Enhancing Perching Capabilities of Flapping Wing Robots with Silicone-based Electromagnetic Claws

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ABSTRACT

Flapping wing micro air vehicles (FWMAVs) have garnered significant attention over the past few decades for their potential in various applications. However, developing an effective grasping mechanism for these vehicles still poses a critical challenge. Researchers have explored several solutions focusing on FWMAV perching, which are mainly focused on either cylindrical or planar perching. This study presents a novel approach to FWMAV perching based on a magnet-based claw structure utilizing an electromagnet integrated within a silicone-based soft gripper. The proposed solution enables perching on circular, cylindrical, and planar surfaces. The goal was to optimize the claw's ability to maintain stable perching across different perch geometries. The magnetic claw was tested under various conditions and on multiple surfaces to determine the feasibility of the perching mechanism. Additionally, the mechanism was integrated on two different commercially available platforms for further testing, and they demonstrated promising results. Results demonstrate the current approach's effectiveness and give insight into the limitations. For example, a major limitation is the ability to only perch on ferromagnetic surfaces. In conclusion, by providing comprehensive insight into the design, development, manufacturing, and testing of a magnetic claw-based solution, this research advances our fundamental understanding of the challenges faced by FWMAV perching mechanisms and proposes a solution. This work opens new avenues for the real-world use of FWMAVs by addressing the critical problem of grabbing and perching.

1 INTRODUCTION

The demand for micro air vehicles is continuously increasing. Their applications include surveillance, data collection, outdoor sensing, traffic control, mapping of unknown areas, search and rescue, disaster response, and delivery. The mission capabilities of micro air vehicles are expanding with today's technological advances. However, several challenges remain, which include a silent operation during surveillance missions and operating safely when close to nature, i.e., humans or trees/flowers, etc. Flapping wing micro aerial vehicles (FWMAVs) use a flapping wing motion to fly and produce less noise than the rotor blades of conventional micro air vehicles. They are also generally safer to operate thanks to their low weight, flexible wings, and lack of propellers. Therefore, the popularity of FWMAVs is gradually increasing. These bioinspired micro aerial vehicles mimic the motion of natural flyers, like birds and insects, generally operate in a low Reynolds number regime, and have highly complex aerodynamics.

However, micro-aerial vehicles (MAVs), and especially FWMAVs, have drastically limited endurance. This can be addressed by using a grasping mechanism that will assist the vehicle to attach or grasp on a surface and, thus, consume little to no energy while remaining perched. This will increase the overall endurance. This will significantly improve the applications of FWMAVs, which are generally safer and silent; however, they have limited payload capacity and thus have limited endurance.

Researchers have proposed various perching mechanisms in the past, e.g., as discussed by Meng *et al.*[1] and Hammad *et al.*[2] in their respective reviews. Some of the examples are discussed here to give a perspective of existing advancements in the field of aerial grasping. Grasping has been studied extensively for multi-rotor aerial vehicles [3, 4, 5, 6, 7]. A bioinspired, underactuated perching mechanism weighing 478g was developed by [8]. A 9g claw-like grasping mechanism was installed and tested on a 25g vehicle by [9]. A passively actuated, lightweight mechanism weighing 28g mounted on a 593g vehicle was developed by [10]. Broers and Armanini [11] developed a lightweight, passively actuated gripper mechanism inspired by the fin ray effect.

Attaching is also another mechanism used for effective perching. Rather than using the conventional grasping method to perch, these vehicles use magnets [12], adhesives [13], or vacuum pumps [14] to attach themselves to the surface. For very small-scale FWMAVs, magnets have been used as a mode for perching [15]. Most of the work with such mechanisms has been done for conventional non-

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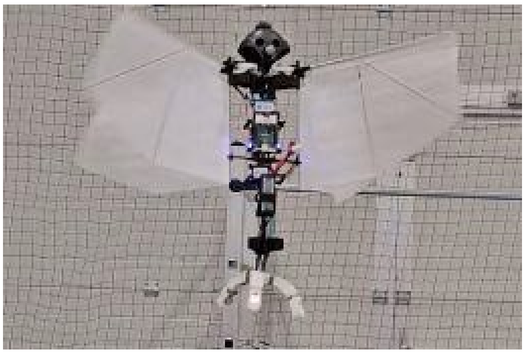

Figure 1: Magnetic Gripper Installed on Entomopter

flapping wing vehicles. A micro-spine-based attaching mechanism for a fixed-wing UAV enabling it to perch vertically on the surface was developed [16, 17, 18]. The use of micro-spines as a means for attaching mechanisms for MAVs was also demonstrated by [19, 20].For MAVs perching, dry adhesives [21] and electro-adhesives [22] have also been used. A heavier quad-rotor weighing 1.77kg was equipped with a vacuum pump to enable perching [23].

Most existing research on grasping and perching has focused on quadrotors and fixed-wing vehicles. Only limited work has been done to investigate perching mechanisms for FWMAVs. Gomez *et al.* [24] developed an SMA-actuated perching mechanism. This mechanism relied on active actuation. An ultra-lightweight mechanism was installed on an ornithopter by [12] and used magnets to hold onto the surface. Another mechanism with carbon fiber claws, passively closed by a spring and used a servo motor to open the claws again, was developed by [25]. Attaching-based perching mechanisms are also quite popular, and recently, Lau *et al.* [26] studied electro-adhesive and dielectric elastomers-based perching mechanisms for FWMAVs.

The above research shows that advancement in perching mechanisms for FWMAVs is still required, especially since there is a need for mechanisms that can adapt to various surfaces. It also highlights the need for a perching mechanism to not only improve the efficiency of a vehicle but also make it more versatile, hence making it more useful for different types of missions and essentially making it easier to achieve autonomous operation in the long term. This gap is covered with the presented mechanism. This paper presents a magnetic-based, lightweight perching mechanism that can adapt to various surfaces and increase the overall flight time of FWMAVs (Figure. 1). The designed mechanism demonstrates successful perching both on cylindrical and planar ferromagnetic surfaces. The mechanism combines grasping and attaching techniques and utilizes an electromagnet in a lightweight silicone-based claw adaptive to circular, cylindrical, and spherical surfaces. The electromagnets attach themselves to the required surface, while the silicone-based soft gripper is used to grasp the object. The mechanism is easier to control and requires a simple actuation. Details of the mechanism are given further in section 2.

2 SYSTEM OVERVIEW

The requirements mentioned in section 1 demand a novel approach and combine grasping and attaching mechanisms to develop an effective perching system. Various grasping methods were considered, and a silicone-based robotic gripper mechanism was finalized. Soft robotics has shown promising progress recently, and their applications are becoming wider with further research [27, 28]. The silicone-based gripper was coupled with an electromagnet, thus providing more active control. Secondly, the drone did not show adequate thrust to release the gripper once takeoff was required; hence, the choice was made to use an electromagnet rather than a permanent magnet. The gripper mechanism was attached to a commercially available Entomopter weighing 114g and an Ornithopter weighing 450g. This section covers the magnets, silicone gripper design, and vehicle characteristics used in the current study.

2.1 Electromagnets

Electromagnets were selected for the perching mechanism as they provided more control. Moreover, using magnets provided the advantage of attaching to various surface shapes, e.g., circular, cylindrical, and planar. They are easier to actuate, thus eliminating the use of more complex actuation mechanisms and simplifying the transition from perched to flying mode.

It is crucial to select an appropriate electromagnet since a stronger magnet would also become heavier and require a bigger battery. The vehicle may drop while perched if the magnetic force is too low. The respective spacing between the magnets is also an important parameter to consider since the magnets were required to be installed and help the silicone-based claw to close, especially for circular and cylindrical surfaces. Keeping the space too small would mean excessive use of magnets, which was also unfavorable. Available data suggested that the distance should be more than 10mm to have effective perching and to avoid attractive and repulsive forces between the magnets [29]. The holding force is also essential, especially in selecting the appropriate electromagnet and the battery used for actuation. For the current design, it was desired that the manufactured gripper be widely applicable rather than optimized the design for a specific FWMAV. Therefore, it was decided that the claws could hold FWMAVs weighing as low as 100g to as much as 800g. Electromagnets of strengths 2N and 3N were tested with different batteries to determine the effect of the battery on the holding force. Table. 1 details the tested batteries and the output. It was decided to use the 3s battery for experimentation with the 2N Electromagnet. The measured holding force was also deemed reasonable for perching tasks.

Battery/Voltage	3N Electromagnet	2N Electromagnet
3.7V(1S)	1.3N	1.49N
7.4V(2S)	2.39N	3.05N
11.1V(3S)	3.74N	3.85N
12V	4.64	4.03N
14.8V(4S)	5.3N	4.52N

Table 1: Physical and Kinematic data of Ornithopter [30]

Four magnets of strength 2N each were used and housed inside the silicone-based claw. Such a configuration provides enough gripping strength to land a vehicle weighing 0.2kg to 0.8kg. Additional weight may also be carried, and only a change in the electromagnet is required, whereas the complete design may remain the same. For bigger vehicles, using a two-claw mechanism is also a suitable option.

2.2 *Gripper Design*

The claw was constructed from silicone since it provides adequate flexibility, is easier to manufacture, is lightweight, durable, and easily molded. A three-finger design in Y configuration was selected for simplicity. The length of each finger was kept at 60mm to ensure that the gripper can grasp on a range of surface sizes, especially for cylindrical perching, and that it does not become too heavy. The magnets alone can also successfully demonstrate perch on different ferromagnetic objects [15, 12]. This, however, becomes difficult, especially for larger vehicles that do not possess vertical takeoff and landing capability. Perching at a certain angle can still be managed such that the vehicle's center of gravity is always in line with the magnets, and no additional moment is generated due to angular perching. This can be overcome by using the claws since, for a wider range of angles now, the center of gravity remains within the claw range, ensuring a successful perch. This additional advantage led to using silicone-based claws as part of the gripper mechanism.

Electromagnets were placed at the tips of the claw and one at the center to provide adequate support during perching. The mold was prepared by 3D printing, and silicone was poured inside. It is pertinent to mention that the mixing ratio is essential; otherwise, it may result in a too-hard claw that does not bend or becomes too soft and bends with its weight. Leaving air while pouring also causes brittleness to the claw. The electromagnets were housed inside the holes seen in Figure. 2. Wire channels were made within the design so the wires powering the electromagnets do not create hindrances during perching. The final weight of the gripper was 42g. Since neither of the two FWMAVs used to test the mechanism were intended to carry any payload, lightweight is essential.

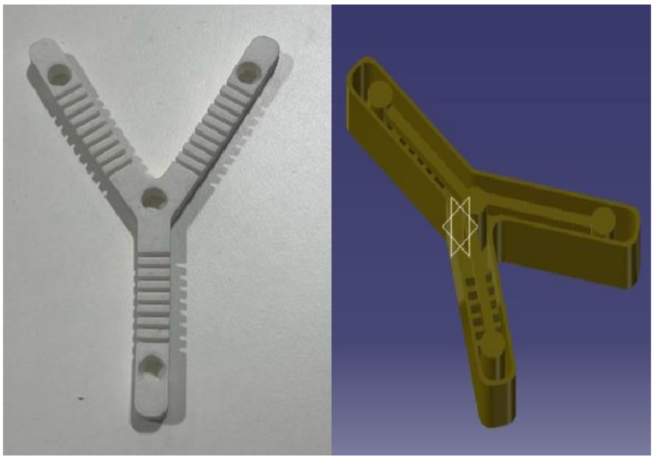

Figure 2: Claw Structure (left) and CAD Model (right)

A spacer was designed to attach the claw to the respective vehicle (Figure. 3). The spacer made it easier to mount the claw on the FWMAV, but experiments showed that it could fall off due to high vibrations during flight. Therefore, an adhesive was used between the spacer and the claw to avoid such failure during flight. Actuation of the electromagnets was a simple process. A transistor was required, connected to the flight controller, which was used to actuate the magnets. A 900 Ohm resistor was used to limit the current passing through; otherwise, it could lead to transistor damage. Various configurations were tested to place the transistor in the circuit.

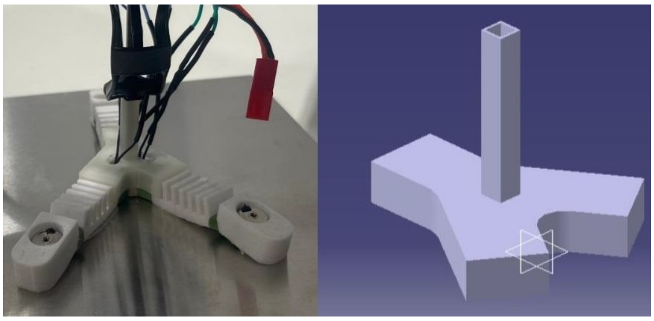

Figure 3: silicone-based claw (left) and spacer (right)

2.3 *Drone Platforms*

Since the goal was to develop a generic system that may be applied to multiple vehicles, it was decided to demonstrate its effectiveness and functionality on two significantly different platforms. These platforms are further detailed in this section and shown in Figure. 4.

2.3.1 Test Platform 1

Table. 2 gives the detailed parameters of the Entomopter developed by Flapper Drones [31] used for the study. The vehicle is based on the DelFly Nimble [32]. This FMWAV was chosen because it shows vertical takeoff and landing ability,

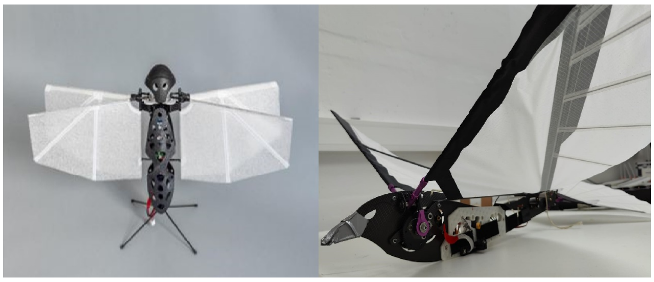

Figure 4: Entomopter (Left) and Ornithopter (Right)

making it easier to test the developed mechanism. The critical challenge to address for this vehicle was the weight constraint since, for the mechanism weight, we had to remain within the allowable range.

Parameters	Values
Wingspan	0.049m
Weight	102 g (min. take-off weight) 127 g (max. take-off weight)
Payload Capacity	60g (shells & landing gear removed)
Flight Time	8 min (forward 3 m/s, min. weight) 5 min (hover, max. payload)

Table 2: Characteristics of the Entomopter [31]

The total weight of the Entomopter includes electronics and the structure. The flapper drone has a recommended payload capacity of 25g [31] with all components on board. For the current case, the protective shells, the existing landing platform, and other additional components that are not required were removed, increasing the vehicle's payload capacity. This payload capacity was tested in the lab, and it was observed that its effect on the overall endurance of the vehicle was not that significant. A relatively lightweight gripper weighing 32g with a 40mm finger length was also tested during the design process. However, a smaller gripper size leads to an unstable perch for the second test platform due to its larger surface area, lack of VTOL capability, and higher moment while perching. This was also confirmed with experimentation. Therefore, further experimentation was performed with the design suitable for both vehicles, which is presented in the paper.

2.3.2 Test platform 2

The Orthinopter platform from Ornihobby [33] was used to test the perching mechanism. Characteristics of the vehicle are given in Table. 3.

Parameters	Values
Mean chord length of each wing	0.455 m
Aspect ratio	1.42
Mass of the ornithopter	450 g
Flight speed of the ornithopter	10–25 km/h
Range of wingbeat frequency	3.5–4.5 Hz
Half Wing Span	70 cm

Table 3: Physical and Kinematic data of Ornithopter [30]

3 Results and Discussion

The claw mechanism was tested on different ferromagnetic surfaces to ensure it could withstand the loads it was subjected to and successfully land on objects of various sizes and shapes. Experiments were conducted with the mechanism alone and the mechanism attached to the FWMAV test platforms. The obtained results are shown in this section.

3.1 Static Tests

Static tests were conducted to check the strength and adaptability of the claw, first on its own and then while attached to an FWMAV vehicle. In particular, the goal was to evaluate whether the mechanism could attach successfully to cylindrical and planar surfaces and whether the electromagnets supplied the required forces.

The claw in its open state can be seen in Figure. 5 (left). Figure. 5 (right) shows the claw in its closed state attached to a cylindrical rod, while Figure. 6 shows the flaw attached to a ferromagnetic planar surface. In these tests, the claw was manually attached to the different structures, and the electromagnets were activated and able to attach successfully to the metallic surfaces.

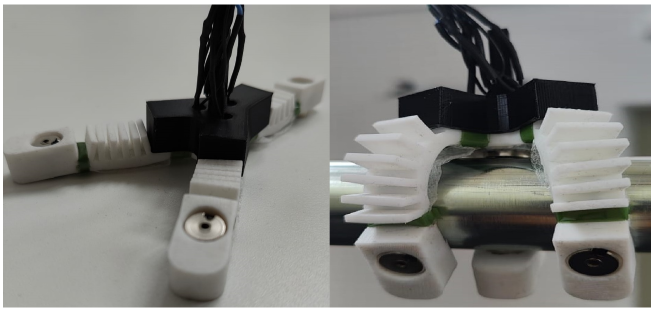

Figure 5: Claw in Open (left) and closed (right) state

These tests demonstrate the adaptability of the claw to different structure shapes. After proving that the basic design requirements were met, the claw was installed on the FWMAV for further testing.

Figure. 7 shows static tests performed with the claw attached to the FWMAV. Successful perching was demonstrated for both the planar and the cylindrical surfaces. An inverted perching test was also conducted where the FWMAV was hung upside down on the cylindrical surface and then attached to the surface by activating the magnets, which suggests that the claw mechanism is strong enough to withstand

Figure 6: Magnetic-claw attached to Planar Surface

the complete weight of the Entomopter.

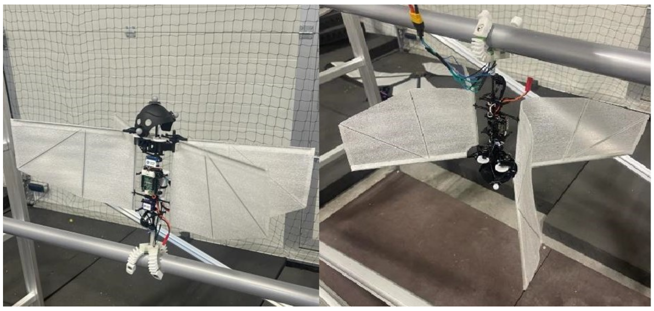

Figure 7: Cylindrical and Inverted Perching

Static tests were also conducted to demonstrate successful attachment while installed on the Ornithopter. A rectangular bar with rounded edges was used to show the adaptability to the different shapes and that the silicone-based electromagnetic claw mechanism can withstand the vehicle's weight and perform successful perching tasks. This is shown in Figure. 8.

3.2 *Flight Experiments*

Flight experiments were conducted on the Entomopter to evaluate the feasibility of the designed claws in flight and perching tasks. The claws demonstrated successful perching on various surfaces. Cylinders of various sizes were used to analyze the perching capabilities of the claw mechanism. The smallest radius on which the claw demonstrated a successful perch was 17mm Figure. 9 (left). Landing on circular cylinders with radii greater than that was also demonstrated. Since the surface tends to become more flat as the radius increases, landing on cylinders with larger diameters was relatively straightforward, as seen in Figure. 9 (right). Since the gripper mechanism is actuated actively, the electromagnets are already turned on when contact is made. Thus, the attachment of these electromagnets with the ferromagnetic surface is instant.

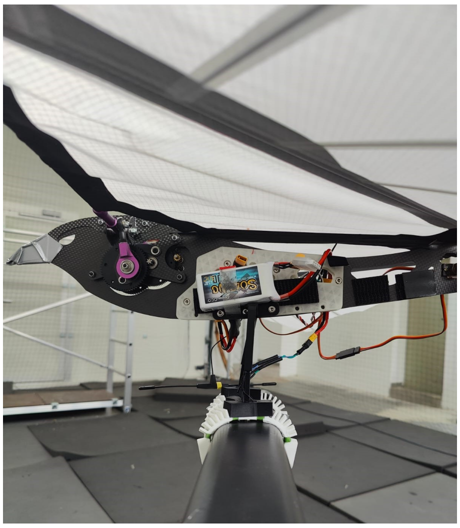

Figure 8: Static Test on Ornithopter

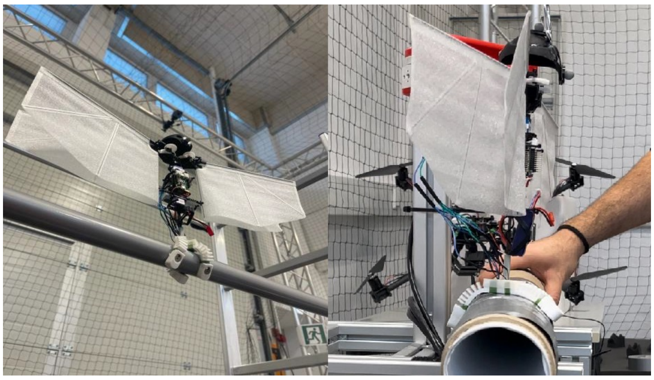

Figure 9: Landing on Cylinders of Different Radii

Similarly, landing on a planar surface was performed and is shown in Figure. 10. This showed the overall versatility of the claw mechanism and its adaptability to various shapes. While perching on the cylinders of smaller radii, it was observed that a greater approach velocity is required than landing on cylinders with larger diameters. This was owing to the increased bending requirement for the silicone-based structure to successfully envelop the cylinder. A higher impact force ensured that the fingers would wrap around the cylinder and the subsequent engagement of magnets with the surface.

The electromagnets were integrated with the onboard flight controller and connected to a separate channel on the transmitter. The activation was done by simply switching the channel on. This made the whole actuation process simpler. The silicone-based claw's bending occurs under the vehicle's weight and the impact force with the surface. There was no

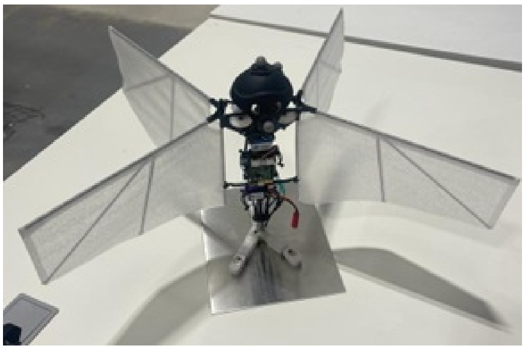

Figure 10: Planar Landing

additional actuation requirement for the bending as it occurs passively.

Another foreseen issue in the claw mechanism was planar perching. The claws were to open when hitting a planar surface and not curl up, which would lead to a failed perch. This issue was addressed at the design level while the silicone structure was prepared. The mixing ratio was maintained at an appropriate level so that the silicone-based structure had enough stiffness that the claw did not curl up upon impact. It was also noted that too high of stiffness can result in a failed perch during cylindrical perching as the claw will not close.

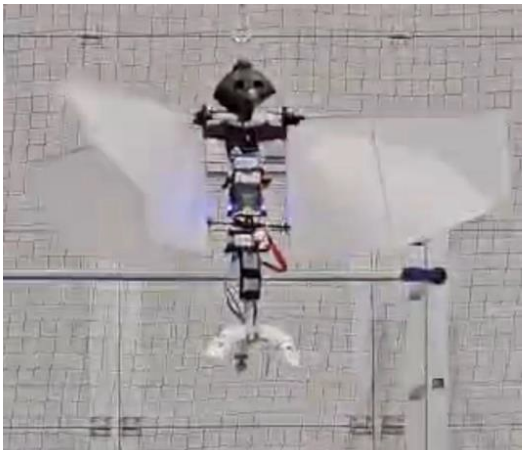

Figure 11: Flight after Perching

Figure. 11 shows successful takeoff and subsequent flight from a perched position. The detachment mechanism was simple, as the electromagnets could switch off swiftly. It should be noted that with the electromagnets turned off, the FWMAV could stay in a perched position for some time. However, while taking off from an inclined perched position, it will instantly become unstable and start to fall. Therefore, the wing flapping sequence should begin once detachment is initiated.

The above experiments demonstrate successful perching on planar and cylindrical ferromagnetic surfaces. Static tests for both Entomopter and Ornithopter show a wide range of capabilities. Using electromagnets is promising, and housing them inside a silicone-based claw gives more adaptability to different surfaces. The tests further show that the mechanism can be applied to vehicles of various sizes and configurations and can hold a variety of vehicles with varying weights up to 600g (including the weight of the mechanism and supports). Moreover, the mechanism could be easily adapted to achieve higher holding strength, e.g., by changing the electromagnet used without changing the overall design of the claw.

4 CONCLUSION

With the goal of enabling perching of lightweight FWMAVs on both cylindrical and planar surfaces, a novel electromagnetically actuated silicone-based claw mechanism was designed. A prototype of the proposed concept was manufactured, weighing just 42g. It was tested for suitability on two FWMAVs, an insect-like Entomopter weighing 102g and a bird-like Ornithopter weighing 450g. The design process involved integrating the electromagnets into the silicone-based claw and an in-depth analysis of perching on various ferromagnetic surfaces. The flexible structure of silicone improves its ability to perch on various surfaces. The success achieved in stable perching on various surfaces highlights the potential practical application of this technology in MAVs, particularly in FWMAVs. While significant progress has been achieved, there are still opportunities for further advances and optimization. Future research could focus on optimizing the configuration of the electromagnet, exploring alternative materials, or delving deeper into the dynamics of the perching process. Essentially, this work represents advancing the FWMAV's perching capabilities by developing a magnet-based claw structure. The practical application of this new type of perching mechanism is demonstrated through comprehensive testing, including successful perching experiments on various ferromagnetic surfaces.

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