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Reconfigurable Soft Gripper Based on Eversion and Electroadhesion for Cluttered Environments

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***Abstract*— Robotic grasping in cluttered and real-world human environments is a challenging task. It requires unique kinematic capabilities to deal with spatial constraints as well as compliance and softness to offer collision safety and safe manipulation of sensitive objects. To address this challenge, we propose a novel robotic gripper with two steerable fingers whose lengths can be adjusted by way of a soft eversion mechanism. This enables the gripper to work in confined spaces while interacting safely with the environment. We also developed a new Electroadhesion (EA) pad design with a multilayer structure and a single insulating layer that can be safely integrated with the evertable fingers avoiding short-circuiting or dielectric breakdown to enhance the gripper payload. The resulting gripper can retrieve an object in a confined space and partially occluded by a barrier. It exhibits remarkable versatility in terms of object sizes, grasping objects with varying widths at least ranging from 70 mm to 600 mm. These results provide a promising avenue for new robotic applications in real-world environments.**

I. INTRODUCTION

Grasping is a crucial functionality in robotics that has positively impacted many domains, such as manufacturing, packaging, and warehousing. In recent years, there has been growing interest in expanding the use and consequent benefits of robotics to cluttered and complex environments such as in agriculture and nuclear decommissioning, as well as real-world human environments to aid us in daily tasks [1]–[3]. These new applications bring with them significant new challenges, such as the necessity for compliance, robustness to collisions, versatility in terms of object sizes and types, as well as high dexterity.

Soft robots are characterized by their intrinsic compliance and adaptability to the surrounding environment [4]. This feature has sparked an increased use of soft robots in grasping applications, as they outperform rigid grippers in their high adaptability and ability to handle unknown objects [5], [6]. Achieving versatile performance using rigid grippers is hindered by the requirement for complex control and external perception capabilities [7]. For these reasons, several soft grippers have been proposed, as they can manipulate objects of different materials, shapes, and other physical properties while offering safety during collisions in constrained environments [8], [9]. However, current soft gripper designs have a limited range and require the robotic manipulator upon which they are installed to access the cluttered workspace. Due to the form and rigid construction of most current manipulators, tasks such as grasping and retrieving objects from a cluttered space can be challenging, with associated collision risks to the robot as well as to surrounding objects in its immediate environment.

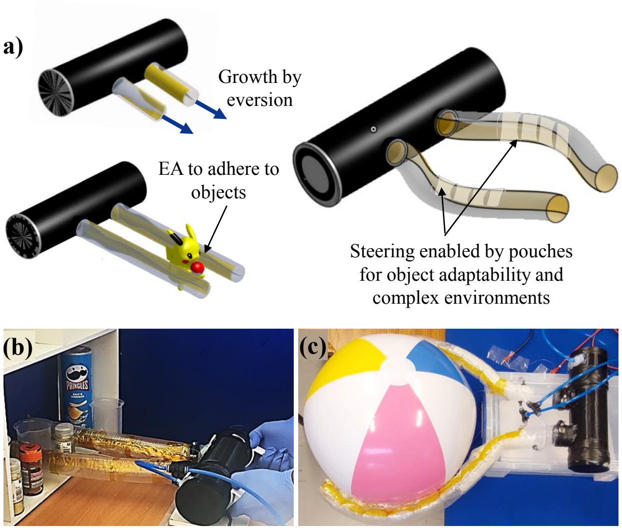

Fig. 1: (a) Conceptual schematic of the proposed gripper with variable length fingers enabled by eversion. Augmented by EA and steering capabilities, the gripper can operate in cluttered environments and adapt to different object sizes. (b) grasping a small object of 70 mm diameter in a cluttered environment, and (c) a balloon of 600 mm diameter.

Mechanisms offering the possibility of reconfiguration on demand have been used to realize grippers that can adapt their morphology to cater to different object shapes [10]. In-built kinematic mechanisms combined with reconfigurability of the gripper fingers have been employed to achieve object manipulation in confined spaces [11], [12]. Besides kinematic mechanisms related to finger orientation, changes in finger length by way of extendable fingernails (for certain specific object shapes) and a folding mechanism embedded in a finger that enables easy access to narrow working spaces have both been proposed [13], [14]. However, these grippers do not address the challenges of reaching distant objects or tackling objects of different length scales using a single grasping system. Furthermore, the folding mechanism itself is constructed from rigid materials posing collision hazards while also requiring a direct line of sight.

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In this paper, we propose a novel reconfigurable gripper with adjustable finger length based on a soft eversion mechanism and enhanced payload capability through integrated Electroadhesion (EA) as illustrated in Fig. 1a. By exploiting the high mobility offered by the eversion mechanism, the gripper can safely grasp distant objects within a cluttered environment, even when occluded by other objects as shown in Fig. 1b. Furthermore, as shown in Fig. 1c, through the integration of steerable eversion fingers whose length and shape can be independently controlled, our versatile gripper can handle objects of significantly different sizes. In summary, the key contributions of this paper are the following:

1) Integration of EA for enhanced payload capabilities of eversion based gripper through novel EA pad design suitable for eversion.
2) Development of a versatile gripper with steerable and variable-length fingers based on eversion. These features allow versatility in terms of object sizes through a single mechanism capable of grasping objects ranging from 70 mm to 600 mm in diameter as well as distant occluded objects in cluttered environments.

The rest of the paper is organized as follows. Section II discusses related works on eversion and EA, highlighting the research gaps. Section III presents the design of the reconfigurable gripper and the fabrication methods. Section IV evaluates two different EA pad designs and the effect of various design and control parameters on the performance of the gripper. The novel capabilities unleashed by the proposed gripper are demonstrated in Section V. The conclusions and future work are summarized in Section VI.

II. RELATED WORKS

Eversion robots are characterized by their ability to grow through tip extension when pressure is applied. They can therefore adapt their length, extending from centimeter scale to several meters [15]. These robots are intended for applications that require navigation in unstructured environments [16], [17]. To exploit these features in handling objects, several methods based on utilizing eversion robots as manipulators have been proposed [18]. Attaching a rigid mount or gripper to the robot's tip for object manipulation was introduced in [19], [20]. Fabric-based inflatable fingers have also been proposed to achieve grasping functions [21]. Abrar *et al.* embedded the body of an eversion robot with pneumatically actuated pouches that can contract upon application of pressure, thereby creating a curvature-based steering mechanism [22]. The pressurized central chamber acts as the robot's backbone, such that its overall stiffness can be controlled by modulating the pressure within [23]. High pressure in the central chamber helps the robot move payloads while low pressure is beneficial for exploration in unknown environments as the robot is more compliant and applies smaller forces to its environment. Similarly, while a gripper under low pressure can safely access and function in sensitive environments, the slender form factor of lengthening eversion robots leads to a reduction in payload capabilities [24].

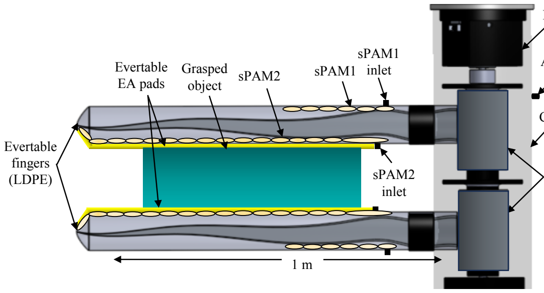
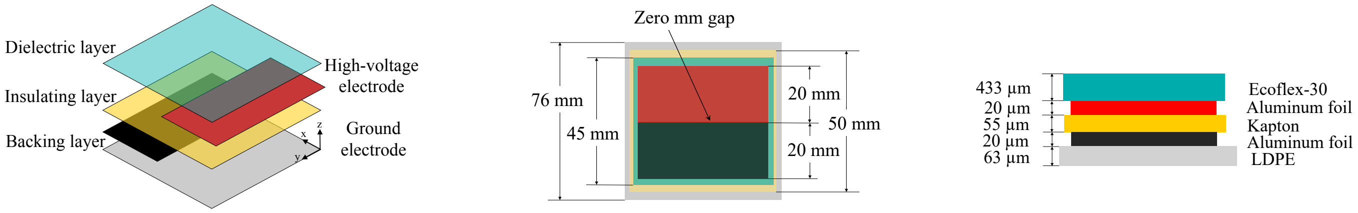


Fig. 2: Schematic showing the components of eversion gripper with steerable fingers and integrated electoadhesion

EA pads consist of two spaced electrodes encapsulated within a dielectric material. Applying a high voltage in the range of kilo-volts between these electrodes generates a strong electric field. When the EA pad is placed on the object, the electric field induces polarization in insulating materials and generates image charges in conductive materials, leading to the generation of attraction forces between the pad and the object [25]. Several studies have explored the application of EA to soft robots and grippers to achieve versatile performance and enhance payload capabilities [7], [26]–[31]. The integration between dielectric elastomer actuators and EA was proposed to handle objects of different shapes, such as flat or cylindrical objects, as well as those with different properties, such as fragile and deformable objects [7]. Based on this integration soft grippers with a high payload of up to 16.8 kg [30] and the ability to handle concave objects with proprioceptive and exteroceptive capabilities were proposed [27]. Furthermore, pneumatically actuated grippers [32] and sensors [31] were incorporated with EA pads to handle objects with complex geometries. EA pads were also embedded in other soft actuation mechanisms such as granular jamming, layer jamming, and fin structure to provide grasping functions [28], [29], [33]. EA offers opportunities to scale the payloads of grippers based on varied actuation methods. However, achieving versatility in terms of object sizes, which could help expand the applications of soft grippers to provide universal grasping capability, has not been targeted.

Real-world environments are generally characterized by the unorganized placement of objects and pose a myriad of kinematic challenges to robotic systems. A typical task such as picking a fruit from a tree or retrieving an object from a kitchen shelf poses complex challenges to the design of robotic hardware. The eversion mechanism enables growth through tip extension and offers a safe way to access constrained spaces. In addition, embedding steering capabilities further enhances a gripper's dexterity and versatility with respect to object sizes. Combining the advantages offered by the eversion mechanism along with the improvement in grasping forces offered by EA, we propose a novel soft gripper with unique access and grasping capabilities in unstructured environments.



(a) (b) (c)

Fig. 3: Proposed EA pad design with a single insulating layer between the non-planar electrodes illustrated in (a) exploded view (b) top view, and (c) side view showing layer thicknesses

III. Design and Fabrication of the Gripper

The gripper consists of a main chamber and two soft parallel fingers as shown in Fig. 2. When pressure is applied to the main chamber, the fingers evert from the tip and grow in length. Based on the size and location of the target object, the everted length of the fingers can be controlled by the motor. To maintain synchronization between the fingers, the ends of both fingers are rolled onto the same spool fixed to the motor shaft. Additionally, an evertable EA pad is fitted to the wall of each fully everted finger such that the pads face each other. This allows for contact between the EA pads and the object lodged between the fingers, enhancing the payload capability of the gripper.

Additionally, each of the eversion fingers is embedded with two sets of contractile actuators based on pneumatic pouches to provide steering and adaptability functions. These contractile actuators, originally termed series Pneumatic Artificial Muscles (sPAM) [34], contract in length when pressurized providing the required bending angle, Further elaboration on the sPAMs is provided in Section V.

A. Pressure Chamber and Eversion Fingers

The main chamber of the gripper is an airtight, hollow cylindrical tube of diameter 80 mm and width 280 mm. The chamber is 3D printed as three separate parts - one is a longer central cylindrical section while the other two are shorter forming the two end caps. The chamber has two cylindrical pipes projecting out of it which act as the attachment points for the eversion fingers (Fig. 2). A stepper motor is firmly attached to one of the end caps with the motor shaft placed along the symmetric axis of the cylinder. A 3D-printed structure with two spool holders is firmly attached to the motor shaft using a shaft coupler.

The eversion fingers are fabricated from off-the-shelf tubular sheets made from Low-Density Polyethylene (LDPE) and are of 76 mm in width and 63 μm in thickness. One end of a tubular sheet is mounted on the cylindrical tube using a metal clamp, forming the base of the finger. The other end is folded inwards, drawn inside the cylindrical chamber, and attached to one spool holder. The spool is then rotated using the motor to load the finger material onto the spool. The outer chamber has a narrow pneumatic inlet which is connected to the output of a pneumatic valve. The wires of the electric stepper motor are drawn out of the chamber through a tiny hole which is sealed using hot glue. Once the fingers are assembled, the end caps are attached to the larger cylindrical section housing the spool, using a tolerance fit. The interface is made airtight using hot glue and tape.

When air pressure is applied through the pneumatic inlet, it creates an eversion pressure in the fingers. The motor controls the length of both fingers by controlling the rotation of the spool and also supports the retraction of the fingers after object retrieval. These evertable fingers endow the gripper with the ability to operate in an unstructured environment while ensuring safe interactions with its surroundings. To achieve versatile performance in terms of object sizes and reach objects at different distances, the length of fingers is controlled. Moreover, the fingers are equipped with EA pads to increase the grasping forces. The use of EA pads provides additional versatility in terms of objects' shapes and materials, therefore, they can be utilized to manipulate fragile objects. Under these circumstances, high stiffness is not desirable, and so the pressure applied to the eversion fingers can be reduced.

B. Integration of EA into Eversion Fingers

To integrate the EA pads into the eversion fingers, we identified a key requirement. The fingers with EA pads need to be able to evert and retract safely without short-circuiting the electrodes or causing dielectric breakdown. With this in mind, we developed a new multilayer structure for the EA pads with a single insulating layer as shown in Fig. 3a. The layered design places the positive and ground electrodes on different planes with a high breakdown strength dielectric layer separating the planes. This structure gives increased yield in fabrication and provides resistance to short-circuits or electrical breakdown [35]. A bi-layer structure with dual insulation was proposed in [36]. However, this structure decreases the EA forces compared to the single layer under the same applied voltage. Additionally, while double insulation allows for the application of higher voltage, practically this capability will be limited by the dielectric strength of the insulating material.

Our proposed pad design has a single insulating layer separating the two electrodes in the direction perpendicular to the layer planes (i.e. z direction) while there is no gap (zero-gap) between the electrodes in the x direction in the top view as shown in Fig. 3b. As the electric field between two conductive layers increases with reduction in distance, this design allows us to achieve a high electric field, so as to generate high EA force, while at the same time simplifying fabrication and providing protection against short-circuiting the system. Section IV evaluates this design in comparison with a traditional EA pad design that houses both electrodes in the same plane.

The width of the EA pads attached to the fingers affects the pressure required for eversion. We set the width of the EA pad to be 65% of the finger width to allow smooth eversion and retraction. Due to the shape of the fingers when inflated, increasing the width of the EA pad would not increase the contact area of the EA pad with the object to be grasped.

The tubular fingers made of LDPE act as the backing layer for the EA pads. On the top of each finger, the evertable EA pads are fabricated as follows. First, aluminum foil is attached to the LDPE layer to form the ground electrode. A Kapton film of 55 μm thickness is used as the dielectric material to separate the non-planar electrodes and is attached over the first electrode layer (Fig. 3c). It has a high dielectric strength of over 200 MV/m. A second layer of aluminum foil acting as the positive electrode is attached over the Kapton film, adjacent to the bottom electrode. An Ecoflex 0030 layer (433 ± 85 μm) fabricated in the lab is then attached to the top of the electrodes while a Kapton film is attached all along the boundaries of the Ecoflex layer.

IV. EA PADS AND GRIPPER PERFORMANCE CHARACTERIZATION

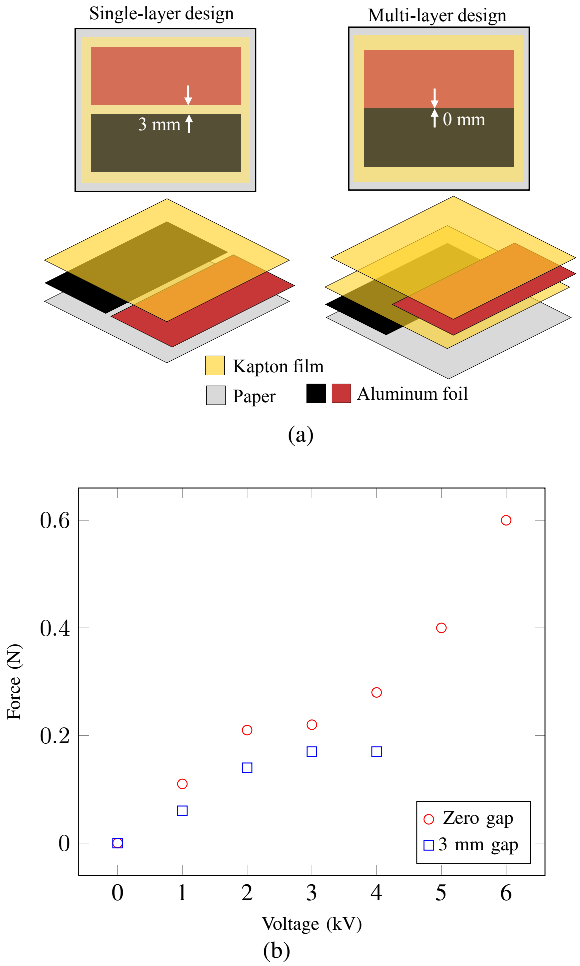
A. *Proposed EA Pad Design Evaluation*

The generated EA force is known to have a quadratic relation with the applied voltage [30]. However, experimentally, this relation is valid only within certain ranges [37], and other practical factors may affect the generated force, such as the backing layer thickness [38]. Therefore, to characterize the performance of the proposed design, the generated normal force at different voltages is measured, and the average of three readings is used for each data point. A 16 cm^2 pad, weighing 0.6 grams, was created with paper as the dielectric layer, aluminum foil for electrodes, and Kapton for the backing and insulating layers. Additionally, the performance of this structure is compared with a single-layer design of 3 mm gap (Fig. 4a).

As shown in Fig. 4b, the proposed design outperforms the single layer design with a 3 mm gap, generating higher forces for the same applied voltage and withstanding higher voltages. For example, at 4 kV, the multilayer structure generates 0.28 N compared to 0.17 N for the single layer. Additionally, it can withstand a higher voltage of 6 kV, resulting in a force increase of more than double, whereas the single-layer design can only withstand 4 kV.

B. *Performance Characterization of the Proposed Gripper*

To characterize the performance of the proposed gripper, a pull-off test is conducted to study the effect of two factors: pressure and length on grasping force. This test indicates the practical capabilities of the gripper and provides a context for comparison with grippers developed in other research [39]. To perform this test, the fingers grasped a 7 cm diameter cylinder, and then the force required to pull off this object was measured using a load cell attached to a motorized linear actuator as shown in Fig. 5. Two cases are assessed: gripper based on eversion only and gripper based on the integration of eversion and EA. In all tests, the EA pads are actuated with 5 kV and the average of three measurements is considered.



(a)

(b)

Fig. 4: EA pads performance characterization (a) structure of single-layer pad with 3 mm gap and proposed multilayer pad with zero mm gap (b) measured normal forces of each design at different voltages

The applied pressure plays an important role in the grasping process as it affects the stiffness of the fingers which directly impacts the grasping forces. To study this effect, different pressure values ranging from zero to 15 kPa were applied. The results in Fig. 6 show that as the pressure increases, the grasping forces increase linearly in the range between 3-15 kPa for both cases - with and without EA. Furthermore, an almost constant difference of 1.6 N between the two curves is noticed which can be attributed to the EA forces. Additionally, it can be concluded that in this range, the pressure variations do not affect the EA forces. At 0 kPa the EA forces were sufficient to grasp the object. Therefore when a high grasping force is needed, the pressure can be increased and when manipulating fragile or sensitive objects,

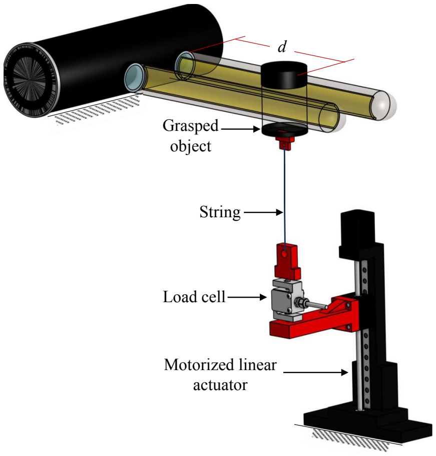


Fig. 5: Experimental setup of pull-off test to characterize the effect of finger length and pressure on the grasping force

the pressure can be decreased and grasping functionality can still be achieved using EA.

In another experiment, we investigated the effect of the length of everted fingers on the grasping forces. The pressure was fixed at 15 kPa and the cylinder was placed at different distances, *d*, as shown in Fig. 5. The maximum length considered in this experiment was 54 cm. According to Fig. 7, the grasping forces decrease gradually with increase in length. The maximum length at which the object can be grasped without EA was 38 cm. With EA pads attached, the gripper was able to hold the object over the entire length of 54 cm. It is also worth noting that in this experiment the same cylinder was placed at different eversion lengths which means the contact area between the object and the EA pads was constant. However, it is expected that when the finger lengths are adapted based on object size, larger objects will naturally form a larger contact area between themselves and the EA pad, leading to higher resultant EA forces which helps to achieve versatility in terms of object sizes.

V. APPLICATION AND DEMONSTRATION

A. *Grasping in a Cluttered Environment*

We created a mock setup of a kitchen shelf with various objects arranged inside the shelf to simulate a cluttered environment (Fig. 8). The target object to be retrieved is an empty plastic beaker weighing 36 g and 7cm in diameter. It is placed behind a spice bottle made of glass. The shelf has a relatively low height of 28.5 cm and has a closed top which makes it difficult for a standard robotic manipulator to retrieve the target object without rearranging the other objects.

We utilize our eversion gripper with parallel fingers to conduct the grasping and retrieval task (Fig. 8a-d). The gripper is first positioned such that the centre of the fingers is aligned with the centre of the beaker. The air chamber is pressurized making the fingers evert, allowing them to reach the target object (Fig. 8b-c). When the fingers make contact with the object, they extend further around the object. The EA pads are activated with a voltage of 5 kV to achieve a firm grip on the object. The gripper is then lifted up and moved away from the shelf to retrieve the target object from its position completing the required manipulation as shown in Fig. 8d.

B. *Steerable Eversion Fingers for Grasping Objects of Different Sizes*

We now exploit the ability of the gripper fingers to change in length to grasp objects of different sizes and shapes by embedding the sPAM actuators and incorporating steerability to the fingers. The pouches are encapsulated on the inner side of the eversion structure so that when they are pneumatically actuated, their contraction does not affect the contact area between the EA pad and the object as shown in Fig. 2. The sPAMs are actuated via specially designed inlets which allow decoupling the actuation of the pouches from the main body and allowing the control of each set of pouches separately. When a set of these pouches is attached to the body of the eversion tube, it contracts when actuated and causes bending

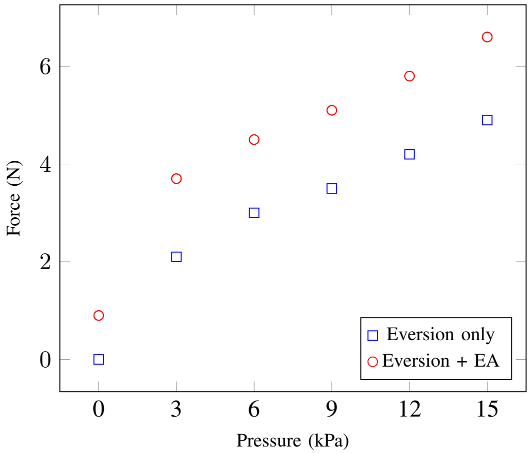


Fig. 6: Effect of pressure on grasping forces. Force increases linearly with pressure. The EA forces are independent of the pressure between 3 and 15 kPa.

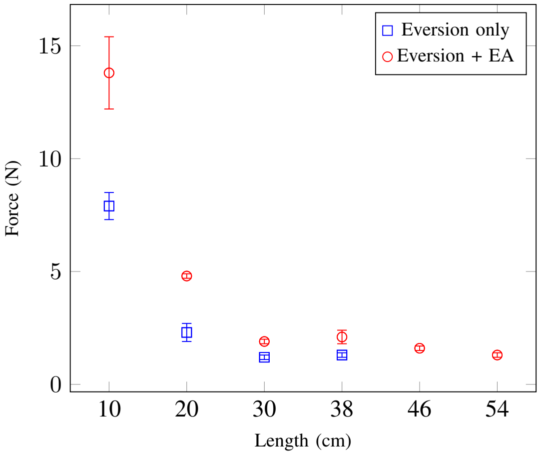


Fig. 7: Effect of the length of fingers on grasping forces. As the length increases, the force decreases with eversion gripper failing at 38 cm. Gripper with integrated EA can grasp the object over the entire range considered.

towards the side on which they are attached. The first set of two pouch actuators, sPAM1, is attached inside the eversion tube close to the base of the fingers on the peripheral side of the wall (Fig. 9b). The second set of pouch actuators, sPAM2 is attached along the entire tube on the wall facing the centre of the gripper (Fig. 9e).

We first conduct the grasping of an inflated plastic balloon of diameter 600 mm and weighing 130 grams (Fig. 9). To achieve this, we apply a very low pressure to the central chamber and apply a higher pressure to the actuators sPAM1. This causes the fingers to bend outwards (Fig. 9b). The gripper is moved forward to engage the balloon in contact with the two fingers. Now, the pressure in the central eversion chamber is increased which will cause the fingers to grow in length and the pressure in sPAM1 is decreased (Fig. 9d). Then the pressure in sPAM2 is increased making the gripper engulf the balloon at which point the supporting plank underneath the balloon is removed (Fig. 9e-f).

To further demonstrate the versatility of this gripper in grasping objects of different sizes, we conduct grasping of a soft toy of 120 mm width and weighing 175 grams (Fig. 10). We first apply a very low pressure to the central chamber and a higher pressure to the actuators sPAM1 causing the fingers to bend outwards (Fig. 10a). Now, the pressure in the central eversion chamber is increased and the fingers grow in length making contact with the target object (Fig. 10b). The pressure in sPAM1 is then decreased making the fingers elongate and engulf the target object (Fig. 10c). Finally, the supporting plank underneath the toy is removed demonstrating the stable grasp of the target object (Fig. 10d). These two experiments demonstrate that the growth and steering capability of the eversion gripper is key to its ability to grasp objects of widely differing sizes. Planning and control of steering to navigate and grasp different objects in cluttered environments is an interesting subject that deserves further investigation.

VI. CONCLUSIONS

In conclusion, this paper presents a novel reconfigurable gripper based on eversion and enhanced by EA. This innovative eversion-based design offers remarkable gripper capabilities, including retrieving occluded objects closely surrounded by other objects and grasping objects of varying sizes. We introduced the integration between eversion and EA technologies to tackle the challenge of payload capabilities in slender eversion structures. The effect of eversion pressure and length on grasping forces and EA forces have been studied. Our new EA pad design with positive and negative electrodes arranged in different planes with a single insulating layer enhances EA forces by more than 100%. Future work involves miniaturizing the gripper design and integrating it into a mobile robotic manipulator for grasping in terrestrial environments.

VII. ACKNOWLEDGEMENTS

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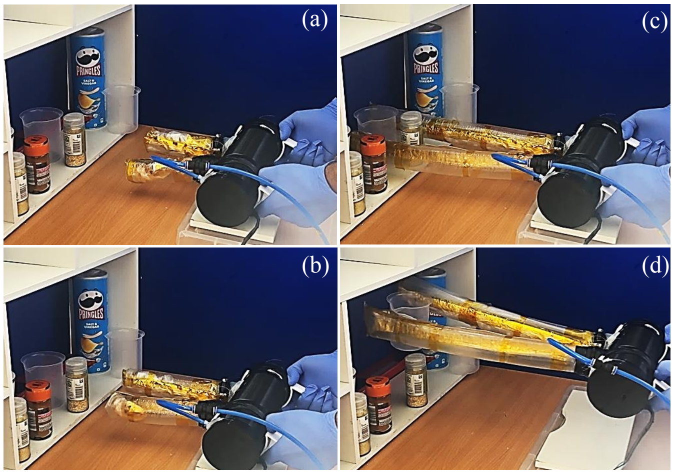

Fig. 8: Demonstration of object grasping and retrieval in a cluttered environment using the eversion gripper. (a) Initial configuration, (b) 40% eversion, (c) full eversion and object grasp, and (d) object being retrieved

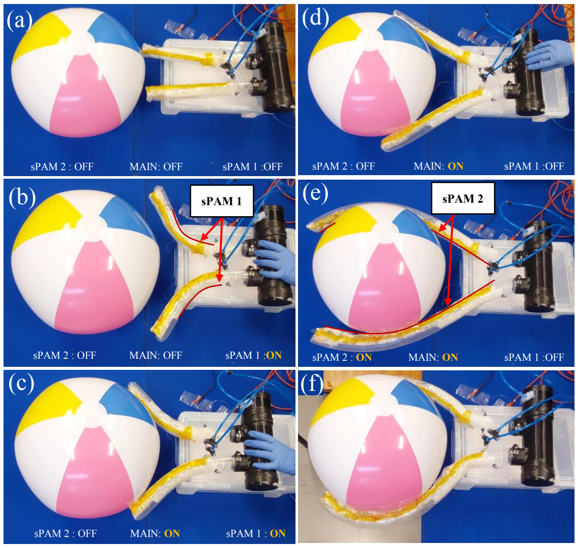

Fig. 9: Grasping of a large object of 600 mm diameter by the gripper integrated with sPAM actuators. Sequence of actions: (a)No pressure applied, (b) pressure applied to sPAM1 and the gripper open, (c) main chamber and sPAM1 activated simultaneously to adjust grasping pose,(d) only main chamber activated to achieve full eversion,(e) both main and sPAM2 are activated to encapsulate the object, and (f) object grasped.

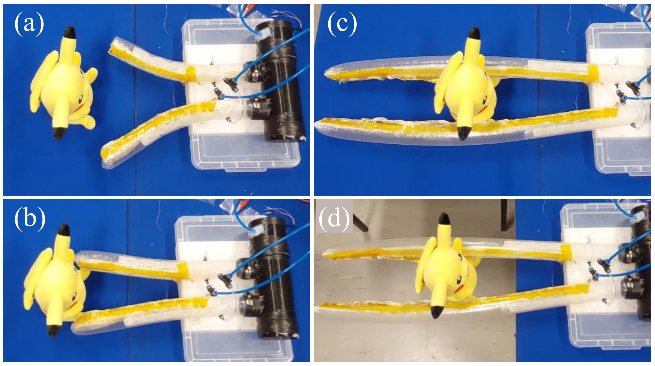

Fig. 10: Grasping sequence of a plush toy of 120 mm width

REFERENCES

[1] 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, p. 105694, 2020.

[2] I. Vitanov, I. Farkhatdinov, B. Denoun, F. Palermo, A. Otaran, J. Brown, B. Omarali, T. Abrar, M. Hansard, C. Oh, *et al.*, "A suite of robotic solutions for nuclear waste decommissioning," *Robotics*, vol. 10, no. 4, p. 112, 2021.

[3] N. Correll, K. E. Bekris, D. Berenson, O. Brock, A. Causo, K. Hauser, K. Okada, A. Rodriguez, J. M. Romano, and P. R. Wurman, "Analysis and observations from the first amazon picking challenge," *IEEE Transactions on Automation Science and Engineering*, vol. 15, no. 1, pp. 172–188, 2016.

[4] M. Wehner, R. L. Truby, D. J. Fitzgerald, B. Mosadegh, G. M. Whitesides, J. A. Lewis, and R. J. Wood, "An integrated design and fabrication strategy for entirely soft, autonomous robots," *nature*, vol. 536, no. 7617, pp. 451–455, 2016.

[5] D. Rus and M. T. Tolley, "Design, fabrication and control of soft robots," *Nature*, vol. 521, no. 7553, pp. 467–475, 2015.

[6] C. Laschi, B. Mazzolai, and M. Cianchetti, "Soft robotics: Technologies and systems pushing the boundaries of robot abilities," *Science robotics*, vol. 1, no. 1, p. eaah3690, 2016.

[7] J. Shintake, S. Rosset, B. Schubert, D. Floreano, and H. Shea, "Versatile soft grippers with intrinsic electroadhesion based on multifunctional polymer actuators," *Advanced materials*, vol. 28, no. 2, pp. 231–238, 2016.

[8] R. Deimel and O. Brock, "A novel type of compliant and underactuated robotic hand for dexterous grasping," *The International Journal of Robotics Research*, vol. 35, no. 1-3, pp. 161–185, 2016.

[9] H. Godaba, A. Sajad, N. Patel, K. Althoefer, and K. Zhang, "A two-fingered robot gripper with variable stiffness flexure hinges based on shape morphing," in *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 8716–8721, IEEE, 2020.

[10] J. H. Low, P. M. Khin, Q. Q. Han, H. Yao, Y. S. Teoh, Y. Zeng, S. Li, J. Liu, Z. Liu, P. Valdivia y Alvarado, I.-M. Chen, B. C. K. Tee, and R. C. H. Yeow, "Sensorized reconfigurable soft robotic gripper system for automated food handling," *IEEE/ASME Transactions on Mechatronics*, vol. 27, no. 5, pp. 3232–3243, 2022.

[11] A. Pagoli, F. Chapelle, J. A. Corrales, Y. Mezouar, and Y. Lapusta, "A soft robotic gripper with an active palm and reconfigurable fingers for fully dexterous in-hand manipulation," *IEEE Robotics and Automation Letters*, vol. 6, no. 4, pp. 7706–7713, 2021.

[12] A. Hassan, T. Abrar, F. Aljaber, I. Vitanov, and K. Althoefer, "Eversion-capable fabric robot gripper with novel retraction mechanism," in *2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 10232–10237, 2023.

[13] S. Jain, T. Stalin, V. Subramaniam, J. Agarwal, and P. V. y Alvarado, "A soft gripper with retractable nails for advanced grasping and manipulation," in *2020 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 6928–6934, 2020.

[14] T. Nishimura, T. Muryoe, Y. Asama, H. Ikeuchi, R. Toshima, and T. Watanabe, "Single-fingered reconfigurable robotic gripper with a folding mechanism for narrow working spaces," *IEEE Robotics and Automation Letters*, vol. 7, no. 4, pp. 10192–10199, 2022.

[15] E. W. Hawkes, L. H. Blumenschein, J. D. Greer, and A. M. Okamura, "A soft robot that navigates its environment through growth," *Science Robotics*, vol. 2, no. 8, p. eaan3028, 2017.

[16] M. M. Coad, L. H. Blumenschein, S. Cutler, J. A. R. Zepeda, N. D. Naclerio, H. El-Hussieny, U. Mehmood, J.-H. Ryu, E. W. Hawkes, and A. M. Okamura, "Vine robots," *IEEE Robotics & Automation Magazine*, vol. 27, no. 3, pp. 120–132, 2019.

[17] D. Mishima, T. Aoki, and S. Hirose, "Development of a pneumatically controlled expandable arm for rescue searches in tight spaces," *The International Journal of Robotics Research*, vol. 25, no. 1, pp. 103–110, 2006.

[18] L. H. Blumenschein, M. M. Coad, D. A. Haggerty, A. M. Okamura, and E. W. Hawkes, "Design, modeling, control, and application of everting vine robots," *Frontiers in Robotics and AI*, vol. 7, p. 548266, 2020.

[19] S.-G. Jeong, M. M. Coad, L. H. Blumenschein, M. Luo, U. Mehmood, J. H. Kim, A. M. Okamura, and J.-H. Ryu, "A tip mount for transporting sensors and tools using soft growing robots," in *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 8781–8788, IEEE, 2020.

[20] F. Stroppa, M. Luo, K. Yoshida, M. M. Coad, L. H. Blumenschein, and A. M. Okamura, "Human interface for teleoperated object manipulation with a soft growing robot," in *2020 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 726–732, IEEE, 2020.

[21] F. Aljaber, A. Hassan, T. Abrar, I. Vitanov, and K. Althoefer, "Soft inflatable fingers: An overview of design, prototyping and sensorisation for various applications," in *2023 IEEE International Conference on Soft Robotics (RoboSoft)*, pp. 1–6, IEEE, 2023.

[22] T. Abrar, F. Putzu, A. Ataka, H. Godaba, and K. Althoefer, "Highly manoeuvrable eversion robot based on fusion of function with structure," in *2021 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 12089–12096, 2021.

[23] A. Ataka, T. Abrar, F. Putzu, H. Godaba, and K. Althoefer, "Model-based pose control of inflatable eversion robot with variable stiffness," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 3398–3405, 2020.

[24] H. Godaba, F. Putzu, T. Abrar, J. Konstantinova, and K. Althoefer, "Payload capabilities and operational limits of eversion robots," in *Towards Autonomous Robotic Systems: 20th Annual Conference, TAROS 2019, London, UK, July 3–5, 2019, Proceedings, Part II 20*, pp. 383–394, Springer, 2019.

[25] J. Guo, J. Leng, and J. Rossiter, "Electroadhesion technologies for robotics: A comprehensive review," *IEEE Transactions on Robotics*, vol. 36, no. 2, pp. 313–327, 2019.

[26] J. Guo, K. Elgeneidy, C. Xiang, N. Lohse, L. Justham, and J. Rossiter, "Soft pneumatic grippers embedded with stretchable electroadhesion," *Smart Materials and Structures*, vol. 27, no. 5, p. 055006, 2018.

[27] J. Guo, C. Xiang, and J. Rossiter, "A soft and shape-adaptive electroadhesive composite gripper with proprioceptive and exteroceptive capabilities," *Materials & Design*, vol. 156, pp. 586–587, 2018.

[28] Y. Piskarev, A. Devincenti, V. Ramachandran, P.-E. Bourban, M. D. Dickey, J. Shintake, and D. Floreano, "A soft gripper with granular jamming and electroadhesive properties," *Advanced Intelligent Systems*, p. 2200409, 2023.

[29] R. Chen, R. Song, Z. Zhang, L. Bai, F. Liu, P. Jiang, D. Sindersberger, G. J. Monkman, and J. Guo, "Bio-inspired shape-adaptive soft robotic grippers augmented with electroadhesion functionality," *Soft robotics*, vol. 6, no. 6, pp. 701–712, 2019.

[30] G. Hwang, J. Park, D. S. D. Cortes, K. Hyeon, and K.-U. Kyung, "Electroadhesion-based high-payload soft gripper with mechanically strengthened structure," *IEEE Transactions on Industrial Electronics*, vol. 69, no. 1, pp. 642–651, 2021.

[31] C. Xiang, J. Guo, and J. Rossiter, "Soft-smart robotic end effectors with sensing, actuation, and gripping capabilities," *Smart Materials and Structures*, vol. 28, no. 5, p. 055034, 2019.

[32] G. Gu, J. Zou, R. Zhao, X. Zhao, and X. Zhu, "Soft wall-climbing robots," *Science Robotics*, vol. 3, no. 25, p. eaat2874, 2018.

[33] R. Chen, Z. Zhang, J. Guo, F. Liu, J. Leng, and J. Rossiter, "Variable stiffness electroadhesion and compliant electroadhesive grippers," *Soft Robotics*, vol. 9, no. 6, pp. 1074–1082, 2022.

[34] R. Niiyama, X. Sun, C. Sung, B. An, D. Rus, and S. Kim, "Pouch motors: Printable soft actuators integrated with computational design," *Soft Robotics*, vol. 2, no. 2, pp. 59–70, 2015.

[35] M. Dadkhah, D. Ruffatto III, Z. Zhao, and M. Spenko, "Increasing adhesion via a new electrode design and improved manufacturing in electrostatic/microstructured adhesives," *Journal of Electrostatics*, vol. 91, pp. 48–55, 2018.

[36] Y.-J. Jeong, T.-H. Hong, H.-J. Lee, and K. Kim, "Optimal design of the electroadhesion pad with a dual-insulating layer for climbing robots," *Actuators*, vol. 11, no. 2, 2022.

[37] J. Guo, T. Bamber, J. Petzing, L. Justham, and M. Jackson, "Experimental study of relationship between interfacial electroadhesive force and applied voltage for different substrate materials," *Applied Physics Letters*, vol. 110, no. 5, 2017.

[38] A. S. Chen and S. Bergbreiter, "A comparison of critical shear force in low-voltage, all-polymer electroadhesives to a basic friction model," *Smart Materials and Structures*, vol. 26, no. 2, p. 025028, 2017.

[39] Z. Yoder, D. Macari, G. Kleinwaks, I. Schmidt, E. Acome, and C. Keplinger, "A soft, fast and versatile electrohydraulic gripper with capacitive object size detection (adv. funct. mater. 3/2023)," *Advanced Functional Materials*, vol. 33, no. 3, p. 2370018, 2023.