Received: 9 March 2024 | *Revised: 3 May 2024* | *Accepted: 5 May 2024*
DOI: 10.37917/ijeee.21.2.19 *Early View | December 2025*

Open Access

Iraqi Journal for Electrical and Electronic Engineering
Original Article

Design and Implementation of a Climbing Robot Limb for Clinging to Rough Walls

Mohammed K. Jodah*[1,2], Mofeed Turky Rashid[1], Raed S. Batbooti[3]
[1]Electrical Engineering Department, University of Basrah, Basrah, Iraq
[2]Computer Engineering Department, University of Basrah, Basrah, Iraq
[3]Thermal Mechanical Engineering Department, Southern Technical University, Basrah, Iraq

Correspondance
*Mohammed K. Jodah
Computer Engineering Department, University of Basrah, Basrah, Iraq
Email: mohammed.kade@uobasrah.edu.iq

Abstract
In recent years, the urgent need for robotics applications in various sensitive work areas and high buildings has led to a significant development in the design of robots intended for climbing rough surfaces. Where, attention became focused on the ideal clinging mechanism. In this paper, a gripper of the climbing robot has been designed to achieve clinging on rough walls. The objective of this design is to be lightweight with high performance of clinging, therefore, a robot gripper has been designed based on a model of a limb inspired by the hand and claws of a cat, in which the robot claws were implemented by fishing hooks. These hooks are arranged in an arc so that each hook can move independently on the wall's surface to increase the force of clinging to the rough wall. SolidWorks platform has been used to design the clinging limb and implemented using a 3D printer. In addition, the proposed design has been validated by performing several simulations using the SolidWorks platform. Experimental work has conducted to test the proposed design, and the results proved the success of the design.

Keywords
Climbing Robot, Clinging Mechanism, Gripper Device, SolidWorks, Rough Wall.

I. Introduction

In recent decades, interest and great growth in robotics has taken a large part. Research on climbing robots is considered attractive research, as they can be an alternative to humans in many fields, in which these robots are placed in dangerous or high places where humans cannot reach them, such as cleaning and inspecting high places, monitoring, maintaining, and diagnosing oil and gas storage tanks, nuclear and petrochemical power plants, and many facilities whose maintenance and monitoring cost huge sums of money [1–5].

There are several types of climbing robots used in vertical structures such as column climbing robots, pipe climbing robots, tree climbing robots, cable climbing robots, and wall climbing robots [3]. Wall climbing robots have a special operation mechanism in extreme environments. Climbing robots attach themselves to wall surfaces using four mechanisms: vacuum suction, magnetic attraction, adhesives, claws, or hooks as shown in Fig. 1. For smooth and glass-like surfaces, the adhesive or suction adhesive mechanism is effective, but it becomes unstable due to the influence of vibrating wall surfaces [1, 2, 6, 7].

The magnetic attraction technique is very powerful, but its application is limited, because it is only used for ferromagnetic surfaces, and fails for wall surfaces under long-term vibrations, such as diagonal cable bridge towers and bridge piers. In other climbing robots, adhesives techniques are used that uses special glue for sticking to the surface. These glues are added in the climbing limbs, which makes them adhere to the surfaces, but the adhering capacity of the limbs decreases gradually, making lost sticking with the wall. Therefore, these techniques are limited too. For rough surfaces such as rocks, bricks, and rough concrete, the grasping technique is the most

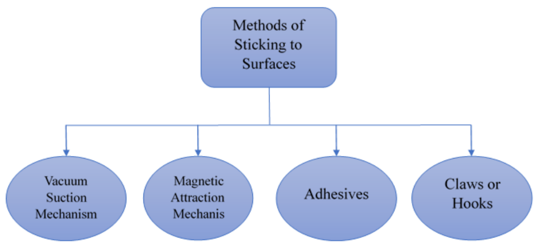


Fig. 1. Classification of adhering methods on the walls [6].

effective and powerful method [2,4,6–9].
The climbing robot with a gripper is a kind of climbing mechanism that uses a gripper to cling and is also an important part of the climbing robot in the mobile robot field, where the climbing robot can also imitate the climbing movements made by humans and animals on some specific surfaces [3,10–14]. Many researchers have been interested in designing mechanisms for adhesion and climbing on rough vertical surfaces, which have achieved good results. However, there are still many challenges that require more study. Some of this research and the methods that were relied upon to make the climbing process successful will be discussed. Meng et al designed a climbing robot that performs specific tasks and has several limbs, it relies on a mechanism that uses claws that resemble fishing hooks. The wall-climbing robot is 8 feet tall and consists of four pairs of limbs, each with a gripper with eight claws attached to it. The robot can climb tall buildings to carry out the tasks assigned to it, including inspection and investigation. Its disadvantages are the lack of independence in the movement of the claws between them, as the gripper moves with the group of claws as one piece, and this effectively weakens the gripping process. Further, the number of limbs for the robot is 16, and this increases the complexity in terms of cost and design. Finally, the maximum load is only 1 kg [9].
Sintov proposed a wall-climbing robot equipped with a hooked claw called CLIBO [15], which can remain on a rough building surface in a fixed position for long periods. Cats were simulated climbing trees using their claws on their four limbs. At the end of each leg, there are 12 hooks in the form of an array, so that each hook can move independently on the surface of the wall. The CLIBO's design and movement planning enables it to climb over rough surfaces and remain stationary for a long period. This robot faces problems such as maneuvering restrictions due to the lack of a tail, as well as the use of many hooks, and at least 16 servo motors and this large number leads to an increasing the robot's weight and cost.
Mustafa [16] proposed a hybrid design of a climbing robot arm, which consists of a gecko-like arm while the wall hanging way is based on a cat's claw mechanism. The climbing robot arm is called CLARC (Claw Climbing Arm). The researcher reduced the number of servo motors in the joints due to the movement mechanism based on the gecko's arm movement mechanism. It is noted from the design that the robot's gripper is attached to the arm sideways, which reduces the pressure on the wall, and thus weakens the process of clinging to the wall. It also did not use the process of controlling the robot's movement and the process of grasping and climbing, and its work was limited to climbing the metal clamp only because it failed to climb rough surfaces.
Rui et al [17], designed a foot for a climbing robot equipped with iron needles in the form of claws with sensing sensors. The foot or gripper of the robot is made of a flexible polymeric material with the function of sensing by placing a sensitive element, through which the robot can sense when clinging or climbing. The claws are fixed on the gripper and arranged in a flat pattern. After simulation experiments conducted on the gripper, it was found that it has a good repeatability of the expansion process after loading and the adaptation of the foot or gripper to rough surfaces due to the flexibility of the material from which the foot is made. Despite this, practical experiments have not been conducted on it, and this design will be weak in the face of the challenges and conditions of various rough surfaces, due to the lack of springs behind the hooks that perform the task of pushing the hooks to cling to the surface of the wall during climbing, and thus the adhesion or clinging process is weak. It may lead to the robot slipping and failing.
In this paper, the mechanism action of clinging to the rough wall has been studied to design a gripper for a climbing robot and the extent of its tolerance to pressure and force. The proposed design of a gripper is inspired by a cat's hand, therefore, the biological structure of the cat and the method of using its hand and claws in the climbing process were studied. As a result of this study, fishing hooks will be used as the claws of the proposed gripper. It is worth that the number of hooks, the type of hook, and the size of the hook are important factors in designing a climbing robot gripper. There is a relationship between the number of hooks and the size of the hook, which affects the ability of the gripper and thus the climbing robot to carry more loads. Therefore, many experiments were conducted to improve these parameters required to improve the gripper performance of the climbing robot. Force analysis was performed using the SolidWorks platform, and the performance measurement was calculated for the shape and pattern of the arrangement of the fingers and claws of the gripper (flat and curved) and with a different number of claws. The optimal model was chosen with the number of claws being seven. A set of practical experiments was conducted to prove the

success of the model, and the comparison between simulation results and practical results was close.
The contributions of this paper are summarized in the following points:

1. The robot's gripper was designed and built in an arc shape instead of flat according to design criteria used in this work.

2. The (PLA) material is selected in printing the gripper due to its excellent properties such as fast hardening, little deformation, water resistance, and lightweight.

3. The size and number of hooks are adopted in order to increase the performance of clinging on rough walls.

4. A new mechanism is proposed to avoid the overlap of hook with the neighbor hooks. To improve the robot clinging performance.

II. Background

By observing the climbing feline animals, it was found that their feet are used for running and climbing and that they have a high talent for climbing trees and rough surfaces as shown in Fig. 2. Therefore, designing a robotic claw gripper for tree and rough surfaces climbing inspired by the claws of feline animals, including cats, could contribute to the development of clinging techniques in climbing robots. The domestic cat (scientific name: Felis Catus) is the only domesticated animal from the feline family because it roams freely and loves to approach and communicate with humans. Therefore, it has become easy to monitor it. By imitating the movements of cats' claws when climbing walls and buildings with rough surfaces, this process provides robots with a flexible method extremely good for climbing rough surfaces. Most cats have five claws on their front paws and four on their back paws. The cat's claw has its unique characteristics as an organ, combining solid support with high-friction soft tissue. Cat claw pads (soft part) provide good traction and adhesion and cat claws (hard part) provide good grip on the rough surfaces. The hard and soft combined design results are suitable for the proposed rough surfaces-climbing robot handle inspired by cat claws [9].

Cats have the advantage of adaptive climbing in complex wall environments, in which have strong limbs, and sharp claws extensible, meaning they can extend their claws (when needed) from a retracted resting position [17, 18]. These long claws can help cats with self-defense or predation, jump, climb on vertical walls, and also help them hold firmly in all types of rough surfaces and rocks, the claw anchor is installed by deliberately pulling it (see Fig. 3 [18]. The challenge lies in meeting the special requirements in the process of simulating the mechanism of a cat's fingers and feet, so that the mechanism is reliable and simple, further, the robot foot must be also lightweight to improve inertia. Therefore, taking into account the use environment and requirements of the wall-climbing robot, the claw stab foot should meet [17]:

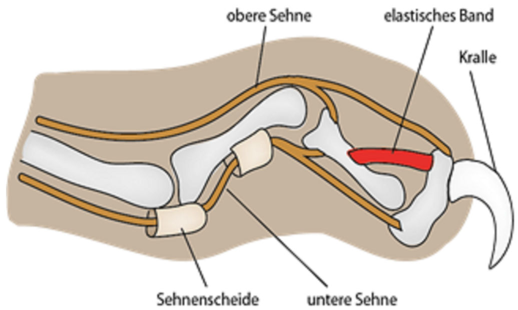
(a) Rock

(b) Tree

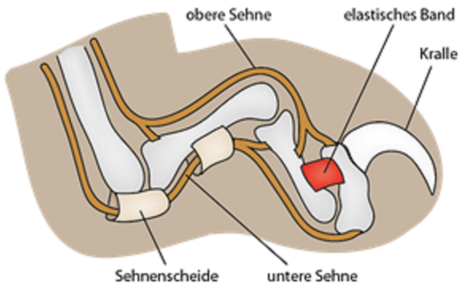
Fig. 2. Cat's climbing on rough surface.

1. Strong grasping ability: four feet need to carry the weight of the robot body. Even in extreme cases, a single foot has to bear all the mass, so the grasping force provided by a single claw is more than 3/2 of the total mass, thus avoiding most of the risks.

2. Strong adaptability: the actual working environment of the wall-climbing robot is complex, facing the tests of an irregular wall structure and different roughness and



(a) Relaxed and claw retracted condition.



(b) Intended and claw protracted

Fig. 3. Cat Claw tendon-bone protracting mechanism.

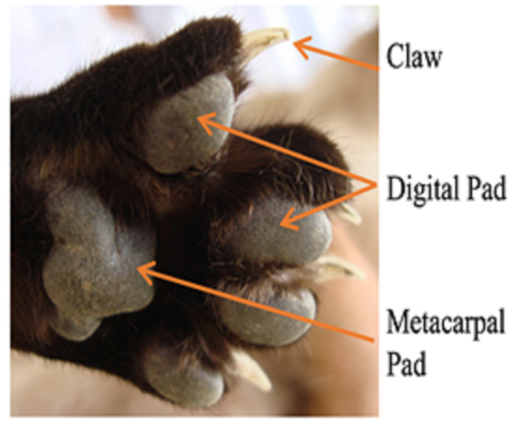
dust interference. Therefore, it has a high adaptability to the foot [16, 17].

A specific toe mechanism with hooked fishing hooks was developed to resemble the claws of cats' feet. Therefore, the foot structure of the robot was designed to mimic a cat's foot as shown in Fig. 4, and polylactic acid (PLA 1.5 mm) was used to construct the foot structure. This material has excellent properties such as lightweight and strong water resistance. PLA is also the best material to start printing a handle with a 3D printer because it: hardens quickly has minimal thermal stress has minimal deformation, and the acetone-resistant BQ PLA filament is made from 100 % PLA. As for the cat's claws, they are simulated using fishing hooks made of alloy steel. Although ordinary carbon steel is an alloy of iron and carbon with small amounts of manganese, silicon, sulfur, and phosphorus, the term alloy steel is applied when one or more elements other than carbon are introduced in sufficient quantities to significantly modify its properties. The robot's gripper is equipped with seven fishing hooks, like the claws of a cat's feet. Each claw is fixed inside the gripper by an iron nail.

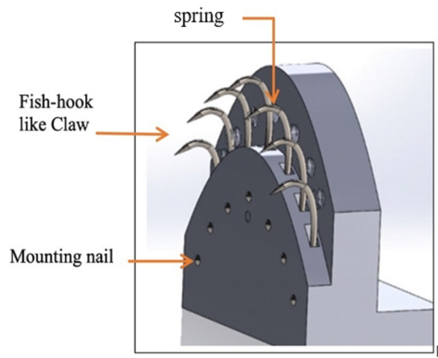
This design has two advantages:

First, the multi-toed design increases the possibility of the soles of the hook claws hitting a rough surface.

Second, multiple toes do not overlap each other; that is, the transition between adhesion and separation of one toe does not affect the condition of adjacent toes.



(a) The cat's foot.



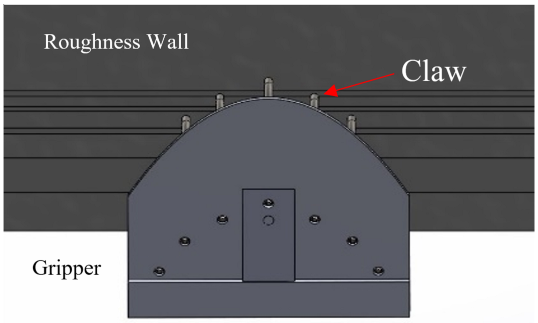
(b) The proposed robot's gripper

Fig. 4. The foot of real Cat vs gripper of Climbing Robot.

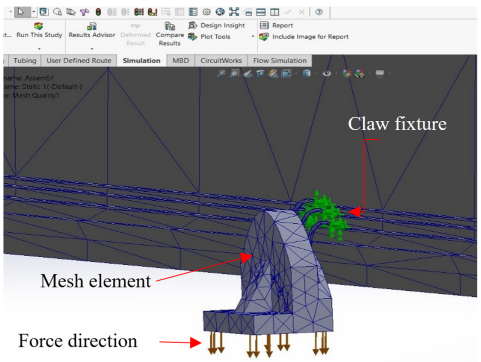
The rigidity of each toe is high; therefore, the flexibility of the foot and the stringy action of the cat's toe are replaced by a spring placed behind each hook for mechanical retraction. Furthermore, applying a small preload to the sole can make each hook come into contact with the uneven surface.

III. Modelling of The Proposed Design

The gripper of the robot consists of several components: the structure of the gripper, claws, mounting nails, and spring, furthermore, the rough wall on which the robot will climb, as shown in Fig. 5a. When using mesh in SolidWorks, the model is divided into smaller parts called elements. Based on the geometric dimensions of the model, SolidWorks simulation suggests a default size for the element (in this case 147.384 mm), which can be changed as needed. The mesh parameter was chosen as mesh based on curvature and the total number of the elements is (10528), as shown in Fig. 5b



(a) Gripper with seven claws.



(b) Gripper with mesh parameter.

Fig. 5. SolidWorks simulation.

A. Stress Von Mises

In materials science and engineering, the Von Mises yield criterion is also formulated in terms of the Von Mises stress or equivalent tensile stress, oV. The distortion-energy theory states that yielding occurs when the distortion strain energy per unit volume reaches or exceeds the distortion strain energy per unit volume for yield in simple tension or compression of the same material. In other words, a material begins to yield when the Von Mises stress reaches a value known as yield strength, oy. The Von Mises stress is used to predict the yielding of materials under complex loading from the results of uniaxial tensile tests. The Von Mises stress satisfies the property where two stress states with equal distortion energy have an equal Von Mises stress [8, 19, 20]. The unit volume below is subjected to any three-dimensional stress state designated by the stresses σ_1, σ_2, and σ_3. So, in terms of the principal stresses σ_1, σ_2, and σ_3, the Von Mises stress is expressed as:

$$\sigma_v = \sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2}{2}} \quad (1)$$

Where σ_v is the Von Mises stress.

In the current work, the mechanical design failure criteria are considered based on Von Mises Stress. The maximum Von Mises stress occurs at the clamping head of the claw (see Fig. 6), the accepted design should have yield strength greater than the induced Von Mises stress.

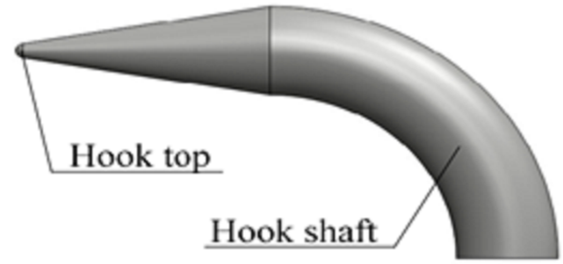


Fig. 6. Claw head.

B. Safety Factor

The safety factor indicates the reliability and safety of the gripper against static loading and thus the safety of the robot. It is represented by n, where:

$$n = \frac{\sigma_y}{\sigma_v} \quad (2)$$

where: σ_y is the yield strength, σ_v is the Von Mises. The factor of safety is used to assure that the maximum stress is within accepted limits by considering factor of safety more than one.

C. Material Model

The material which is made of the gripper is Polylactic acid (PLA) material, while the claws (fishing-hooks), mounting nails and springs are made of steel alloy. According to the characteristics analysis of fishing hooks and PLA 1.5 mm materials, the mechanical properties of these are listed in Table I.

TABLE I.
SOLIDWORKS PARAMETERS SETTING FOR THE GRIPPER MATERIALS.

Mechanical Properties	Alloy steel	Polylactic acid PLA
Yield strength	$620.43 MPa$	$1230 MPa$
Tensile strength	$723.83 MPa$	$50 MPa$
Elastic modulus	$210000 MPa$	$3600 MPa$
Poisson's ratio	0.28	0.3
Mass Density	$7700 Kg/m^3$	$1020 Kg/m3$

IV. Simulation of The Proposed Design

The gripper shown in Fig. 4, which mimics the way cats grip objects or surfaces when climbing, is a new device designed specifically for robot movement that can grip crevices in the wall and hold up to 2.4 kg of weight. The gripper device consists of seven steel fishing hooks mounted on a PLA structure. The hooks are fixed to the PLA body by steel nails through small holes located in the middle of the handle. Experiments with a series of hooks trying to grab onto a rough wall simultaneously showed that hooks tied together interfere with the ability to grab. Therefore, the hooks are placed inside longitudinal runners separated by evenly spaced barriers that prevent them from interlocking with each other, and prevent the hook from moving horizontally or twisting, so that the movement of the hooks back and forth is only in the wall direction. Therefore, this arrangement provides independent holding capacity for each hook.

According to the actual situation in the gripping process, the claw is set as the fixed end and the gripper is placed on a rough wall surface, and the test to be performed is to compare the yield strength σy and Von Mises σv and calculate the safety factor by "(1)," with different loads using SolidWorks software. Initially, this test was performed on an arc gripper.

Step 1: Initially, a single hook attached to the foot (see Fig. 7) is used (for testing and comparison purposes), and the bottom of the foot is set as the force end. Based on the expected structural weight and payload ratio of the robot, force and payload loads ranging from 1 to 24 N were tested. By observing Fig. 9a, when the load is increases, the Von Mises stress begins to increase, where its value equals the yield strength at a load of 3 N, then it increases more with increasing load until the value of the yield strength becomes less than the Von Mises stress, and this means failure of the mechanical design.

Step 2: The experiment was repeated, and the same previous test was performed, but the number of fingers or claws was gradually increased, as shown in Fig. 8. In each case, the load was gradually increased, and the yield strength was compared with the Von Mises stress. We noticed that each case was better than the previous one in terms of its endurance for loads. In the case where the number of claws becomes seven, it represents the best case, as the yield resistance force in this case is much greater than the Von Mises stress, and this means the success of the mechanical design, as shown in the Fig. 9 (b-e) which represent the simulation results.

As for the safety factor, it is calculated according to the "(2)," and as we mentioned previously in section III(B), the use of a safety factor is to ensure that the maximum stress is within acceptable limits by taking into account a safety factor of more than one. Fig.10 shows a comparison of the safety factor between different cases, as the safety factor is approximately 3 in the case of 1 hook. In the case of 7 hooks, the value of the safety factor is (217), which is a large and comfortable value.

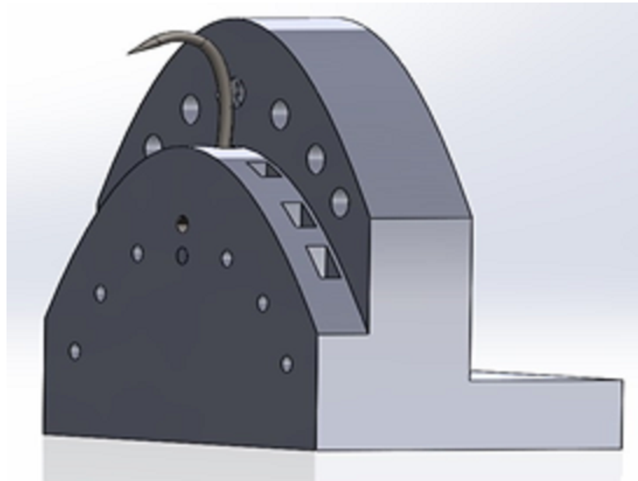


Fig. 7. Robot gripper with single fishing-hook.

Also, the other design model for the gripper (flat) was chosen, as shown in Fig. 11, and the same previous test was performed in the second step (i.e. comparing the yield strength and von Mises) on the flat model, with 7 claws, as shown in Fig. 12. Since the force resistance Submission is greater than Von Mises stress.

To demonstrate the preference for either design, a comparison was made between the arc and flat gripper designs. This was done by conducting the previous tests in Step 2, i.e. (calculating the yield strength and von Mises) for both designs with 7 hooks. and as shown in the results in Fig. 13. Fig. 14 shows the comparison between the arc and flat gripper by calculating the safety factor for each. Through the previous

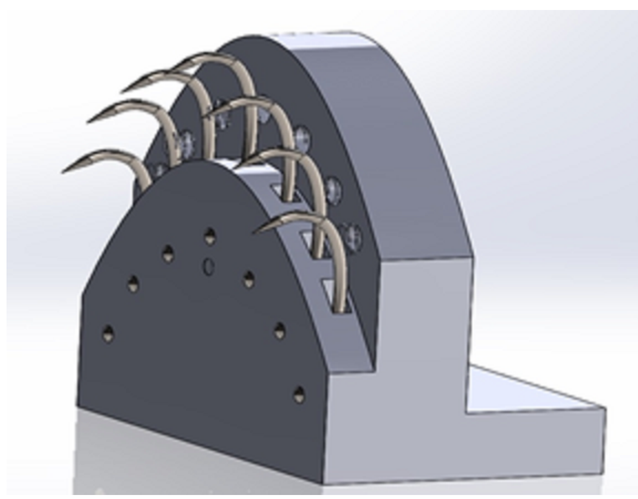
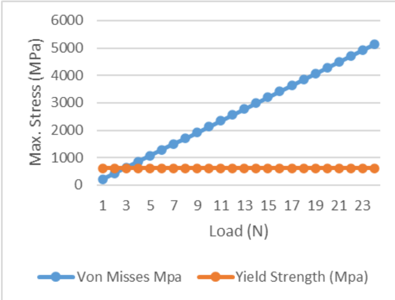
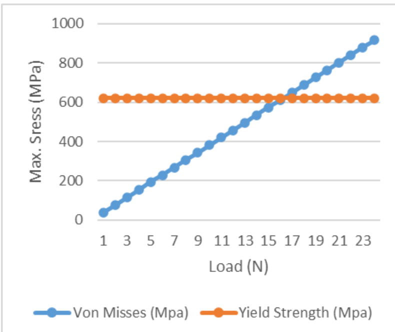


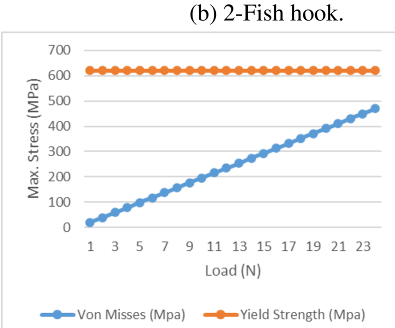
Fig. 8. Robot gripper with seven fishing-hook.



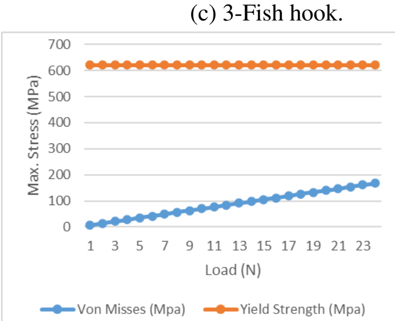
(a) 1-Fish hook.



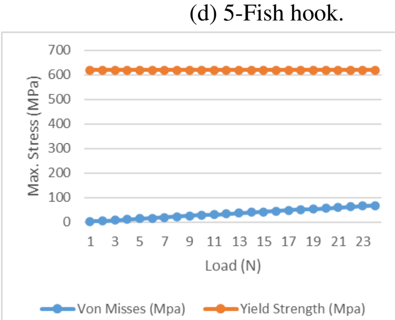
(b) 2-Fish hook.



(c) 3-Fish hook.



(d) 5-Fish hook.



(e) 7-Fish hook.

Fig. 9. Maximum Stress (Von Misses) with versus Yield Strength.

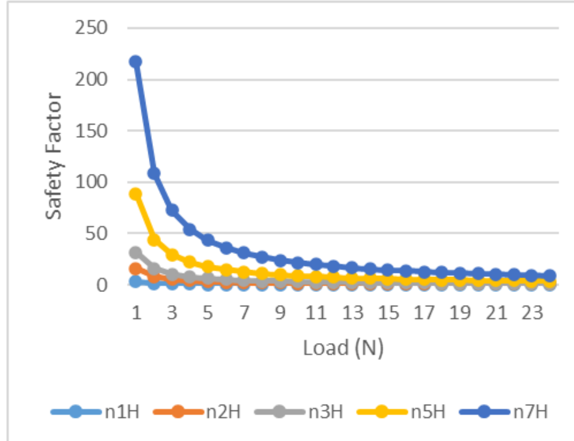


Fig. 10. Safety Factor of various cases.

results shown in Fig. 13 and Fig. 14, the superiority of the arc-shaped gripper design was determined.

V. The Practical Experiments

The robot's gripper was made of PLA material which was previously mentioned. The arc design of the gripper was chosen as it was the most appropriate and according to the results obtained from previous sections, with the number of claws being seven. Since cat claws are curved, strong, and have a sharp end, therefore, fishing hooks were used as a suitable alternative due to their strength, because they are made of steel alloy, with some modifications being made to the amount of bending and curvature in the hook head. The process of pulling and pushing the claws in cats at the climbing state has been inspired by placing a spring inside a cylindrical cavity

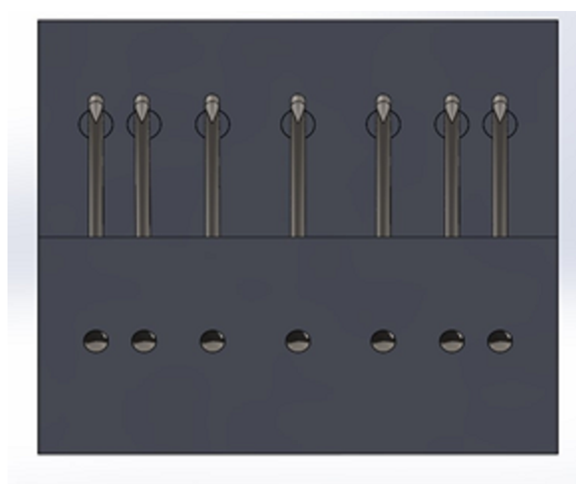


Fig. 11. Robot gripper (Flat)

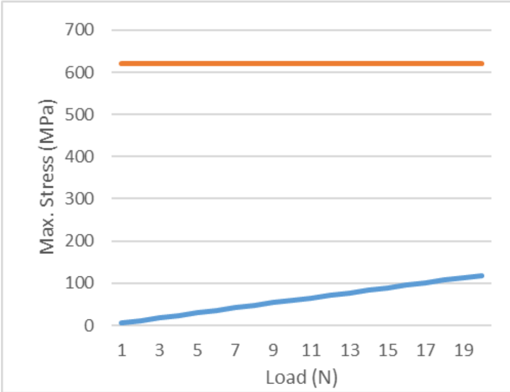


Fig. 12. Maximum Stress versus yield strength of the Flat gripper.

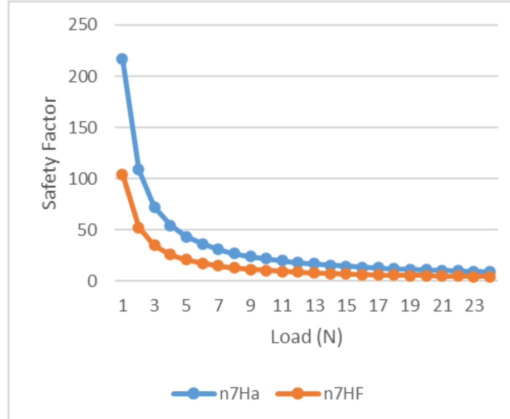


Fig. 14. Safety Factor between Arc and Flat Gripper.

located behind the hook, where the spring starts to push the claw insight the wall direction at the climbing state and obtain movement of the claw is forward and backward in one direction. Each hook was placed in a longitudinal cavity inside the gripper's body to prevent them from twisting and interfering with each other, and the hooks were fixed by iron nails.

Here we would like to emphasize that this gripper is a prototype designed to prove the concept of the climbing process. For the model to be successful, it can bear the weight of the robot, which must not exceed 2 kg, and carry another weight when need, which must not exceed 1 kg.

Several experiments of loading tests were done on the gripper to prove the strength of a single hook. where it was placed on a rough wall to grip the rough bulges of the wall and hung weights of different values gradually, until the weight reached approximately 1.5 Kg as shown in Fig. 15, the claw collapsed and began to slide and fall. Sometimes, if the wall roughness is very high, the clinging process is strong, therefore, the sliding process may not occur, but it leads to distortion of the bend of the hook in the event of a significant increase in the load.

Cases of claw slip can be treated and reduced by using a small hook because it is not possible to rely on using a large hook in the process of climbing or clinging to the wall. After all, the tip of the hook is not pointed enough, although the large hook can hang on the wall with moderate roughness, the small hook is still the one that has a greater load because the small hook hooks better. "The smaller the hook size, the less likely slippage will occur" as for the problem of deformation, it can be treated by increasing the number of hooks to a specific number, so that the gripper can bear the increase in weight to the maximum extent possible. Therefore, the hooks were increased by one to become 2, and the same procedure

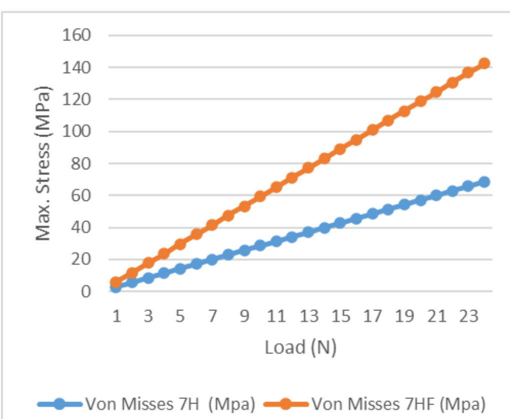


Fig. 13. Von Misses comparison between Flat and arc gripper.

Fig. 15. One fishing-hook that hanging on the concrete wall with 1.5 Kg payload (Sliding moment).

Fig. 16. Seven fishing-hook that hanging on the concrete wall with 3.75 Kg payload.

as before was performed on it until it collapsed and began sliding at approximately 1.8 Kg. And so, gradually until the number of hooks reaches seven as planned, we notice that the gripper has become more stable in the gripping process and carrying a weight of up to twice the planned mass, i.e. more than 2.4 Kg. The experiment setup is shown in Fig. 16 where the number of hooks starts with only one hook and then increases systematically. For each number, several weights have been used to evaluate the maximum payload, to 3.75 kg in the seven hooks case.

To compare between practical and simulation results, the arc design of the handle was chosen because it is the most appropriate. In case of increased load, a very rough surface must be used so that the clinging process is strong, and slippage does not occur. To monitor cases that lead to deformation and bending of the hooks with increasing loads. Therefore, in the case of a single-hook gripper, deformation occurs at low loads, and this is evident in the simulation and practical results.

The issue of deformity in the hook was treated by gradually increasing the number of hooks till seven, which represents the best case, and we notice that the handle has become more stable in the gripping process and can bear a large weight.

VI. Conclusion

In this research, the handle for a climbing robot on rough surfaces was designed inspired by a cat's foot, and the design was achieved by simulating the attachment and clinging mechanism used by cats. A comparison was made between two models of gripper: the arc and the flat type (according to the pattern and shape of the distribution of hooks in the gripper structure), through the experiments conducted and the mechanical properties measured applying quantities of different values, and the arc type was chosen because it has the best performance. Through experiments conducted on the model, it became clear that there is a relationship between the number, type, and size of hooks, as the strength and stability of clinging is directly proportional to the number of hooks and inversely proportional to the size and measurement of the hooks. As the gripper cannot bear large loads if a single hook is used, or the hook may be deformed and bent. When the number of hooks increases, the load and weights can be increased, and the best case is when the number of hooks is seven. The springs behind the hooks also increase the gripping force and prevent slipping. The results of practical experiments showed high durability of the gripper in the clinging process.

Conflict of Interest

The authors have no conflict of relevant interest to this article.

References

[1] P. Pradhan, *Design and Application of a Legged-Wall Climbing Robot*. Asian Institute of Technology, School of Engineering and Technology: Thailand, 2015.

[2] M. F. Silva, J. A. Tenreiro, K. Oka, and J. K. Tar, "A survey of technologies for climbing robots adhesion to surfaces," in *IEEE 6th International Conference on Computational Cybernetics*, November 2008.

[3] G. Fang and J. Cheng, "Advances in climbing robots for vertical structures in the past decade: A review," *Biomimetics*, vol. 8, 2023.

[4] F. Xu, X. Wang, and G. Jiang, "Design and analysis of a wall-climbing robot based on a mechanism utilizing hook-like claws," *International Journal of Advanced Robotic Systems*, vol. 9, 2012.

[5] Y. Lu, K. Zhou3, and N. Ye, "Design and kinemics/ dynamics analysis of a novel climbing robot with tri-planar limbs for remanufacturing," *Journal of Mechanical Science and Technology*, vol. 3, pp. 1427–1436, 2017.

[6] A. Laskar, "Wall climbing robots: The artificial lizards of moderns days," *International Journal of Scientific Development and Research*, vol. 1, 2016.

[7] M. Akhtaruzzaman and N. L. Samsuddin, "Design and development of a wall climbing robot and its control system," in *International Conference on Computer and Information Technology*, December 2009.

[8] Q. Jiang and F. Xu, "Grasping claws of bionic climbing robot for rough wall surface: Modeling and analysis," *Applied Sciences*, vol. 8, 2018.

[9] F. Meng, Y. Guo, and F. Xu, "The graspable algorithm for a wall-climbing robot with claws," *Intelligent Robotics and Applications*, vol. 11741, pp. 60–71, 2019.

[10] R. Wang and C. Cheng, "Cat-paw-inspired tree climbing robot gripper," 07 2023.

[11] P. Zi, K. Xu, Y. Tian, and X. Ding, "A mechanical adhesive gripper inspired by beetle claw for a rock climbing robot," *Mechanism and Machine Theory*, vol. 181, 2023.

[12] J. Xia, B. Li, K. Ushiroda, and Q. Song, "Rise-rover: A wall-climbing robot with high reliability and load-carrying capacity," in *IEEE Conference on Robotics and Biomimetics Zhuhai, China*, December 2015.

[13] A. Milella, R. Maglietta, M. Caccia, and G. Bruzzone, "Robotic inspection of ship hull surfaces using a magnetic crawler and a monocular camera," *Sensor Review*, vol. 37, pp. 425–435, 2017.

[14] M. Eich, F. Bonnin, E. Garcia, and A. Ortiz, "A robot application for marine vessel inspection," *Journal of Field Robotics*, vol. 31, pp. 319–341, 2014.

[15] A. Sintov, T. Avramovich, and A. Shapiro, "Design and motion planning of an autonomous climbing robot with claws," *Robotics and Autonomous Systems*, vol. 59, pp. 1008–1019, 2011.

[16] M. Y. Hassan, *Design and Implementation of an Autonomous Climbing Robot*. College of Engineering University of Basrah, 2019.

[17] R. Li, S. Yan, and C. Zhou, "Design of the paw of wall-climbing robot with spiny and sensing function," *Journal of Physics: Conference Series*, vol. 2537, 2023.

[18] H. Liu, Q. Huang, and W. Zhang, "Cat-inspired mechanical design of self-adaptive toes for a legged robot," *International Conference on Intelligent Robots and Systems*, vol. 1, pp. 2425–2430, 2016.

[19] B. Nisbett, *Mechanical Engineering Shigley's Mechanical Engineering Design*. McGraw-Hill Primis, 2008.

[20] J. Steffen, *Analysis of Machine Elements using SolidWorks Simulation 2011*. SDC Publications, 2022.