conducted relevant studies in this field. Liu et al. proposed a dual-track guiding mechanism to solve the problems of detachment and jamming in the track-type pawl system [8]. However, most of these studies have focused on large robots that need to achieve climbing functions, while research on small fixed robots is still relatively scarce. Due to the fact that the geometric parameters of the fixed structure itself (such as the inclination angle) can affect the static anchoring force, it is necessary to conduct systematic quantitative research and analysis on the geometric structure of small fixed monitoring devices under the premise of controlling variables such as material properties, providing a reliable theoretical basis for the design of small fixed devices.

3. Working principle of passive barb anchoring

In nature, insects and spiders climb by using micro spines on their bodies to catch on surface asperities [9]; some climbing plants attach to rough surfaces via hook-like microstructures [10]. These attachment methods all rely on micro-scale mechanical interlocking as their core mechanism.

The passive barb anchoring structure designed in this paper follows the same principle. When the barb tips are under pressure, they rub against the structure on the bark surface. Subsequently, when the robot experiences lateral forces downward along the trunk, the barb tips embedded in the cracks produce a wedge tightening effect. This enables the device to be secured. No active driving or adhesive is required throughout the entire operation, and the robot consumes zero power when stationary [9].

4. Experimental design and tests

4.1. Preparation of experimental apparatus

In this experiment, a test setup was fabricated using 3D printing. To eliminate the interference caused by local elastic deformation of the material, photopolymer resin was uniformly used to prepare the test specimens. To minimize the impact of printing variations on the experimental results, the same setup was used throughout the experiment, and controlled experiments were conducted by replacing the barb components with different angles. Given that photopolymer resin is prone to brittle fracture under high stress at the tip, the load-bearing barbed section of the test specimens was formed by bending a 1 mm diameter rigid iron wire (see Figure 1.) and precisely set to five predetermined test angles (15°, 30°, 45°, 60°, 75°).

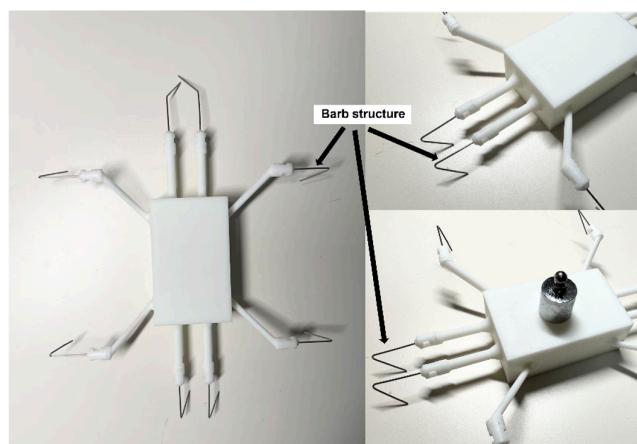


Figure 1. Actual photo of a test specimen with a 45° barbs angle

4.2. Experimental process

Given that the surface of natural bark is highly irregular, which can obscure the mechanical patterns resulting from variations in the angle of the barbs, this experiment selected a rough fabric surface as a standardized test substrate. To simplify the experiment, a horizontal pull-out test was employed. The test specimen was placed horizontally on the substrate, with standard weights of 100 g and 50 g placed directly above it to simulate the weight of the monitoring device and provide a constant normal preload. During the test, a high-precision spring balance was used to pull the test specimen horizontally at a constant speed, and the balance reading was observed as the specimen slid. For each combination of angle and weight, the reverse anchoring force was measured, with each set of experiments repeated five times to obtain a reliable average value.

4.3. Experimental results

Experimental results indicate that the angle of the barbs influences their passive anchoring performance, as shown in Figure. 2. According to the data recorded by the high-precision force gauge, as the angle between the barb and the vertical plane becomes larger, the force required to pull the test piece increases. Thus, it can be concluded that the static anchoring force and the angle of the barb show a significant monotonically increasing trend. This phenomenon can be explained by the effect of mechanical interlocking: the barbs in a nearly vertical state can be embedded into the microscopic pores of the base material with greater normal stress, thereby generating stronger resistance at the macroscopic level and achieving a fixing effect.

In addition, by comparing the experimental data with normal loads of 100 grams and 50 grams respectively, it can be found that the static anchoring force at the test point is positively correlated with the normal load. Therefore, this research has shown that in order to fix the heavier monitoring equipment, the passive fixation structure needs to be designed to form sufficient positive adhesion with the surface of the tree trunk, thereby effectively converting the macroscopic gravitational load into static anchoring force. Meanwhile, since maximizing the anti-detachment adhesion of the equipment is the primary design goal, for static monitoring nodes that need to be stably deployed in the field for a long time, it is a more ideal engineering solution to select a larger blow-down Angle (for example, 75) within the allowable range of the structure to obtain the maximum static anchoring force.

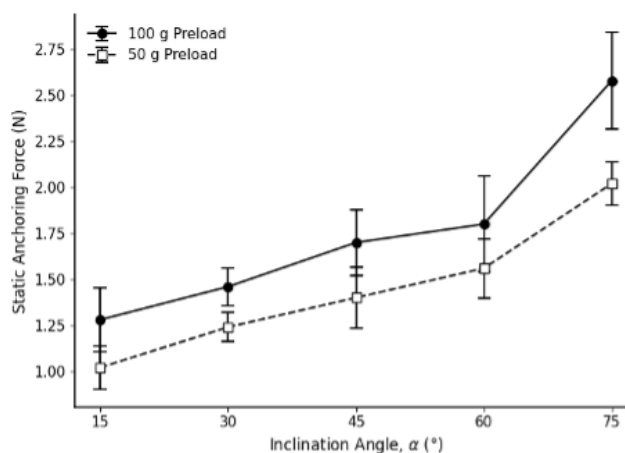


Figure 2. Static anchoring force versus barb inclination angle. Data are evaluated under 100 g and 50 g normal preloads (mean $\pm$ SD, n = 5)

5. Conclusion

This paper addresses the challenges of long-term field deployment of ecological and environmental monitoring devices, which are often hindered by high power consumption and visual conspicuousness, by proposing a passive barbed anchoring mechanism inspired by flora and fauna in nature. By designing a combination of a rigid base and wire barbs, and conducting level frame tests on a standardized, uniform substrate, this study quantitatively eliminates the interference of material elasticity, thereby purely revealing the influence of barb geometric angles on passive adhesion performance. The study found that the more perpendicular the barbs are to the contact surface, the greater the static anchoring force. This research not only provides a reliable physical design approach for the passive fixation of micro-monitoring robots but also lays a solid technical foundation at the underlying hardware node level for the maintenance-free deployment of large-scale wireless sensor networks (WSNs) and the continuous, stable collection of forest ecological big data (Data Science).

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