Design and Analysis of a Spring-supported Parallel Two-Jaw Gripper

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***Abstract*—This paper presents the design and analysis of a novel parallel two-jaw gripper equipped with spring mechanisms to enhance its gripping capability. This gripper employs a rack and pinion mechanism consisting of two racks and a pinion gear. Two compressive springs attached to each end of the rack enhance the grasping actuation by providing supportive force. This integration of the rack-and-pinion mechanism with spring mechanisms enables the design to surpass the limitations of conventional grasping systems. It offers several advantages including reduced torque requirements, increased handling capacity, enhanced operational safety, and improved reliability. Furthermore, the gripper design prioritizes simplicity and ease of fabrication to facilitate practical deployment and maintenance. Comprehensive modelling and evaluation of the gripper are conducted through simulations and analytical calculations, highlighting its effectiveness and power efficiency in automated handling systems.**

***Index Terms*—Parallel Gripper, Rack and Pinion, Spring Mechanism, Robot End effector, Object Manipulation**

I. Introduction

In automation and robotics, a gripper is an essential mechanical device used for grasping, manipulating, and transferring objects, improving productivity and enabling automation across industries. It functions as the robotic equivalent of a human hand, facilitating interaction between a robotic system and its environment [1]. Grippers are widely used in manufacturing, assembly, and packaging, where they reduce human labor, minimize errors, and increase production speeds [2]. Their design and operational efficiency are critical, directly influencing automation systems' ability to perform complex tasks with precision. Grippers are indispensable as industries embrace greater automation and Industry 4.0 technologies [3].

Among the various types of grippers, the parallel two-jaw grippers are mostly used. These grippers use two opposing jaws that open and close in parallel, mimicking the action of human fingers [4]. The simplicity of its design and operation makes it highly effective for a wide range of tasks. However, despite their widespread usage, there remains significant scope for enhancement in terms of minimizing energy consumption during manipulation tasks and increasing safety in manipulation operations.

Conventional gripper mechanisms, which are often used in similar applications, face challenges such as higher torque requirements, limited adaptability to varying loads, and complex fabrication processes, which the rack and pinion mechanism seeks to address. The conventional designs of these grippers also often face challenges in dynamic and unstructured environments where objects vary in shape and size [5]–[7].

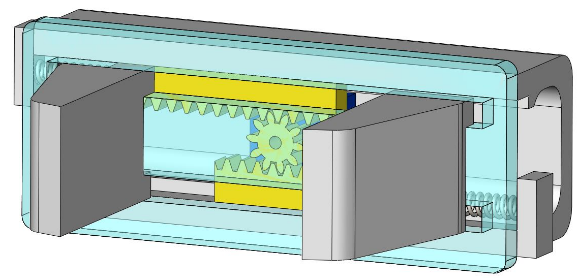


Fig. 1. Parallel two-jaw gripper 3D design

Optimizing these grippers lead to more sophisticated automation capabilities, specially in industries where precision and reliability are paramount [2], [8]. The continuous development and enhancement of two-jaw grippers are essential for advancing robotic technology and expanding its applications [9].

In this study, a novel design of a parallel two-jaw gripper (see Fig. 1) is introduced which is actuated by a rack and pinion with the support of spring mechanisms. This design prioritizes simplicity and ease of fabrication with more practicality. Ultimately, the spring mechanism is to maximize support for the motor during manipulation tasks, thereby enhancing reliability during gripping operations. By addressing the limitations of conventional parallel two-jaw grippers, this design offers a more energy-efficient, safe and adaptable solution for diverse applications. The proposed gripper is evaluated by simulations and Finite Element Analysis (FEA).

The paper's structure is as follows: Section II provides a comprehensive review of the relevant literature, setting the stage for the study. Section III delves into the fundamentals of mechanical design, laying out the core concepts and methodologies. After that, Section IV presents and analyzes the simulation results. Finally, Section V summarizes the key findings and provides concluding remarks.

II. Related Work

Various types of grippers are used in the industry and are classified by the number of fingers, type of actuation, mode of gripping, mechanism used, and method of gripping [2]. The two-jaw gripper is notably prevalent, accounting for approximately 70% of grasps in manufacturing, particularly for objects with cuboid, pyramidal, and cylindrical shapes [2]. This popularity is mirrored in human talent, where two-fingered grasps are common for handling such objects. While multi-fingered grippers offer secure grasps, they entail complex control strategies, often making them less desirable for widespread application. Parallel two-jaw grippers are commonly utilized for pick-and-place operations in diverse sectors [1], [2]. Their simple designs and manufacturability led to widespread adoption in industry and research.

Among various actuation mechanisms, the rack and pinion system remains one of the most widely utilized across numerous industrial applications [10]–[12]. A significant portion of robotic end-effectors in the industry rely on this mechanism for its simplicity and effectiveness [2], [13]. Notable examples include the work of Wang et al. who developed a five fingered underactuated dexterous hand (UADH) that integrates rack and pinion and linkage slider mechanisms, complemented by a torsion spring. This design allows the UADH to efficiently grasp a wide variety of objects, enhancing both stability and adaptability in dynamic environments [14]. Similarly, Hattori et al. introduced a multifunctional parallel gripper featuring a rack and pinion mechanism that can switch between large and small fingers. This innovation enables the gripper to handle objects of different sizes and shapes, improving performance in confined spaces and providing robust three face grasping, which further enhances functionality in dynamic operational settings [15].

Existing literature on grippers incorporating spring mechanisms is relatively limited. Among them, Nuttall et al. have developed a parallel jaw gripper with preloaded springs implemented to the jaws to obtain compliant behavior in the horizontal direction [16]. Moreover, rotary spring-driven gripper consists of curved parts with each incorporating numerous compression springs is developed by Lama et al. to manipulate objects of various sizes and shapes without the need for a closed-loop control system [17]. However, the rack and pinion and spring mechanisms are both simple and reliable. When combined effectively, they can optimize the gripper design by reducing motor torque requirements and enhancing system safety. Considering these facts, this paper aims to propose a novel gripper designed to achieve the aforementioned improvements.

III. Mechanical Design

A. Handling Objects

The gripper's mechanical structure and actuation method are designed specifically for handling objects with particular characteristics. This gripper is created to handle cuboid shaped objects that are between 2 cm to 10 cm in width size and weight up to 2 kg. The friction coefficient between the object and the gripper's jaws is a crucial factor in determining the required motor torque. For this analysis, the gripper jaws made of PLA use a friction coefficient of 0.3 with the object. This coefficient aligns with the most common gripping scenarios, as noted by Shooter [18].

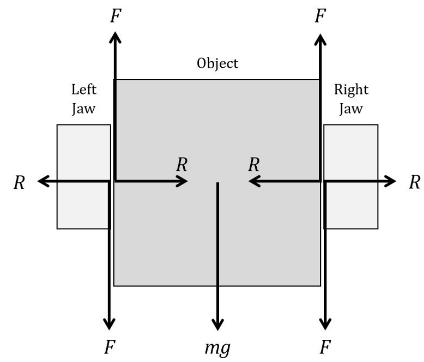


Fig. 2. Free body diagram

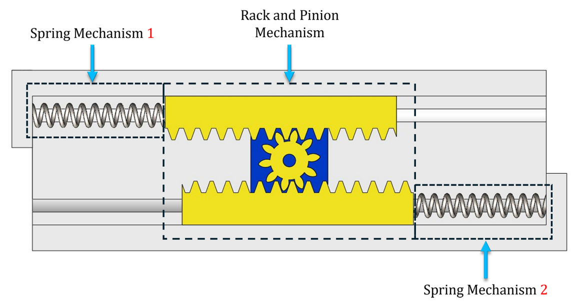


Fig. 3. Rack and pinion equipped with spring mechanism

The forces exerted on the gripper during the gripping task are shown on the free body diagram (refer Fig. 2). The mathematical equations for the friction force (F) calculations are provided below, showing the relationship between object's weight (m), acceleration of gravity (g), horizontal reaction force (R), and friction coefficient (μ).

$$2F = mg \tag{1}$$

$$F \leq \mu R \tag{2}$$

Considering an gripping object weight (m) of 2 kg with a friction coefficient (μ) of 0.3, these calculations yield a friction force (F) of 9.81 N and a minimum horizontal reaction force (R) of 32.7 N.

B. Rack and Pinion Mechanism

The gripper operates using a rack and pinion mechanism. Each of the two jaws is connected to a separate rack, and these racks are engaged with a single pinion gear that is connected to the motor (refer Fig. 3).

The key design considerations for the rack and pinion mechanism include dimensions, speed, and force. In this

TABLE I
RACK AND PINION MECHANISM DESIGN PARAMETERS

Parameter	Value
Pitch Diameter	20 mm
Number of Teeth on Pinion	10
Module	2
Pressure Angle	20°
Length of Rack	90 mm
Material	PLA
Allowable Bending Stress	60 MPa
Tooth Width	10.00 mm
Circular Pitch	6.28 mm
Addendum	2.00 mm
Dedendum	2.50 mm
Shear Area	23.20 mm^2

design, a spur gear rack and pinion type is selected due to its ease of fabrication, absence of additional axial thrust forces, and suitability for low speeds. The dimensions of the gripper and the rack and pinion mechanism depend primarily on the dimensions and weight of the object to be handled. Table I outlines the basic parameters of the designed rack and pinion mechanism for the gripper.

The mathematical equation provided below details the necessary torque calculations and illustrate the relationships between horizontal reaction force (*R*), pitch diameter (*d*) and required motor torque (*T*).

$$T = 2 \times R \times \frac{d}{2} \tag{3}$$

From Eq. 3, given a horizontal reaction force (*R*) of 33 N and a pitch diameter (*d*) of 20 mm, the required motor torque (*T*) to grip the object is calculated as 0.66 Nm.

Table II outlines the main failure parameters for estimating tooth strength in the rack and pinion mechanism. These calculations were performed with a factor of safety of 2. All calculated maximum tangential forces exceed the horizontal reaction force exerted on the rack. Moreover, axial force will not be exerted because required motor torque for gripper actuation is less than minimum torque to create axial force in this mechanism. Consequently, these calculations indicate that the rack and pinion mechanism is improbable to fail during actuation [19].

C. Spring Mechanism

Two compressive springs are connected to each rack to enhance the rack and pinion mechanism by providing supportive force during the grasping. On the other hand, these spring mechanisms necessitate additional torque from the gripper motor to counteract the spring force during release actuation. In the release actuation, the required motor torque is considerably reduced as there is no need to counteract the horizontal reaction force typically encountered during the grasping phase. The supportive force provided by the springs varies according to their characteristics. In this study, the results were analyzed with varying the spring constant (*k*) in the given range, assuming springs have a linear spring constant throughout the compression and adhere to Hooke's Law. The parameters of these springs are also within the range of commercially available ones. The main parameters of these springs are detailed in Table III.

TABLE II
RACK AND PINION MECHANISM FAILURE PARAMETERS

Parameter	Value
Max. tangential force to shear failure	942.23 N
Max. tangential force to bending failure	905.47 N
Max. allowable tangential force (rack)	452.73 N
Min. torque to create axial force	4.82 Nm

TABLE III
SPRING SPECIFICATIONS

Parameter	Value
Spring Constant (*k*)	0.1 - 1.0 N/mm
Coil Diameter	8 mm
Free Length	87.5 mm
Number of Coils	20
Wire Diameter	1.5 mm
Maximum Deflection	56.79 mm
Material	Stainless Steel 302

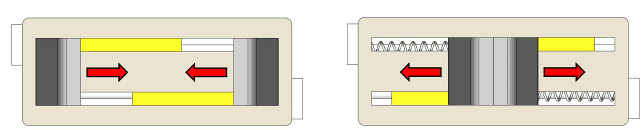
IV. RESULTS AND DISCUSSION

To analyze the design of this parallel two-jaw gripper, motion studies were performed to determine the required motor torques across all gripper configurations and object sizes. Ultimately, Finite Element Analysis (FEA) was utilized to evaluate the mechanical strength of the gripper under various configurations and actuation types. This comprehensive analysis included assessments of stress, displacement, and factor of safety to ensure the gripper's reliability and performance under operational conditions.

A. Motor Torque Analysis

Motion studies were conducted to analyse the grasping and releasing actions for a 2 kg object, as shown in Fig. 4. The object size varied from 2 cm to 10 cm in width, and the spring constant (*k*) ranged from 0.1 to 1.0 in increments of 0.1. Each actuation was completed within a 5 s time frame. The motor torques for grasping and releasing were analyzed separately. In this study, friction between components of the gripper is neglected.

a) Without Spring Mechanism: In this gripper configuration, the motor torque was analyzed for the existing rack and pinion mechanism without spring mechanisms. Through



(a) Grasp (b) Release

Fig. 4. Actuation types

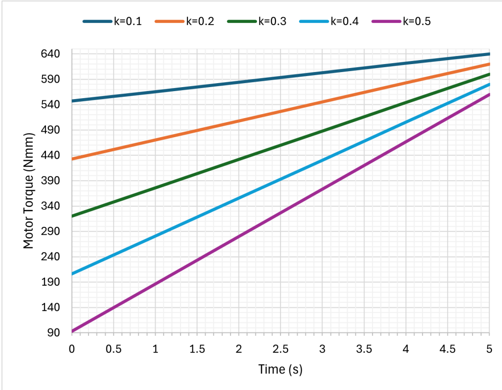


Fig. 5. Motor torque need to grasping actuation (k = 0.1 to 0.5)

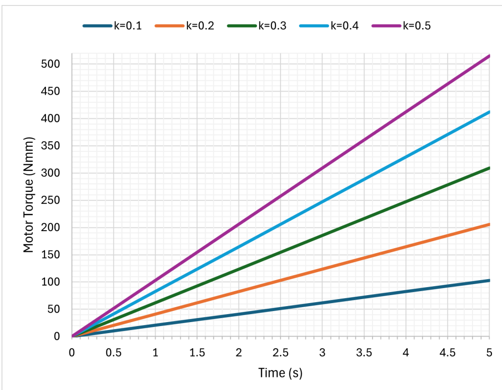


Fig. 6. Motor torque need to release actuation (k = 0.1 to 0.5)

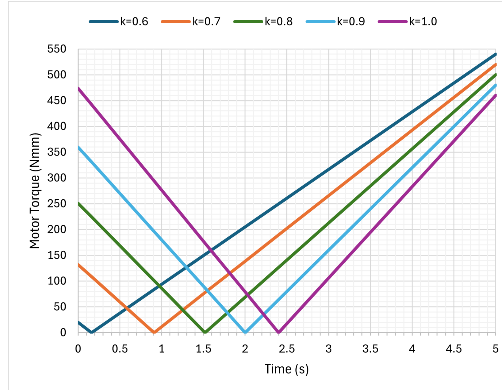


Fig. 7. Motor torque need to grasping actuation (k = 0.6 to 1.0)

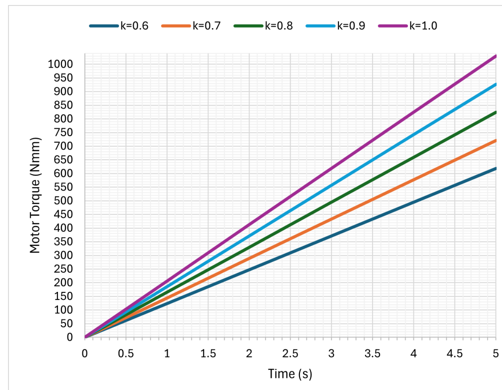


Fig. 8. Motor torque need to release actuation (k = 0.6 to 1.0)

calculations and simulations, it was determined that a constant torque of 0.66 Nm is required for the grasping actuation. For the releasing actuation, no torque is required from the motor because the friction between the components was neglected.

b) Spring constant (k) from 0.1 to 0.5: As the k increased within this range, a decrease in motor torques for grasping actuation was observed (refer Fig. 5) while an increment in motor torques for releasing actuation was observed (refer Fig. 6). Ultimately, it was found that the maximum torque required to actuate the gripper properly decreased with the incorporation of spring mechanisms across this range of k values.

c) Spring constant (k) from 0.6 to 1.0: When k increased, the motor torque required for releasing actuation exceeded 0.66 Nm observed in gripper without the spring (refer Fig. 8). During the grasping actuation, motor torque initially registers a nonzero value, subsequently reduces to zero, and then gradually increases (refer Fig. 7). This variation occurs because, the motor must work against the high compressive forces exerted by the springs at initial phase. Consequently, the maximum torque required for grasping is significantly reduced as k increases. However, the excessive compressive force exerted by the springs poses a disadvantage, as it necessitates the motor working against these forces throughout this range of k. This aspect represents a potential drawback of this gripper.

B. Optimization of Spring Mechanism

Due to the aforementioned phenomena, it is necessary to optimize the spring mechanisms to enhance the gripper's performance based on the object being handled or the motor specifications available. Therefore, there are two approaches to achieve this optimization: adjusting the spring mechanism according to the weight of the object, and tailoring it to the specifications of the selected motor.

a) Optimization for Object Weight: A series of iterative motion studies were conducted to identify the k that results in the minimum motor torque required for both grasping and releasing actions, as detailed in Table IV. It was determined that a k of 0.535 achieves optimal maximum motor torques, requiring only 0.553 Nm for grasping and 0.551 Nm for releasing (refer Fig. 9). Therefore, a motor torque of just 0.553 Nm is sufficient for the gripper to manipulate the object effectively, representing a 16.21% reduction in required motor torque. This reduction offers a significant improvement in the power efficiency of the gripper.

b) Optimization for Selected Motor: In this analysis, the selected motor has a motor torque of 0.66 Nm. The first step involves identifying the value of k that results in the maximum motor torque for the releasing actuation, ensuring it is equal to or slightly less than 0.66 Nm. k = 0.64 results

TABLE IV
OPTIMIZATION FOR OBJECT WEIGHT MOTOR TORQUE ITERATIONS

Spring Constant (*k*)	**Maximum Grasping Torque (Nm)**	**Maximum Releasing Torque (Nm)**
0.5	0.56	0.515
0.52	0.556	0.535
0.53	0.554	0.546
0.535	**0.553**	**0.551**
0.54	0.52	0.556
0.55	0.55	0.566
0.6	0.54	0.618

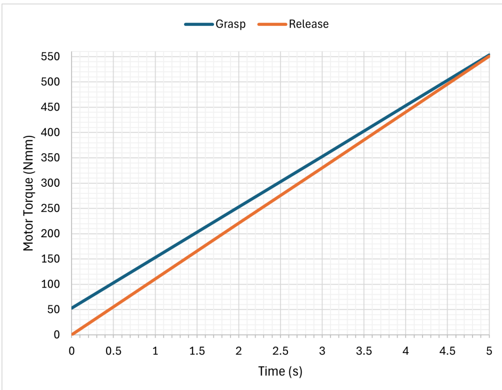


Fig. 9. Motor torque need to both actuations (k = 0.535)

in a maximum motor torque of 0.659 Nm for the releasing actuation. Subsequently, the object weight is increased up to 2.4 kg and results in a maximum motor torque of 0.658 Nm for the grasping actuation as shown in Fig. 10. This configuration allows the gripper to handle 20% more weight, representing a significant improvement in its operational capacity.

C. Finite Element Analysis

In this gripper, all components except springs are fabricated using PLA material. Finite Element Analysis (FEA) was conducted on three configurations as previously discussed, tailored to parameters outlined for handling objects of 2 cm (min. width) and 10 cm (max. width). The FEA focused particularly on grasping actuation phase as the horizontal reaction forces are applied to the gripper. These forces make the gripper more prone to failure during grasping rather than during release. The analysis specifically assessed the mechanical strength and performance under these conditions to ensure reliability and effectiveness.

Fig. 11, 12, and 13 illustrate the stress analysis for the three configurations previously discussed. In each scenario, the stress levels remained below the yield strength of the materials used, confirming that the gripper could handle the specified objects without mechanical failure. In summary, the gripper without spring mechanisms generates higher stress levels within the rack and pinion mechanism, whereas the other two configurations create high stresses in the spring mechanisms. Table V offers detailed parameters from the FEA results, further validating the structural integrity and operational feasibility of the gripper. Additionally, the supportive

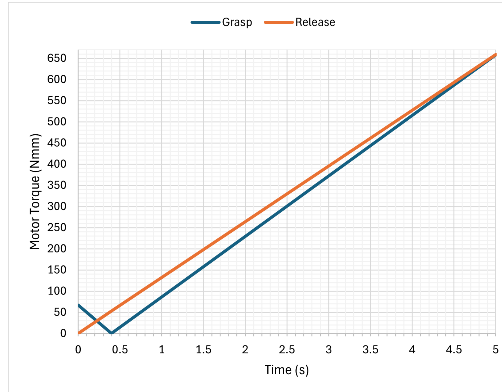
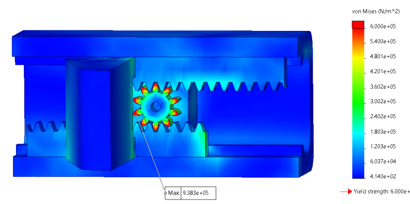
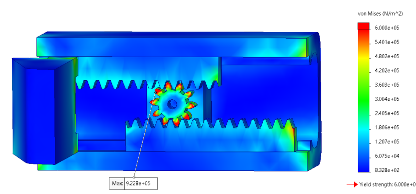


Fig. 10. Motor torque need to both actuations (k = 0.64)



(a) 2 cm Object



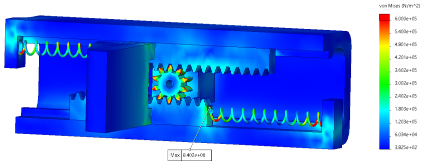
(b) 10 cm Object

Fig. 11. Stress analysis: gripper without spring mechanism

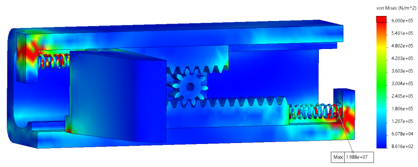
force provided by the spring mechanism serves to prevent the sudden release of the object in the event of motor malfunction, enhancing the gripper's safety.

V. CONCLUSION

This paper has aimed to enhance the gripping power efficiency and load capacity of parallel two-jaw grippers by integrating simple and reliable mechanisms. The design's robustness stems from using commercially available springs, selected based on their displacement lengths and geometries suited for the intended actuation. The design exhibits excellent adaptability, with high safety factors, and can support more weight than estimated while managing objects with lower jaw friction. The key findings demonstrate that the two optimization approaches, one tailored optimized for object weight and the other optimized for the selected motor significantly improve the gripper's performance. These optimizations are reflected in the mechanical strength calculations and the FEA results which confirm that the gripper is capable of handling intended objects. Furthermore, the safety of the gripper also increased specifically because of the integration of spring mechanisms. Future work will involve fabricating this gripper

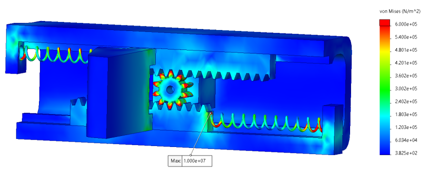


(a) 2 cm Object

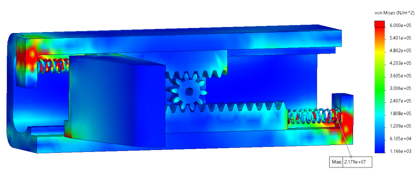


(b) 10 cm Object

Fig. 12. Stress analysis: gripper optimized for object weight



(a) 2 cm Object



(b) 10 cm Object

Fig. 13. Stress analysis: gripper optimized for selected motor

to conduct experimental tests on object handling and compare simulation results with real-world testing results. In conclusion, the enhancements proposed in this study hold considerable potential to advance the functionality and application of parallel grippers.

TABLE V
FEA RESULTS OF GRIPPER CONFIGURATIONS

Gripper Configuration	**Object Size (cm)**	**Max. Stress (N/m^2)**	**Min. Stress (N/m^2)**	**Max. Displacement (mm)**	**Min. Factor of Safety**
Without Spring Mechanism	2	938346	171	0.02	64
	10	922804	833	0.03	65
Optimized for Object Weight	2	8403222	383	0.02	24.6
	10	19880668	861	0.03	10.4
Optimized for Selected Motor	2	10002534	450	0.02	20.7
	10	21792826	1166	0.03	9.5

REFERENCES

[1] K. Tai, A. R. El-Sayed, M. Shahriari, M. Biglarbegian, and S. Mahmud, "State of the art robotic grippers and applications," *Robotics*, vol. 5, 6 2016.

[2] B. Zhang, Y. Xie, J. Zhou, K. Wang, and Z. Zhang, "State-of-the-art robotic grippers, grasping and control strategies, as well as their applications in agricultural robots: A review," *Computers and Electronics in Agriculture*, vol. 177, 10 2020.

[3] D. A. Dhanawade and N. V. Sabnis, "A review: State of the art of robotic grippers," *International Research Journal of Engineering and Technology (IRJET)*, vol. 5, pp. 371–375, 2018.

[4] Z. Hu, W. Wan, and K. Harada, "Designing a mechanical tool for robots with 2-finger parallel grippers," *IEEE Robotics and Automation Letters*, vol. 99, 2 2019.

[5] D. Scholtes, S. S. Seelecke, and P. Motzki, "Design of a lightweight sma driven parallel gripper for collaborative robots," in *SPIE - International Society for Optics and Photonics*, p. 34, SPIE-Intl Soc Optical Eng, 4 2023.

[6] B. Kang and J. Cheong, "Development of two-way self-adaptive gripper using differential gear," *Actuators*, vol. 12, 1 2023.

[7] G. Vitrani, S. Cortinovis, L. Fiorio, M. Maggiali, and R. A. Romeo, "Improving the grasping force behavior of a robotic gripper: Model, simulations, and experiments," *Robotics*, vol. 12, 12 2023.

[8] V. A. Ho, "Grasping by wrapping: Mechanical design and evaluation," in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 6013–6019, IEEE, 2017.

[9] N. Bhatt and N. R. Chauhan, "Design of a two fingered friction gripper for a wheel mobile robot," in *Advances in Intelligent Systems and Computing*, vol. 452, pp. 195–203, Springer Verlag, 2016.

[10] F. Brenner, A. Lechler, and A. Verl, "Acceleration-based disturbance compensation for elastic rack-and-pinion drives," *Production Engineering*, vol. 15, pp. 791–800, 12 2021.

[11] A. G. Bendefy, A. Piros, and P. Horak, "Arbitrary vehicle steering characteristics with changing ratio rack and pinion transmission," *Advances in Mechanical Engineering*, vol. 7, 12 2015.

[12] S. A. Kariyawasam, G. H. Sandeepa, M. K. A. Pathirana, Y. W. R. Amarasinghe, A. G. B. P. Jayasekara, H. A. G. C. Premachandra, and U.-X. Tan, "Wibot 1.0: A modular reconfigurable glass cleaning robot for high-rise buildings," in *2024 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 16759–16765, IEEE, 5 2024.

[13] C. Vilău, N. Bâlc, and D. Leordean, "Design and analyses to determine the minimum acting force of a gripper for handling the parts with robots," *Applied Mechanics and Materials*, vol. 808, pp. 264–270, 11 2015.

[14] D. Wang, Y. Xiong, B. Zi, S. Qian, Z. Wang, and W. Zhu, "Design, analysis and experiment of a passively adaptive underactuated robotic hand with linkage-slider and rack-pinion mechanisms," *Mechanism and Machine Theory*, vol. 155, 1 2021.

[15] T. Hattori and T. Omata, "Multifunctional parallel gripper with three actuators," *IEEE/ASME Transactions on Mechatronics*, vol. 27, pp. 1391–1402, 6 2022.

[16] A. J. Nuttall and A. J. K. Breteler, "Compliance effects in a parallel jaw gripper," *Mechanism and Machine Theory*, vol. 38, pp. 1509–1522, 12 2003.

[17] S. Lama and T. Deemyad, "Using a rotary spring-driven gripper to manipulate objects of diverse sizes and shapes," *Applied Sciences (Switzerland)*, vol. 13, 7 2023.

[18] K. V. Shooter, "Frictional properties of plastics," *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, vol. 212, pp. 488–491, 1952.

[19] A. Dave, "Automatic railway platform system," *Journal of Emerging Technologies and Innovative Research (JETIR)*, vol. 5, pp. 136–145, 2018.