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Soft Robotics in Industrial Automation: Adaptive Industrial Gripper Design and Evaluation

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Abstract

The rapid evolution of industrial automation demands more versatile gripping solutions beyond conventional vacuum, magnetic, and fingered grippers. This study introduces the development and evaluation of an adaptive Universal Jamming Gripper (UJG) optimized for industrial applications. Utilizing a flexible membrane filled with granular materials, the UJG transitions between soft and rigid states under vacuum pressure, enabling secure and adaptive grasping of objects with diverse shapes and materials. Three types of membrane fillings—ground coffee, polystyrene microspheres (EPS), and thermoplastic elastomer granules (TPE)—were assessed for grip stability and force efficiency. Experimental results demonstrate that EPS microspheres provide superior adaptability and stability, offering the highest gripping force across various object geometries. Performance tests on a universal testing machine further validate the gripper's capability to handle differently shaped objects with minimal adjustments. The findings underscore the potential of adaptive gripping technologies in enhancing automation flexibility, reducing operational downtime, and increasing overall industrial efficiency. Future research will focus on long-term durability, integration with robotic automation, and performance assessment in real-world manufacturing environments.

Keywords: adaptive gripper, universal jamming gripper, industrial automation, soft robotics, variable stiffness, robotic grasping, automation flexibility

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1. Introduction

Vacuum, magnetic, and fingered grippers are widely utilized in advancing Industry 4.0 within the industrial sector. Their durability and cost-effectiveness make them a preferred choice among engineers and manufacturers for robotic automation. However, as industrial processes grow more intricate, the rigidity of these conventional grippers often requires frequent tool changes to handle objects with different shapes and material properties. This drawback not only extends downtime but also complicates robotic programming, necessitating complex exception handling when robots unexpectedly stop or fail to grasp objects properly. As industries push for enhanced efficiency, reliability, and automation flexibility, the need for more adaptable and versatile gripping technologies has become increasingly clear. [1, 2]

One strategy to address these limitations is the development of adaptive grippers, which can adjust to various object shapes without requiring predefined grasping configurations. Among these, Universal Jamming Grippers (UJG) present a particularly effective solution by utilizing stiffness modulation to achieve a secure grip. UJGs consist of a flexible membrane filled with granular materials that transition from a pliable to a rigid state when vacuum pressure is applied, as illustrated in Figure 1. This mechanism enables them to conform to an object's shape before solidifying for a stable grasp. Similar principles are employed in soft robotics, where variable stiffness mechanisms and compliant materials improve grasping efficiency [3]. Recent innovations in this domain include honeycomb-Velcro jamming structures for enhanced adaptability [4] and rotational layer jamming grippers for improved force distribution [5].

The field of soft robotics has seen substantial growth in recent years, particularly in material selection and actuation mechanisms aimed at improving gripping capabilities [6]. For example, compliant grippers with passive finger structures have been introduced to enhance adaptability [7, 8], while research has shown that the choice

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of granular material within the membrane significantly impacts grip efficiency. Studies indicate that expanded polystyrene beads provide greater gripping force compared to conventional materials like ground coffee [9, 10]. Additionally, the transition of soft grippers from experimental prototypes to commercial applications has been explored, emphasizing their increasing role in industries such as food handling, agriculture, and collaborative robotics. [11, 12]

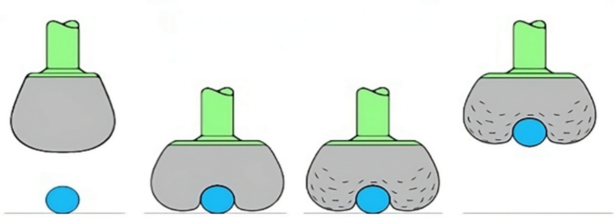

Figure 1. The principle of UJGs gripper [3]

In prior research, where the UJG principle has been used, scientists focused on a delivery solution [13], examined various granulated fillings [14, 15], or investigated underwater usage [13]. Many others have primarily addressed usage for specific use cases such as cluttered bin-picking in research labs [14], delicate food handling in agrifood environments [15], or soft pneumatic actuation for biomedical and agricultural tasks [16, 17], whereas our study targets the performance and reliability of jamming grippers in real-world industrial settings. Despite early commercial attempts to bring jamming grippers to market—most notably the VERSABALL, as can be seen in Figure 2, by Empire Robotics—success has been limited, with companies facing challenges in membrane durability, vacuum control reliability, and the need for frequent component replacement [11]. While these issues contributed to the discontinuation of early commercial products, they also highlighted key technical parameters that require deeper academic investigation. Notably, limited experimental validation was performed on the relationship between object geometry and gripping force, and real-world industrial testing remained superficial [11]. Therefore, our study directly addresses this void by systematically evaluating how various membrane materials and object shapes influence gripping efficiency in a controlled, industrial-relevant setup. By doing so, we aim to bridge not only a scientific gap but also lay the groundwork for overcoming previous commercialization hurdles through more robust, data-driven design. By utilizing low-cost materials and additive manufacturing, our gripper design achieves high performance while remaining extremely economical—making it an accessible alternative even for budget-sensitive automation environments.

Figure 2. Versaball produced by Empire Robotics [11]

This research aims to design, develop, manufacture, and evaluate an adaptive robotic gripper capable of handling objects with undefined positioning. The study focuses on optimizing the gripper's geometry, material properties, and vacuum control mechanisms to improve performance. The proposed gripper will be tested on an industrial robotic arm, with a systematic analysis of its gripping force, adaptability, and practical application conducted in future research. By incorporating insights from recent advancements in intelligent soft grippers [12, 18], variable stiffness mechanisms [19, 20], and adaptive automation strategies [21], this study contributes to the development of next-generation robotic grippers that emphasize flexibility, efficiency, and robustness.

2. Materials and Methods

To demonstrate the concept, the UJG gripper was designed for future robotic attachment, integrating modularity, adaptability, and efficient grasping mechanisms. The gripper was conceptualized to accommodate diverse object geometry and was assembled using a combination of lightweight materials, actuators, and control mechanisms.

2.1. Design and Manufacturing

The design of the UJG gripper was developed using CAD software (SolidWorks 2024) to ensure precise modelling and structural analysis. The gripper structure and membrane mold were 3D-printed from Acrylonitrile-butadiene styrene (ABS-M30) for a balance between strength and weight reduction. The finger (membrane) material was chosen to maximize adaptability to different object shapes and sizes, which was polydimethylsiloxane (PDMS), specifically GMS A05 silicone. To easily separate silicone after pouring it into a mold, Easy Release 200 spray was used.

Membrane Filling

The main objective of this study is to evaluate the performance of a self-manufactured UJG. To determine the most effective grip stability, three different fillings for the silicone membrane were tested: ground coffee, polystyrene micro-spheres (EPS), and thermoplastic elastomer granules (TPE), as illustrated in Figure 3. The weight distribution of these configurations is provided in Table 1.

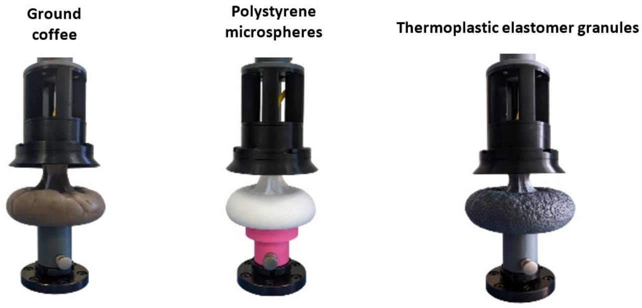

Figure 3. Three kinds of membrane filling

Table 1. Membrane fillings and UJG weight

Membrane filling	Weight of the UJG [kg]
Ground coffee	0.846
Polystyrene microspheres (EPS)	0.571
Thermoplastic elastomer granules (TPE)	1.121

2.2. Experimental Setup

To determine the maximum force the adaptive gripper can exert while securely grasping and holding objects of different weights, it was necessary to conduct force measurements. The LabTest 6.50 testing machine, produced by LaborTech, was utilized for this purpose as shown on Figure 4. This electromechanical device is specifically designed for universal static testing, enabling experiments involving tension, compression and bending. With a load capacity of up to 50 kN, it provides a reliable means of assessing the gripper’s grasping strength. These measurements are crucial for validating the gripper’s capability to handle objects of varying weights and sizes effectively.

Testing Samples

Since the effectiveness of an adaptive gripper's grasp largely depends on the shape of the object being manipulated, various prototype test pieces were created to represent basic geometric forms. As illustrated in Figure 5, these test samples were produced in three distinct sizes—25 mm, 50 mm, and 75 mm—to evaluate the gripper’s adaptability in handling objects of different dimensions. Beyond standard geometric shapes such as cubes, cylinders, and spheres, a custom-designed form was included to determine if the gripping force is enhanced when dealing with shapes that promote form-fit gripping due to their specific configurations.

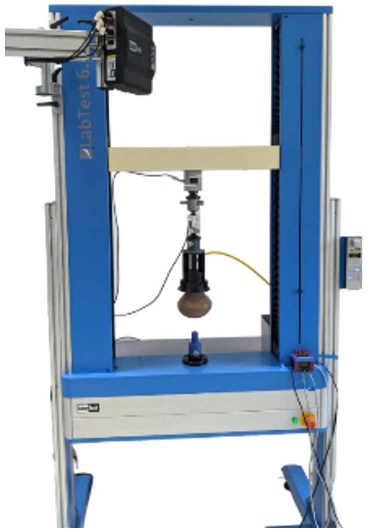

Figure 4. LaborTech LabTest 6.50 testing machine

Figure 5. Examples of grip testing samples

2.3. Testing Procedure

All test specimens were designed for easy attachment to the testing machine, utilizing a pin as a universal mounting mechanism. This ensured compatibility with various test pieces while maintaining stability throughout the testing process.

The measurement procedure followed a specific sequence: initially, the gripper’s membrane was inflated to a predetermined size. The gripper was then lowered until the membrane completely enclosed the test specimen, with the distance between the gripper and the specimen kept consistent for all tests. Once enclosed, the air was gradually released from the membrane, causing it to become rigid. After the membrane fully stabilized, the testing machine

lifted the gripper while simultaneously recording the gripping force. This procedure was repeated ten times for each sample, as illustrated in Figure 4.
This methodology ensured a systematic approach to evaluating the performance and functionality of the UJG gripper, contributing to its potential implementation in robotic manipulation tasks.

3. Results and Discussion

In this paper, the research is divided into the development and manufacturing phases of UJG, followed by its examination.

3.1. Design and Manufacturing

A crucial aspect of this study, essential for confirming all membrane fillings and ensuring the ability to grasp the testing samples, was the development of a functional design. Throughout the development stage, various market components were utilized, ultimately leading to a utilitarian assembly, as shown in Figure 6.

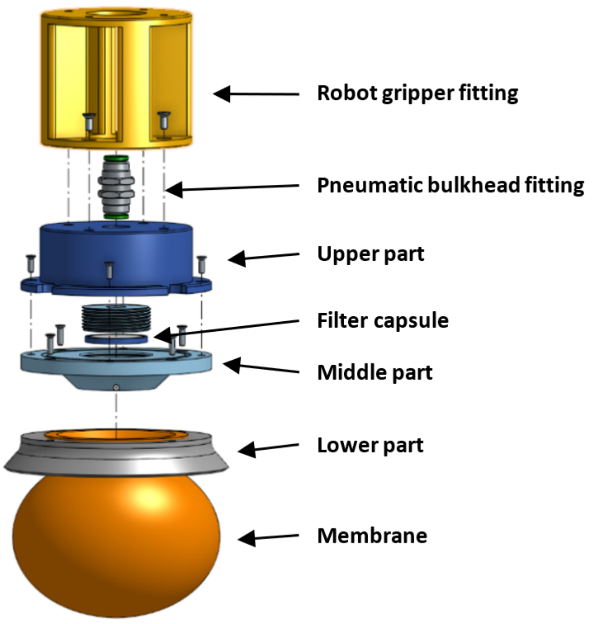

Figure 6. Developed own design of the UJG

Solid Parts

The rigid components of the gripper provide essential structural integrity and serve to connect its various elements, ensuring its functional and reliable operation. These components include the following parts, as depicted in Figure 7:

- *Extension and Reduction Adapter for the Robot* – This adapter enables the connection of the gripper to different robot models in future research. It is secured to the upper part of the gripper using four M4 screws and features mounting holes on its upper side for attachment to the robot. This component is specifically designed to be easily adaptable to various robot flange types.
- *Pneumatic Bulkhead Fitting* – A crucial element for air extraction from the gripper, the pneumatic bulkhead fitting also ensures airtight sealing. The use of an M16 nut and a thermoplastic polyurethane (TPU) gasket guarantees that the vacuum remains within the system without leakage, which is essential for the proper functionality of the pneumatic system.
- *Upper Part* – This component closely adheres to the middle part and is fastened to it using four M3x12 screws. It is designed to provide a firm and stable foundation for the other parts of the gripper while allowing for easy assembly and disassembly.
- *Filter capsule* – The filter serves to prevent contaminants from the gripper’s filling material from entering the airflow path. The filtration element must capture even small particles depending on the chosen filling material. Therefore, a coffee filter paper has been selected as the filtration medium. To keep the filter in its designated position, a filter fixation component is used, which is screwed into place as needed. Due to the removable nature of the filter, the membrane can be filled even after it has already been attached to the lower and middle parts
- *Middle Part* – This part features a specialized groove designed to accommodate an O-ring with an 80 mm diameter and Shore A 70 hardness, ensuring a tight seal between the components. The middle part also houses the gripper’s filtration element, which is screwed into place. Along with the lower part, it forms a robust structure that secures the membrane, aided by four M3x10 screws.
- *Lower Part* – Serving as the primary support for the membrane, this part prevents excessive expansion of the membrane by means of a raised edge. It is critical for the integrity and functionality of the entire gripper, ensuring that the membrane remains securely in place and is protected from damage during operation.

Figure 7. Solid parts of the UJG

Membrane

For the production of the silicone membrane, the casting method was chosen, in which silicone is poured into a precisely manufactured mold. This approach is crucial to prevent unwanted silicone leakage into the parting plane [22]. The entire mold, which may be seen in Figure 8, is secured using four M10x160 screws, tightened with washers and nuts to ensure the mold's strength and stability. The core placement within the mold is ensured by four M8x30 screws, which are positioned with high precision to hold the core in the correct location. The fastening of the nuts is facilitated by special grooves on the sides of the mold, allowing them to be inserted into the mold structure.

The silicone is cast into the mold through four openings located at the top of the core. These openings are designed with high precision to allow the exact insertion and sealing of a 50 ml syringe, through which the silicone is introduced into the mold. This process enables precise and controlled dosing of the silicone, which is essential for achieving the optimal quality of the final membrane.

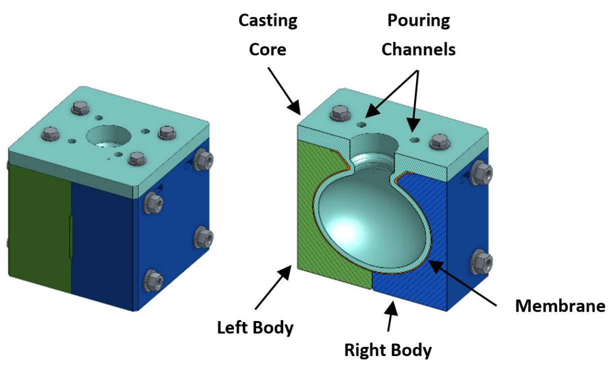

Figure 8. Casting mold

The casting mold was fabricated using 3D printing and subsequently cleaned before being polished with acetone, which dissolves the printed ABS material [23]. After polishing, the inner surface of the mold was treated with a release agent and then assembled using nuts.

For the production of a single membrane, 50 ml of silicone was prepared, with its two components thoroughly mixed to achieve a homogeneous mixture and proper crosslinking. Air bubbles formed during mixing were removed using a vacuum chamber. The silicone was then drawn into a syringe and injected into the mold through a gating channel, with the filling process monitored through adjacent openings. Once the mold was fully filled, additional syringes containing approximately 5 ml of silicone were placed into the gating openings to compensate for shrinkage during crosslinking, ensuring complete filling of the membrane. The process is shown in Figure 9.

Figure 9. Process of filling the casting mold

The selected silicone undergoes crosslinking at room temperature (20 °C) within 3–5 hours. To accelerate this process, the entire mold is placed in a preheated thermal chamber at 50 °C for one hour. After this period, the mold can be opened, and the finished membrane can be removed, as can be seen in Figure 10. Following demolding, only minor trimming is required at the gating channels where excess silicone accumulated. Due to the firm tightening of all mold components, silicone infiltration into the parting line was minimal.

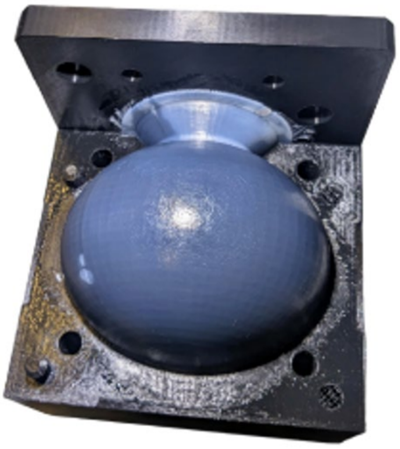

Figure 10. Final silicone membrane after demolding

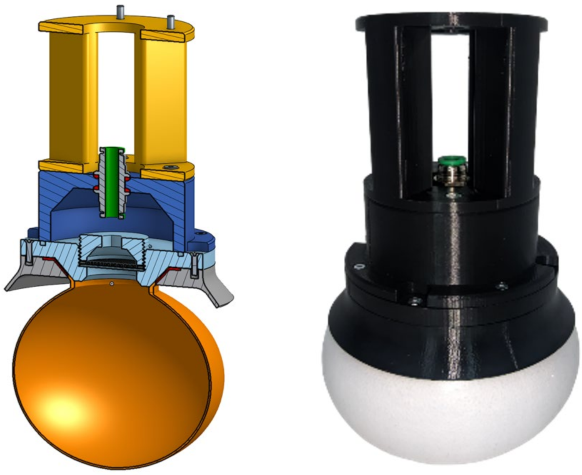

Figure 11. Left: Section view of the 3D model of the gripper; Right: Assembled real gripper

Final UJG Assembling

The assembly begins with placing threaded inserts into pre-drilled holes, providing a foundation for fastening screws that secure the gripper structure. A sealing O-ring is then positioned in a designated groove to prevent air leakage and ensure proper functionality. A gradual tightening of the screws is essential for even force distribution, preventing damage or deformation of the components. The final assembly of the UJG is shown in Figure 11.

3.2. Testing and Discussion

The performance of the developed UJG was evaluated using three different kinds of membrane filling. Figure 12 displays the measured maximum gripping force recorded during testing on the experimental machine.

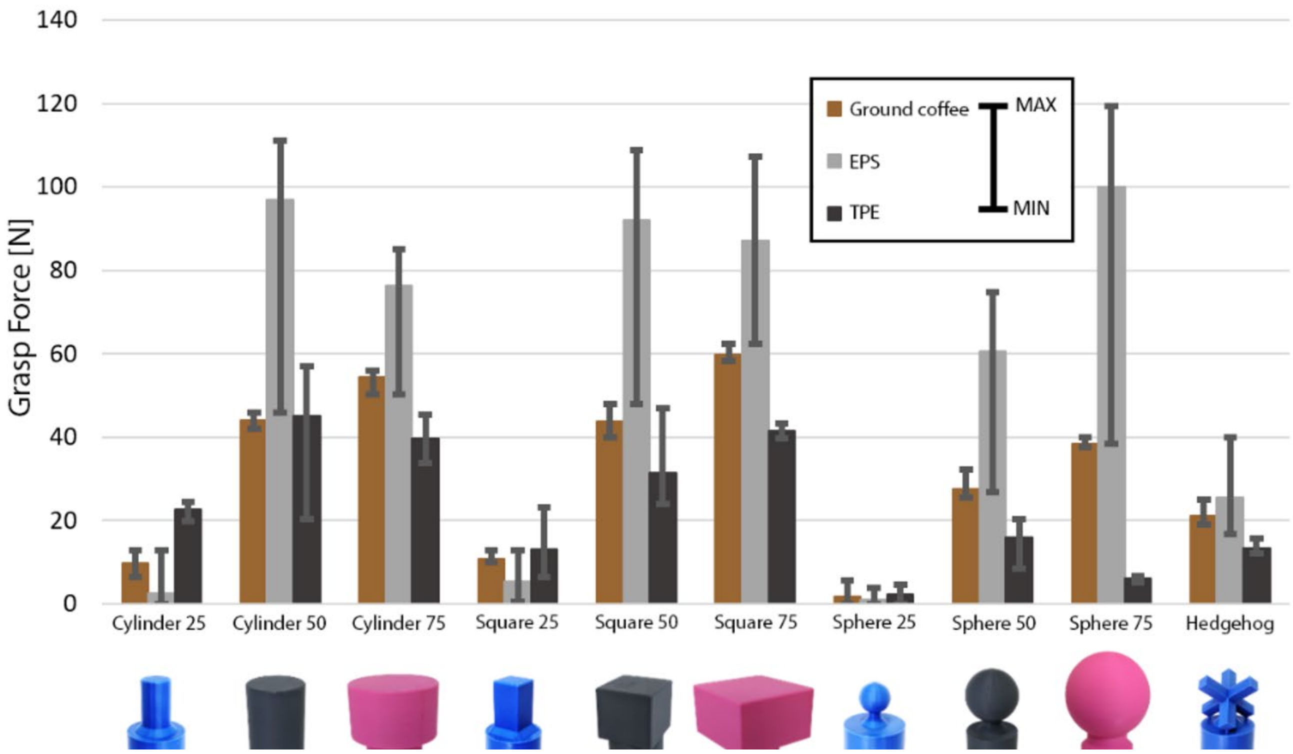

Figure 12. Grasp force measured during testing of different types of parts and membrane fillings

The findings show that both the test object's shape and the type of membrane filling have a significant impact on the gripping force. Objects with geometries that facilitate form-fit gripping tend to exhibit higher forces, especially when granulate-based fillings are used. Furthermore, variations in force measurements among different fillings indicate differences in adaptability and force distribution within the gripper’s membrane.
This analysis offers key insights into the optimal combinations of object shapes and membrane fillings to enhance gripping reliability in adaptive robotic applications.

3.3. Characteristics of force application on the tested object

The gripping force is strongly influenced by the shape of the object being grasped. Analysis of the measured data shows that spherical objects produce the lowest gripping force, primarily due to their minimal contact area with the membrane in the perpendicular direction. In contrast, objects with geometries that allow for increased normal force application, such as cylinders and cubes, enable a significantly stronger grip. As the applied force exceeds 40 N, the membrane begins to stretch, indicating the operational limit of the adaptive system and highlighting the material constraints in sustaining higher forces.

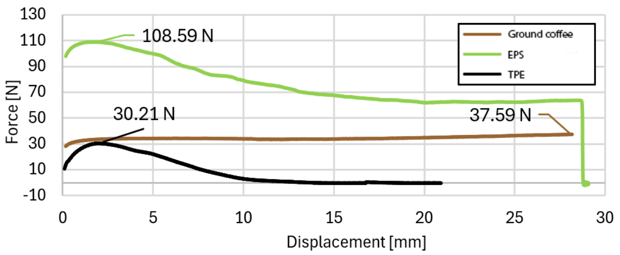

Figure 13. Force progression as a function of gripper displacement for the 50 mm cube

In experiments where the membrane was overstretched, testing was stopped early to prevent damage. This suggests that the optimal gripping force is achieved when the object has a large contact area with the membrane in a perpendicular direction. A larger contact area enhances gripping efficiency by promoting a more even distribution of force across the surface.

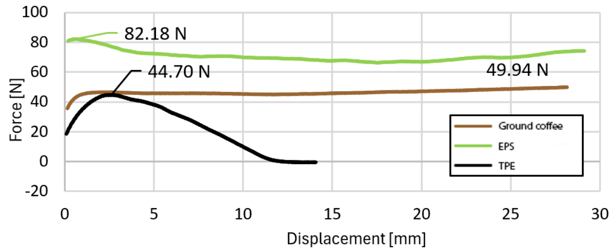

Figure 14. Force progression as a function of gripper displacement for the 75 mm cylinder

The testing of the specially designed hedgehog-shaped object aimed to determine whether its gripping force would be significantly greater than that of standard test pieces. However, the recorded measurements revealed that this particular shape consistently exhibited below-average gripping force across all types of membrane fillings. This result is likely due to the lack of form-fit gripping, which would have otherwise improved gripping performance by increasing surface contact and enhancing interlocking effects.

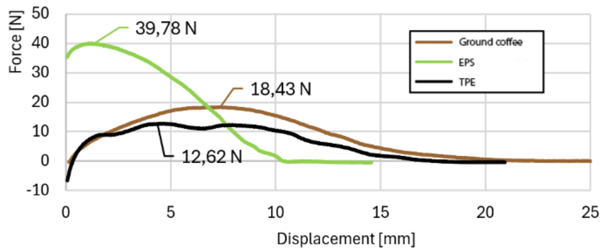

Figure 15. Force progression as a function of gripper displacement for the hedgehog

In this case, the gripping force was generated exclusively by static friction, which resulted in a smaller effective contact area compared to other tested objects. Consequently, the gripper's exerted force was limited and did not achieve the levels observed in objects that better adapted to the shape of the gripper’s membrane.

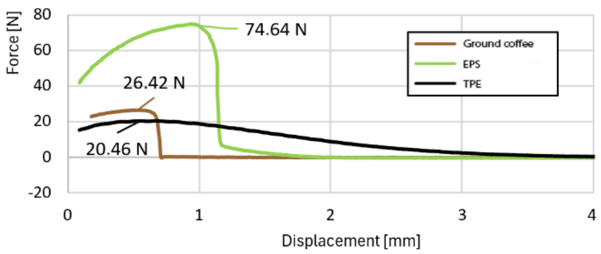

Figure 16. Force progression as a function of gripper displacement for the 50 mm sphere

When expanded polystyrene (EPS) microspheres were used as the filling material, their compression during air evacuation improved the gripping force by enhancing the membrane's shape conformity with the grasped object. This resulted in the highest gripping force among all tested fillings. However, once the force threshold was exceeded, the membrane lost its grip, causing the object to be released.

Overall, the EPS-filled gripper exhibited the strongest gripping performance under vacuum conditions, with measured forces reaching up to twice those recorded for configurations using TPE or coffee fillings. This setup provided the most effective grasp due to optimal force transmission and superior adaptability to the objects' surface irregularities. These findings highlight the importance of selecting an appropriate filling material for adaptive grippers, particularly when handling objects with complex shapes and specific physical properties.

Additionally, the adaptive gripper demonstrated the ability to effectively manipulate objects with diameters ranging from 25 mm to 100 mm. A crucial factor in achieving a secure and firm grip was the shape of the manipulated object. The most suitable geometries were those that maximized perpendicular contact with the gripper's membrane, such as cylinders and cubes. Furthermore, the shape of the object influenced the maximum load capacity, which could reach up to 3 kg under optimal conditions.

4. Conclusion

This study successfully designed, developed, and evaluated an adaptive Universal Jamming Gripper (UJG) aimed at enhancing industrial automation by offering a versatile, efficient, and reconfigurable gripping mechanism. By leveraging granular material-based gripping principles, the UJG demonstrated its ability to conform to objects of varied shapes and sizes, offering adaptability that traditional vacuum, magnetic, and fingered grippers lack. The experimental analysis provided quantitative insights into gripping forces, revealing that polystyrene microspheres (EPS) offered the highest adaptability, grip stability, and force efficiency. Additionally, the study highlighted the critical role of object geometry, as form-fit objects exhibited stronger grip forces than those relying purely on static friction.

The results reaffirm the importance of material selection and vacuum control mechanisms in designing next-generation robotic grippers for automated assembly, logistics, and material handling. The gripper's lightweight, modular design ensures compatibility with various robotic arms, further enhancing its industrial utility.

However, key challenges must be addressed before full-scale deployment. A primary concern is long-term durability, particularly membrane wear, granule compaction, and vacuum integrity. Further testing under continuous high-load and repetitive grasping conditions is needed to ensure reliability. Additionally, real-world application tests with industrial components of various materials, textures, and environmental conditions will provide insights beyond controlled laboratory settings. Developing predictive maintenance algorithms to monitor membrane integrity and vacuum efficiency could further enhance industrial viability.

Another crucial research avenue is integration with advanced robotic control systems. Implementing adaptive force control algorithms and machine learning-based grasp optimization could enable the UJG to dynamically adjust grip strength and configuration for real-time adaptive manipulation in high-speed manufacturing.

By addressing these challenges, the UJG could advance soft robotics and adaptive automation, especially in industries requiring flexibility, precision, and reliability. This study contributes to the ongoing development of intelligent robotic gripping solutions, supporting the transition to more adaptable, efficient, and sustainable automation technologies in modern manufacturing.

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