Increasing the Holding Force of Non-Rigid Materials Through Robot End-Effector Reorientation

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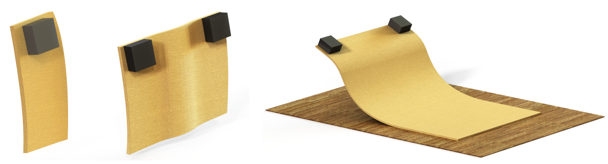
***Abstract*— While manipulation for rigid objects in the context of automated manufacturing processes has been well studied, there are few examples in the literature for how to handle non-rigid objects in an automated fashion. A significant control problem that arises when manipulating non-rigid objects (e.g., films and fabrics) with existing pneumatic grippers is both the inherent deformation of the object during grasp, as well as changes in the object's center of mass. To solve those problems, we introduce an approach to reorient pneumatic gripping devices during vertical movements and present results on the influence of reorienting a gripping device on the holding force for several non-rigid objects. We show that holding force increases with an increase in the orientation angle due to both reduction of depressurization within the suction cup, as well as the ability to leverage friction forces between the object and the gripper. This study is the first step towards future work in real-time robotic controlled reorientation during dexterous manipulation of non-rigid objects.**

I. Introduction

Advances in manufacturing technologies for non-rigid objects, particularly in fields related to textiles, paper, leather, and films are critically important to enable complex manipulation processes that go beyond the planar approaches of today. Grasping and manipulating non-rigid objects, such as these, often poses challenges in automation [1]–[3] due to the fact that during gripping, it is very difficult to predict the influence of object parameters on deformation, frictional properties, and holding force [4]–[6]. As such, the robotics research community has taken strong interest in developing structuring methods for manipulation [7]–[9], designing novel gripping devices [10]–[20], and proposing new concepts on manipulating of non-rigid objects [21]–[25].

Textiles and films of various thicknesses remain some of the most challenging materials to control during automation [26]. These materials easily deform, losing their shape under the force of their own weight, making gripping and manipulating the materials a significant control challenge. However, almost all household robotics tasks include the manipulation of flexible and soft objects, one of the scientific groups focuses specifically on the manipulation of textile (clothing) objects [8], [10], [27]. They proposed a classification of possible methods of manipulation [8] and grasping [28] of non-rigid objects. However, the proposed classification [8] is not complete because the option of grasping with a planar external contact by the edge of the object, or several planar external contacts from one edge is not taken into account (Fig. 2). What prevents the effective use of pneumatic gripping devices for grasping and manipulating non-rigid objects.

Fig. 1: Holding various flexible objects during manipulation using a 90 degree orientation for the gripping device, with a supply pressure of 300 kPa for the vest and 100 kPa for a piece of textile.



(a) (b)

Fig. 2: Methods of manipulating non-rigid objects that are not taken into account in previous studies: (a) planar external contacts with one and two grippers; (b) planar external contacts and holding plane with two grippers.

This situation often occurs in production and in everyday life when the robot is able to grasp the object from only one edge. There may be several reasons why the robot can only do just that: the serviced equipment has overhanging elements that prevent the robot from gripping more of the object; the object of manipulation is much larger than the working area of the robot.

Often, cases arise when it is only possible to grab a non-rigid object from one side [29]. To solve this problem, the authors of [29] proposed a dexterous method of manipulation using electroadhesive fingers. However, various types of

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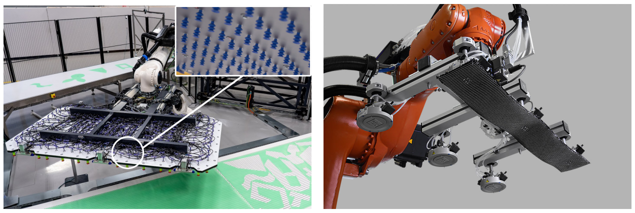

(a) (b)

Fig. 3: Gripping systems for non-rigid materials: (a) – commercially available vacuum system for grasping flexible objects [32], (b) – gripping system is based on the commercially available combined Schmalz Bernoulli-needles grippers [33].

pneumatic gripping devices [30], [31] are often used in production, but they act on a flattened surface of non-rigid material and create a vacuum or air suction to hold objects. The reason for using pneumatic grippers is easier control of the force, the possibility of separating the object from others when placing it in a stack, which is often found in production. However, their biggest drawback is the impossibility of partially grabbing a flexible object by the edge and further manipulation. Which is caused by the loss of rarefaction and depressurization of the suction cup due to the deformation of the flexible object or its porosity. That is why, now pneumatic technologies are used only in cases where the non-rigid object is attracted over its entire surface (Fig. 3a) [32], evenly distributed points, or combined grippers (Fig. 3b) [33] that can damage the object [34].

Therefore, it is an urgent task to provide an effective method of manipulating non-rigid objects with a pneumatic gripping device. Therefore, in this article, for the first time, is proposed to use a pneumatic gripping device with reorientation to increase the holding force of non-rigid materials (Fig. 1) in robotic cells. This allows us to draw conclusions regarding the effectiveness of using reorientation of pneumatic grippers for the manipulation of non-rigid materials and describe the next steps of research to achieve dexterous manipulation.

II. Methodology

In this section, we first discuss the problems of using pneumatic grippers when grabbing non-rigid objects by one edge and next present the method of reorientation to solve the problems.

A. Challenges for Pneumatic Grippers

When planning an application manipulation of non-rigid objects, the first stage is grasping, followed by lifting, then transportation/manipulation and release. Normally, pneumatic gripping devices are not used for gripping non-rigid objects such as textiles. This is due to the fact that a vacuum gripper, such as a suction cup, will depressurize due to the porosity of the material, which will cause the object to fail to grip and fall. Recently, pneumatic gripping devices have begun to appear, which allow the grasping of porous objects [16], [17]. However, for all pneumatic grippers, the lifting stage is the most difficult. Many problems arise when lifting

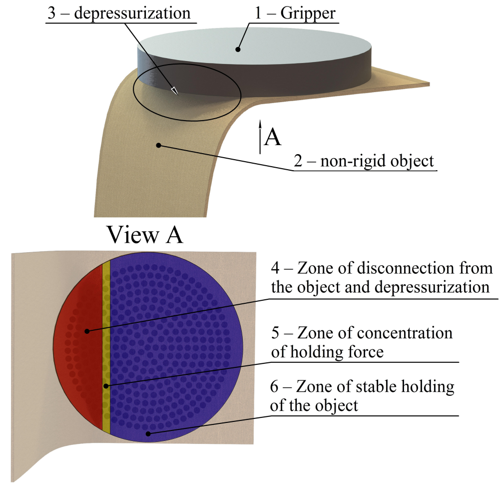

Fig. 4: Problems arising when manipulating non-rigid objects.

non-rigid objects by their edge, as shown in an example of using a pneumatic gripper (Fig. 4, label 1), which is related to the displacement of the center of mass of the non-rigid object during gradual lifting (Fig. 4, label 2). This complex problem depends on the type of pneumatic gripper [30] and the type of contact it forms.

In almost all cases, there is a problem with depressurization of the pneumatic gripper (Fig. 4, label 3), regardless of how the vacuum is formed. When the center of mass is shifted, the non-rigid object of manipulation is deformed on the edge of the gripper (Fig. 4, label 2). As a result, the total forces acting on the overhanging part of the object will act only on the edge of the plane of the gripper (Fig. 4, label 5), which continues to hold the object. This small contact area is not able to hold the hanging portion of the object, which causes separation of the object from the edge of the gripper (Fig. 4, label 4) and its depressurization (Fig. 4, label 3). In grippers, such as suction cups, the separation becomes a failure due to depressurization, while some novel pneumatic grippers [30] have been designed to avoid depressurization, they still suffer from a loss of sufficient holding force.

B. Reorientation

To ensure continuous manipulation and maximum holding force of non-rigid objects, our method changes the orientation of the gripping device to avoid depressurization of the suction cup and uses additional forces arising when the orientation of the gripping device is changed. The research uses a gripping device for non-rigid and porous objects [16], which has a plane contact type.

To study the influence of the change in the orientation angle α on the holding force of non-rigid materials F_h during the vertical movement of the gripper, an experimental setup was developed as shown in Fig. 5, and a scheme of its operation is presented in Fig. 6. From which it can be determined that the holding force is equal to $F_h = F_l \cos\alpha + F_f \sin\alpha$.

The experimental setup (Fig. 5) consists of an ABB IRB-120 industrial robot, to which a gripping device [16] is

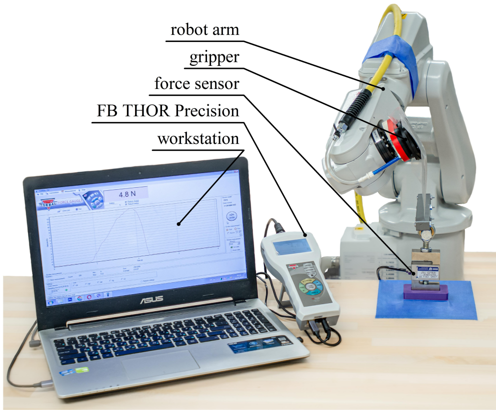

Fig. 5: An experimental setup for determining the holding force of non-rigid materials at different orientations of the gripping device.

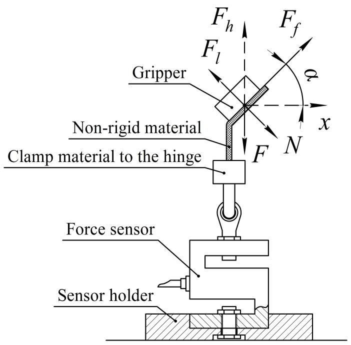

Fig. 6: Scheme of the experimental setup for determining the holding force of non-rigid materials at different orientations of the gripping device: (F_h - holding force, F_l - lifting force, F_f - friction force, α - orientation angle, N - normal reaction arising from the lifting of the material to the gripper).

attached via an adapter, a computer with RobotStudio [35] and Torbal FM [36] software. The IRC5 robot controller and FB THOR Precision force measuring device with an accuracy of ±0.2 percent (Serial No. F12010001252) are connected to the computer workstation. The scheme of the experimental setup in Fig. 6 shows: elements of holding the sensor, the sensor, the clamp of the non-rigid material on the hinge, and the forces acting on the non-rigid material during the vertical movement of the gripper. Each tested material has the same dimensions of 250x150 mm, and 50 mm in length is used for clamping.

III. Materials

To conduct a study of the influence of the orientation of the gripping device on the holding force of non-rigid objects, the following material parameters are important: the coefficient of friction between the material and the contact plane of the gripper k; the lifting force F_l is formed by the gripper with the object of manipulation, which is affected by the porosity of the object.

The coefficient of friction between the material and the gripper contact plane can be calculated using the method proposed in [37]. The technique is that the gripping device is oriented in a horizontal plane with the plane of contact up. The object of manipulation is placed on the gripping device in the middle. In our case, due to the low weight and flexibility of the materials, the object is stuck to a rectangular piece of glass and then lies on the surface of the gripper. After that, the orientation angle of the gripping device $\beta = 180 - \alpha$ changes from 0 degrees (horizontal orientation) until the moment the object begins to slide. The experiment is repeated 10 times, the average value of the angle of the beginning of sliding $\bar{\beta}$ and the coefficient of friction are determined by the equation $k = tan(\bar{\beta})$. A summary Table I of the results of measuring the coefficient of friction between materials and gripping device is presented.

TABLE I: Characteristics of the Studied Materials.

№	Type of material	Coefficient of friction	Lifting force [N]
1	film	0.19	2.20
2	woven	0.40	1.20
3	flannel	0.37	1.23
4	polyester	0.29	1.00
5	poplin	0.33	0.55
6	polyester	0.34	0.4
7	satin	0.39	0.38

All materials except number 1 in Table I are textile materials. Material number 1 is a film used in the packaging of finished products: mass 0.0047 g/cm^2, thickness 0.05 mm. The microscopy (Keyence VHX-70000) of each researched material can be found at the [38] link. The lifting force of each of the tested materials is determined by the same method proposed in the paper [16]. The obtained results of maximum lifting force are entered in Table I

IV. Results and Discussions

Using the proposed method, a study was carried out of the influence of the orientation α of the gripping device on the holding force F_h for different types of materials. For the study, it is proposed to change the orientation angle α of the gripping device in the range from 0 to 120 degrees, with a step of 15 degrees. Experimental evaluation of an orientation angle greater than 120 degrees is prohibitively challenging due to collisions that will occur with the workspace surface during re-orientation, as well as challenges in planning a continuous trajectory for the robotic end-effector, as reorientation forces the robotic arm into a singular configuration. Since the lifting force F_l for material № 1 is the largest, it is obvious that the holding force will also be maximum at all ranges of change in the orientation angle. Therefore, for the initial analysis, the averaged distribution of the holding force of the flexible material during the upward vertical movement of the gripper at different orientation angles was considered (Fig. 7).

In Fig. 7 there is no graph of the distribution of the holding force of the material for the orientation angle of the gripper $\alpha = 0$ and 15 degrees. This is due to the retention area (Fig. 4, label 5) of the gripper is very small and the depressurization causes a critical reduction in the lifting force and subsequent separation. The same situation is observed for all other materials, and at the orientation angle of the gripper

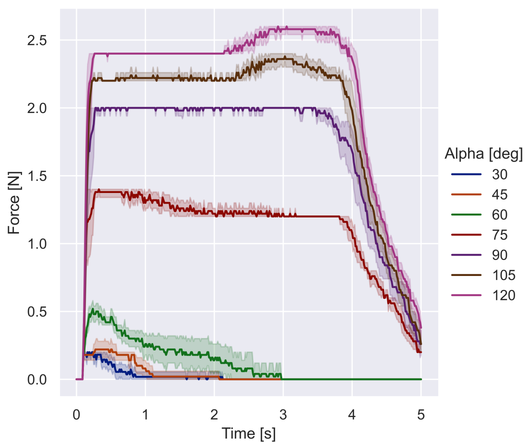

Fig. 7: Change in holding force of film material No. 1 during vertical movement of the gripper, the lines are the average value, and the lighter areas are the deviation.

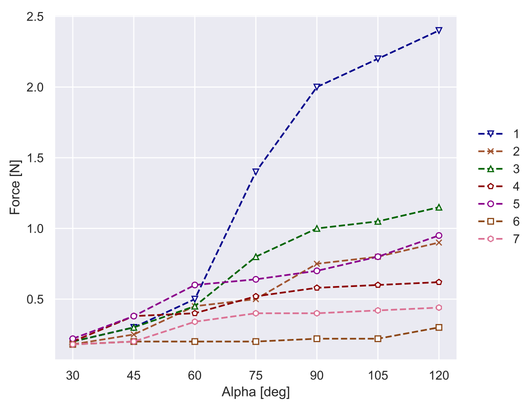

Fig. 8: The influence of the gripping device orientation on the holding force of studied materials (Table I) during the vertical movement of the gripper.

$\alpha = 0$ and 15 degrees, the holding force approaches zero. In particular, it is clear from Fig. 7 that the holding force of the material increases with an increase in the orientation angle of the gripper. The maximum holding force of material № 1 at an angle of $\alpha = 90$ degrees is 10 times greater than at an angle of $\alpha = 30$ degrees. This dependence is caused by many factors, however, in the range of $\alpha = 30$ to 60 degrees, the local deformation of the material has the greatest influence, which reduces the lifting force and the contact zone of the gripper with the material. Fig. 8 is presented to identify further dependencies of the impact of the orientation of the gripping device on the holding force of all studied materials.

From Fig. 8, it is obvious that the holding force increases with an increase in the orientation angle of the gripping device. It should be noted that the maximum holding force will always be greatest at $\alpha = 120°$ regardless of the type of material. However, when performing pick and place operations with non-rigid objects, in most cases it is necessary to gripped the object from a horizontal orientation. After grasping, before starting the movement, you need to reorient the gripper and then start the movement of the gripper together with the object. When using the reorientation angle $\alpha = 120°$ it is very difficult to achieve the continuum path of the end-effector of the robot. As a result, pick and place operations will be complicated or practically impossible. The obtained results of Fig. 8 allow us to state that, on average, for all studied materials at the orientation angle $\alpha = 90°$ the holding force is less by 15% than at $\alpha = 120°$. For further studies, the orientation angle of the gripping device $\alpha = 90°$ will be used, which we will consider rational.

Analyzing the holding force Fig. 8, we see an increase in holding force from orientation $\alpha = 30°$ to $\alpha = 90°$ for material: № 1 by 900%, № 2 by 317%, № 3 by 400%, № 4 by 190%, № 5 by 218%, № 6 by 22%, and № 7 by 122%. It is obvious that the biggest factor affecting the growth of the holding force is the initial lifting force. However, it is possible to replace the fact that a certain sequence of increasing the holding force does not coincide with the sequence of the lifting force (for example, material № 6 and 7). Although material № 6 has a slightly higher holding force than material № 7 and almost the same coefficient of friction, the difference in the 100% increase in holding force is significant. Therefore, we assume that the holding force is affected by additional factors that affect both the friction coefficient and the contact area between the material and the gripping device.

V. Conclusions

This paper investigates the influence of pneumatic gripping device orientation on holding force for non-rigid materials during the vertical movement of an industrial robotic arm. We propose a novel method to change the orientation of the gripper during a vertical motion to avoid depressurization. By increasing the angle of orientation, the robotic system is able to leverage the friction force between the object and the gripper to increase the holding force. Experimentally, we studied the distribution of the holding force during vertical movement for 7 non-rigid materials (e.g., textiles and films), while using different orientation angles for the gripper, ranging from 30 degrees to 120 degrees. We suggest that using an orientation angle of 90 degrees, which only reduces the maximum holding force by about 15 percent relative to a 120 degree holding angle, is a good approach to increasing holding force for flexible objects using pneumatic grippers.

The work in this paper is an initial step into future work for real-time reorientation under dexterous manipulation of non-rigid objects. This could improve automation and reduce costs associated with various complex manufacturing processes involving non-rigid objects. Future work will include the development of a control framework for autonomous dexterous manipulation of non-rigid objects in robotic applications. Another area of future research is the improvement and study of the influence parameters of pneumatic gripping systems on increasing the force and stability of holding non-rigid objects.

REFERENCES

[1] M. Saadat and P. Nan, "Industrial applications of automatic manipulation of flexible materials," *Industrial Robot: An International Journal*, 2002.

[2] A. Björnsson, M. Jonsson, and K. Johansen, "Automated material handling in composite manufacturing using pick-and-place systems–a review," *Robotics and Computer-Integrated Manufacturing*, vol. 51, pp. 222–229, 2018.

[3] G. J. Monkman, S. Hesse, R. Steinmann, and H. Schunk, *Robot grippers*. John Wiley & Sons, 2007.

[4] F. Nadon, A. J. Valencia, and P. Payeur, "Multi-modal sensing and robotic manipulation of non-rigid objects: A survey," *Robotics*, vol. 7, no. 4, p. 74, 2018.

[5] A. Cherubini, "Manipulation of flexible objects," *Encyclopedia of Robotics*, pp. hal–02 518 483, 2020.

[6] V. Lippiello, B. Siciliano, and L. Villani, "Multi-fingered grasp synthesis based on the object dynamic properties," *Robotics and Autonomous Systems*, vol. 61, no. 6, pp. 626–636, 2013.

[7] V. E. Arriola-Rios, P. Guler, F. Ficuciello, D. Kragic, B. Siciliano, and J. L. Wyatt, "Modeling of deformable objects for robotic manipulation: A tutorial and review," *Frontiers in Robotics and AI*, vol. 7, p. 82, 2020.

[8] J. Borràs, G. Alenyà, and C. Torras, "A grasping-centered analysis for cloth manipulation," *IEEE Transactions on Robotics*, vol. 36, no. 3, pp. 924–936, 2020.

[9] H. Yin, A. Varava, and D. Kragic, "Modeling, learning, perception, and control methods for deformable object manipulation," *Science Robotics*, vol. 6, no. 54, p. eabd8803, 2021.

[10] S. Donaire, J. Borras, G. Alenya, and C. Torras, "A versatile gripper for cloth manipulation," *IEEE Robotics and Automation Letters*, vol. 5, no. 4, pp. 6520–6527, 2020.

[11] G. J. Monkman, "Robot grippers for use with fibrous materials," *The International Journal of Robotics Research*, vol. 14, no. 2, pp. 144–151, 1995.

[12] U. Deole, R. Lumia, and M. Shahinpoor, "Grasping flexible objects using artificial muscle microgrippers," in *Proceedings World Automation Congress, 2004.*, vol. 15. IEEE, 2004, pp. 191–196.

[13] K. Nishikawa, K. Hirata, and M. Takaiwa, "Development of pneumatically driven hand capable of grasping flexible objects," *Journal of Robotics and Mechatronics*, vol. 32, no. 5, pp. 923–930, 2020.

[14] D. Mira, A. Delgado, C. M. Mateo, S. Puente, F. A. Candelas, and F. Torres, "Study of dexterous robotic grasping for deformable objects manipulation," in *2015 23rd Mediterranean Conference on Control and Automation (MED)*. IEEE, 2015, pp. 262–266.

[15] E. W. Schaler, D. Ruffatto, P. Glick, V. White, and A. Parness, "An electrostatic gripper for flexible objects," in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2017, pp. 1172–1179.

[16] R. Mykhailyshyn, V. Savkiv, A. M. Fey, and J. Xiao, "Gripping device for textile materials," *IEEE Transactions on Automation Science and Engineering*, pp. 1–12, 2022.

[17] R. Mykhailyshyn, A. Majewicz Fey, and J. Xiao, "Finite element modeling of grasping porous materials in robotics cells," *Robotica*, vol. 41, 2023.

[18] D. Hinwood, D. Herath, and R. Goecke, "Towards the design of a human-inspired gripper for textile manipulation," in *2020 IEEE 16th International Conference on Automation Science and Engineering (CASE)*, 2020, pp. 913–920.

[19] C. B. Teeple, J. Werfel, and R. J. Wood, "Multi-dimensional compliance of soft grippers enables gentle interaction with thin, flexible objects," in *2022 International Conference on Robotics and Automation (ICRA)*, 2022, pp. 728–734.

[20] H. Liu, P. Ferrentino, S. Pirozzi, B. Siciliano, and F. Ficuciello, "The prisma hand ii: a sensorized robust hand for adaptive grasp and in-hand manipulation," in *Robotics Research: The 19th International Symposium ISRR*. Springer, 2022, pp. 971–986.

[21] K. Kleeberger, R. Bormann, W. Kraus, and M. F. Huber, "A survey on learning-based robotic grasping," *Current Robotics Reports*, vol. 1, no. 4, pp. 239–249, 2020.

[22] D. De Schepper, B. Moyaers, G. Schouterden, K. Kellens, and E. Demeester, "Towards robust human-robot mobile co-manipulation for tasks involving the handling of non-rigid materials using sensor-fused force-torque, and skeleton tracking data," *Procedia CIRP*, vol. 97, pp. 325–330, 2021, 8th CIRP Conference of Assembly Technology and Systems. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2212827120314670

[23] F. Nadon and P. Payeur, "Grasp selection for in-hand robotic manipulation of non-rigid objects with shape control," in *2020 IEEE International Systems Conference (SysCon)*, 2020, pp. 1–8.

[24] K. Takács, A. Mason, L. B. Christensen, and T. Haidegger, "Robotic grippers for large and soft object manipulation," in *2020 IEEE 20th International Symposium on Computational Intelligence and Informatics (CINTI)*, 2020, pp. 133–138.

[25] S. Katyara, N. Deshpande, F. Ficuciello, F. Chen, B. Siciliano, and D. G. Caldwell, "Fusing visuo-tactile perception into kernelized synergies for robust grasping and fine manipulation of non-rigid objects," *arXiv preprint arXiv:2109.07207*, 2021.

[26] H. A. Kadi and K. Terzić, "Data-driven robotic manipulation of cloth-like deformable objects: The present, challenges and future prospects," *Sensors*, vol. 23, no. 5, p. 2389, 2023.

[27] I. Garcia-Camacho, J. Borràs, B. Calli, A. Norton, and G. Alenyà, "Household cloth object set: Fostering benchmarking in deformable object manipulation," *IEEE Robotics and Automation Letters*, vol. 7, no. 3, pp. 5866–5873, 2022.

[28] P. Koustoumpardis and N. Aspragathos, "A review of gripping devices for fabric handling," *hand*, vol. 19, no. July 2004, p. 20, 2004.

[29] K. M. Digumarti, V. Cacucciolo, and H. Shea, "Dexterous textile manipulation using electroadhesive fingers," in *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, pp. 6104–6109.

[30] R. Mykhailyshyn, V. Savkiv, P. Maruschak, and J. Xiao, "A systematic review on pneumatic gripping devices for industrial robots," *Transport*, vol. 37, no. 3, pp. 201–231, 2022.

[31] R. Mykhailyshyn and J. Xiao, "Influence of inlet parameters on power characteristics of bernoulli gripping devices for industrial robots," *Applied Sciences*, vol. 12, no. 14, p. 7074, 2022.

[32] "Airborne: Cutting room operations." [Online]. Available: https://www.airborne.com/automation/cutting-room-operations/

[33] "Schmalz bernoulli-needle-grippers." [Online]. Available: https://www.schmalz.com/en-us/vacuum-technology-for-automation/vacuum-components/special-grippers/needle-grippers/needle-grippers-sng-bv-306162/

[34] Y. Ebraheem, E. Drean, and D. C. Adolphe, "Universal gripper for fabrics–design, validation and integration," *International Journal of Clothing Science and Technology*, vol. 33, no. 4, pp. 643–663, 2021.

[35] "Robotstudio: Abb robotics." [Online]. Available: https://new.abb.com/products/robotics/robotstudio

[36] "Torbal fm." [Online]. Available: https://www.torbalscales.com/torbal-fm.html

[37] R. Mykhailyshyn, V. Savkiv, M. Mikhalishin, and F. Duchon, "Experimental research of the manipulatiom process by the objects using bernoulli gripping devices," in *2017 IEEE International Young Scientists Forum on Applied Physics and Engineering (YSF)*. IEEE, 2017, pp. 8–11.

[38] "Substantiation parameters of gripping devices of industrial robots and methods of manipulation of flexible objects." [Online]. Available: https://romanmykhailyshyn.github.io/portfolio/portfolio-1/