Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

Development of New Extensible Components for Enabling a More Flexible Usage of Jamming-Gripper

Rasool Shahsevani*, Sebastian Reitelshöfer, Mohammad Ali Bodaghi and Jörg Franke

Institute for Factory Automation and Production Systems (FAPS), Friedrich-Alexander-University of Erlangen-Nuremberg (FAU), Egerlandstreet 7-9, 91058 Erlangen, Germany;

*Corresponding author. E-mail: rasool.shahsevani@faps.fau.de,

{sebastian.reitelshoefer & joerg.franke}@faps.fau.de, mohammad.ali.bodaghi@fau.de

***Abstract*— In many applications, gripping systems are key elements to turn industrial robots into flexible and versatile handling systems. Depending on the gripping principle those systems can either be rather limited or very flexible in terms of gripping a broad variety of different objects. The so-called jamming-gripper can grasp a wide range of objects by passively adapting to the shape of different workpieces. The purpose of the work described in this paper is to develop extensible components for optimizing the jamming-gripper. Concerning the previous jamming-gripper, the problems related to a mechanical structure, installing a filter, a balloon as a membrane, and filling the balloon with powder are investigated to improve the jamming-gripper system. A new gripper system designed is presented to not only address the existing problems but also to make it even more user-friendly and practical. Tests are performed to determine the influence of three different filling ratios of the membrane on the gripping performance for objects with complex geometries.**

Index Terms – Gripper, Gripper system, Membrane, Extensible, Extensible Components, Jamming, Jamming-Gripper

I. Introduction

Industrial robots assisted with optimized manipulators or grippers play a crucial role in the value chain. The robots are dependent on manipulators while without using them, it is virtually impossible to launch any product lines [1–3]. Handling tasks are performed and controlled by effectors which are connected to the rest of the robot with a power and control unit. Depending on the application, the effectors divide into two groups: passive tools, and complex modules such as grippers [4, 5]. From the economic perspective, an industrial robot brings more value if the connected grippers provide more flexibility and versatility through adapted gripper jaws [6, 7].

An essential task of robotic manipulators is gripping and holding objects. They are often limited in terms of the capability to grip objects with different shapes. Simple gripper jaws can grip a moderate variety of work-pieces without the need to change the components. By increasing the flexibility of grippers, the implementation effort and complexity rises [4, 8, 9]. Substituting the gripper jaws provides the potential to develop a more flexible gripper system.

The jamming-gripper can lift a wide range of objects with different contact surfaces. Multi-finger gripper can also master these objects, but this gripping principle needs complex design and complicated technology. Furthermore, a flexible gripper system can pick up sensitive objects with a reduced probability to damage them. However, manufacturing such a flexible gripper system requires more cost and energy [10–12].

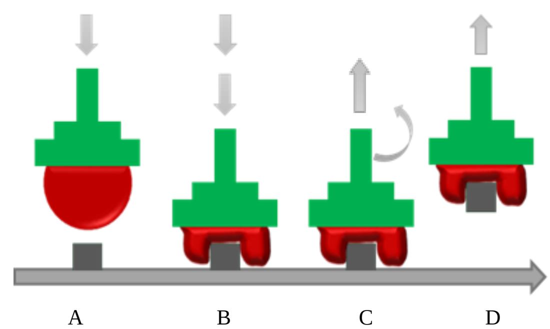

Fig. 1. Schematic of the gripping process for the jamming-gripper. A) approval the object, B) press and deformation, C) hardening the materials by applying a vacuum, D) grasping and picking up. A quite similar theme is also presented in the literature by [10, 13].

Fig. 1 illustrates a schematic representation of the gripping process for the jamming-gripper system. With this type of grippers, the fingers of finger grippers are replaced by a balloon. The balloon is filled with granular material like ground coffee and leads to flexibility. The balloon is deformed in contact with various work-pieces, thereby realizing the ability of gripping objects without crushing. A robot arm applies pressure to grasp the objects before the powder in the balloon is hardened by using a vacuum. The vacuum applies into the balloon for grasping and holding the objects. The power of vacuum depends on the performance of the vacuum pump. Since the material properties

978-1-7281-6321-5/19//$31.00 ©2019 IEEE

and physical factors of objects are different, it is necessary to consider the required time of the vacuum to ensure the safe gripping [10, 13]. Applying the vacuum solidifies the balloon around the objects. Therefore, the jamming-gripper is able to pick up the target object, regardless of the geometries and material properties [10, 12].

The jamming-gripper can grip the widest range of objects, which can be formed around the shape of them by a material, for instance, powder. Simpson [14] has suggested a pocket of granular material to grip surfaces of objects. Schmidt [15] has suggested designing a flexible molding jaw for grippers, which is able to be used for many different gripping tasks. Amend et al. [10] have developed a positive pressure universal gripper and studied the influence of the different material combinations on the gripping. The ideal combination of the materials is the mixture of coffee, sand, and flour [10]. Brown et al. [13] have designed a universal robotic gripper with the ability to grip variable objects with complex geometries in a humid environment. Amend et al. [16] have also developed a magnetically actuated jamming, which included aluminum plates, a membrane, and a switchable magnet. Guo et al. [5] have designed a soft pneumatic gripper by using the principle of electroadhesion to pick-and-place flexible materials as well as delicate objects like a light bulb. Okatani and Nishida [17] have developed a universal robot gripper by using magnetorheological fluid, which is able to grip nonmagnetic objects of various shapes. Kapadia and Yim [18] have developed fingered fluidizing jamming-grippers whose nubs are able to grasp smaller objects. Licht et al. [19] have designed the jamming-grippers to be used in the sea that the holding strength of universal jamming-grippers increases as a function of the jamming pressure to greater than three atmospheres. A bistable soft gripper with mechanically embedded sensing is developed by Thuruthel [20] that the mechanism provides a flexibility on the type of actuation mechanism. A hybrid gripper with soft material and rigid structures is developed to achieve enhanced fingertip force and fast actuation speed by Park et al. [21].

Shintake et al. [22] have presented a critical overview of soft robotic grippers, covering different material sets, physical principles, and device architectures. A commercial balloon is used as the membrane [23], and a mechanical structure is developed to support the balloon or the membrane [24–26]. A granular bag [27] and a latex balloon are made to be used as the membrane [10, 13, 26, 28]. An extensible gripper for clamping the head portions of plastics material plates is invented [29]. Empire robotics as one of the first companies has designed a modular end-of-arm-tool and a quick-change base for replacing the wear components contained in the head, and it is also made the decision that the quick-change design of the base should support multiple head sizes [16]. The push-down force vs. pull-off force (Newton) at different gripper volumes are tested [28]. Holding force to pull out the different gripped objects and the success rate for gripping objects of varying size are evaluated with a positive press universal gripper with the same filled volume of the membrane [13, 23, 30].

In our previous work, a lightweight jamming-gripper is developed to realize expectations of a flexible gripper system as shown in Fig. 2A [23]. Since the improvement of the previous work is an integral part of the development, the weaknesses of the previous gripper are analyzed to fix the vulnerabilities. The problems related to filling the balloon with powder (mix of coffee, sand, and flour), installing the filter in the structure, and assembling the mechanical structure are determined to optimize and design a new gripper system. As shown in Fig. 2B, the is balloon damaged because the balloon has a twisting DOF inside and an unsafe contact with the filter.

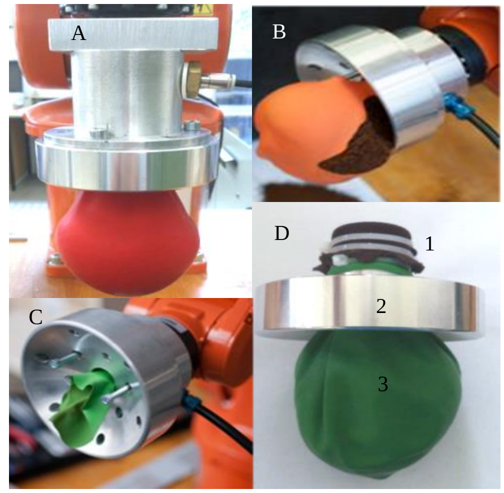

Fig. 2. Developed lightweight jamming-gripper . A) the lightweight jamming-gripper, B) the balloon is damaged, and the powder came out, C) the balloon is damaged due to the twisting, D) 1) filter, 2) the mechanical structure, 3) commercial balloon as a membrane.

The focus of this paper is to design extensible components for optimizing the jamming-gripper. For solving the problems of the mechanical structure, practical and cost-effective extensible components are designed. The problems of filling a balloon with powder and fixing the balloon to the mechanical structure can be resolved by manipulation of a balloon as a membrane. As described in the following, extensible components provide an easy way to fill the membrane with powder. The following issues are investigated in this paper.

- The extensible components to hold the membrane and to provide an easy way to fill the membrane with the powder
- To achieve the best gripper system among the systems with the three different volumes of the membrane for the objects with complex geometries
- To provide a simple mechanism for using a commercial balloon as the membrane
- The influence of a work-piece on the holding force and safe gripping with the three different volumes of the membrane

Furthermore, the physical relation between target objects and the new gripper system is investigated to find optimal configurations by changing the volume of the membrane to pick up objects with complex geometries. In the following, the tests are described to evaluate the influence of various properties of objects on safe gripping.

II. THE EXTENSIBLE COMPONENTS DEVELOPMENT

In this section, the problems of the previous gripper are addressed to improve the jamming-gripper. The problems related to installing the filter, the mechanical structure, a balloon as a membrane, and filling the balloon with powder. The new gripper system includes three main parts, which refer to as extensible components, a membrane, and powder.

A. Design of the Extensible Components

The extensible components are designed to solve the previous problems and make the gripper system more user-friendly and practical. An easy way is provided to assemble the balloon into the components and to fill the membrane with the material. In Fig. 3, a simple concept and practical structure are represented for the new gripper system to provide an ability to pick-and-hold objects with safe gripping and without twisting.

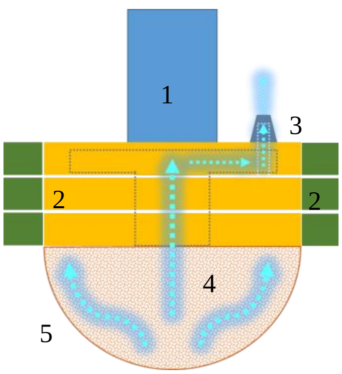

Fig. 3. Schematic concept to design the gripper system. 1) adapter, 2) the extensible components instead of the mechanical structure, 3) vacuum, 4) powder as a material, 5) balloon as membrane.

As shown in Fig. 4, the round pieces are used to design and develop the new extensible components as a screw. The screw threads are created around the round pieces. The parts are manufactured from light material, for instance, aluminum, and plastic. The round pieces provide a possibility in which all of the pieces can be assembled as a one-unit system. Although a range of standard tables exists to calculate screw thread parameters, the size of the screw threads in this work is out of this range. Thus, all parameters of the standards are recalculated for the screw threads. The extensible components consist of different round cylinders (piece number 1 to 6), which are screwed into the housing shell (piece number 7). Fig. 4-6 illustrate the overall structure of the new gripper system consisting of the ten components.

B. Fabrications of the Gripper System

As shown in Fig. 5, the new gripper system includes the membrane and extensible components. The upper and lower sealing rings hold the membrane. Then, they are placed into the housing shell. After filling the membrane with powder, the membrane is fastened by turning the balloon holder downwards. Afterward, other components, e.g., the filter, and the vacuum channel plate are integrated into the housing shell. The gripper system can be connected to the robot arms by using the adapter (piece number 1 in Fig. 5). Eventually, the vacuum tube is connected to the vacuum channel plate.

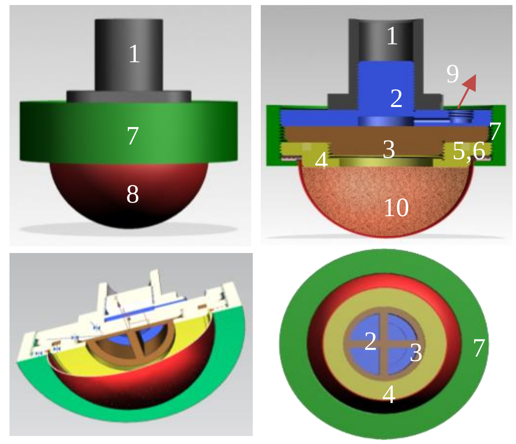

Fig. 4. Assembled the gripper system in four views. 1) adapter (for connecting the gripper system to the robot arms), 2) vacuum channel plate, 3) filter (covered with textile filter), 4) balloon holder, 5) upper sealing ring, 6) lower sealing ring, 7) housing shell, 8) membrane, 9) air input-output, 10) powder.

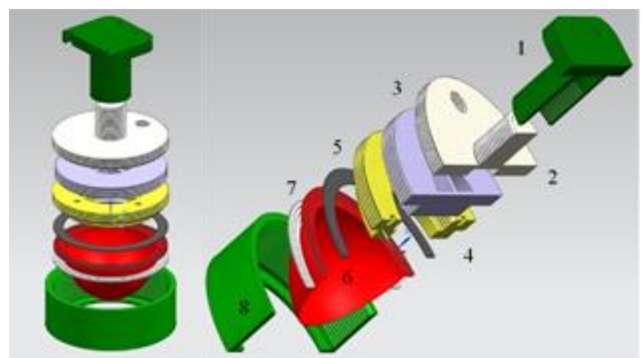

Fig. 5. Exploration view of extensible components. 1) adapter (for connecting the gripper system to the robot arms), 2) vacuum channel plate, 3) filter, 4) balloon holder (90 mm diameter), 5) upper sealing ring, 6) membrane, 7) lower sealing ring, 8) housing shell.

As shown in Fig. 6, a commercial balloon is used to make the membrane. For using a balloon as a membrane, the diameter of the balloon in the horizontal direction must be equal to the external diameter of the balloon holder (piece 4 in Fig. 5). For adding the membrane to the components, a commercial balloon needs to be cut in the vertical direction. Therefore, it is important to know the proper line on the balloon in the vertical direction for cutting. Thus, the situation of relevant components is determined to find a formula to calculate the proper line.

First of all, the components which have a direct relation with the membrane are considered. Since the upper sealing ring and lower sealing ring in Fig. 5 keep the balloon, twice the width of sealing rings is defined as a parameter "S." After that, an experiment is designed to find the optimum size of the balloon in the vertical direction. It is concluded that the membrane fits to the components when 10% of the diameter of the balloon "D" add to the parameter "S" as shown in Fig. 6. Therefore, the line in the vertical direction of the balloon “LB” is calculated and used (1). The formula can apply for different sizes of balloons that can be used as a membrane for different sizes of the gripper system.

$$LB = \frac{1}{2}D + 10\% * D + S \tag{1}$$

Overall, a balloon should be cut off along the red line as shown in Fig. 6A to be used as a membrane in the gripper system. The membrane has a larger entrance “F” compared with that of the commercial balloon “N.” The entrance of the membrane “F” as shown in Fig. 6B provides an ability for filling the membrane with powder much faster than filling the commercial balloon with it.

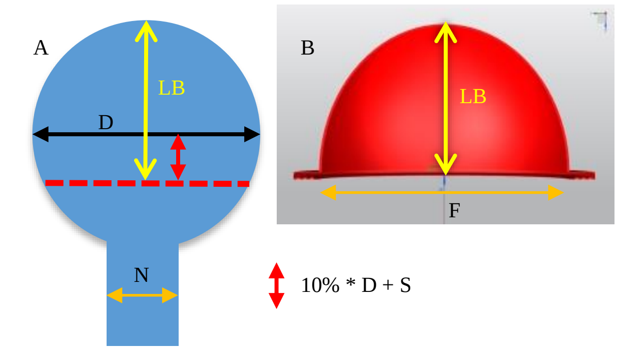

Fig. 6. The balloon and the membrane. A) commercial balloon, (N= entrance of the balloon), (S = 2 * width of sealing rings in Fig. 5), (D is the external diameter of the balloon holder (piece 4) in Fig. 5), B) membrane, (F= entrance of the membrane).

The previous problems such as filling the membrane with powder, installing the filter in the structure, and assembling the mechanical structure are resolved by using the extensible components.

III. Material And Method

The Baxter research robot with two arms, certified for a collaborative usage in the US, as described in ISO 10218-1:2006 [31] is used for pick-and-place of objects in the tests. The setup includes a vacuum pump and high-pressure airlines. A microcontroller controls the vacuum pump in the system. The gripper system is connected to the Baxter robot arms by using the adapter (piece number 1 in Fig. 5). In the literature, some methods are developed to choose the material to fill the membrane [10, 13, 23]. The best material is a combination of three powders with equal volumes including 33.33% flour, 33.33% sand, and 33.33% coffee [23]. Therefore, the material is chosen based on the method by [23] in the paper. Since the holding force for various objects is different [10], as shown in Fig. 7, six objects with different shapes and properties are chosen to evaluate the performance of the gripper system in the tests. The objects are T-shaped wood, plastic cylinder, spring, coin, mushroom-shaped plastic, and a plastic mug. The six objects are gripped for ten times to determine the safe gripping of the gripper system with the different filled volumes of the membrane.

As shown in Fig. 8, the six objects are connected to a string to determine the holding force of the gripper system. The holding forces are measured by a Newton-meter and with a contribution of two rollers mounted vertically on aboard. Other tools such as a scale and mounted spools are also used in the tests. In the previous experiment, the optimum safe gripping is achieved by applying 8 kg pressure in a vertical direction. The pressure is applied downwards by using the Baxter robot arm. Thus, the 8 kg pressure with 0.2 kg deviation (8 kg + - 0.2 kg) is applied to perform the tests as shown in Fig. 8. All tests are done under the same conditions. Since the different fill volumes of the membrane can affect the gripping and flexibility of the gripper system [28], the tests are performed with the three different filled volumes to determine the optimum filled volume.

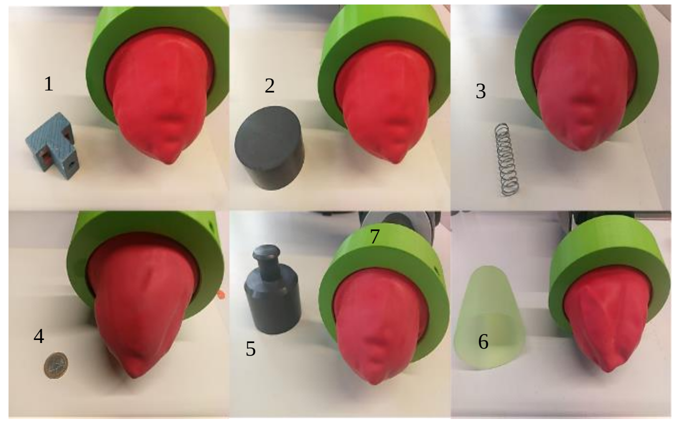

Fig. 7. Objects for using in the tests to grip with the gripper system. 1) T-shaped wood (48g), 2) plastic cylinder (152g), 3) spring of metal (4g), 4) one Euro coin, 5) mushroom-shaped plastic (190g), 6) plastic mug (32g), 7) the gripper system.

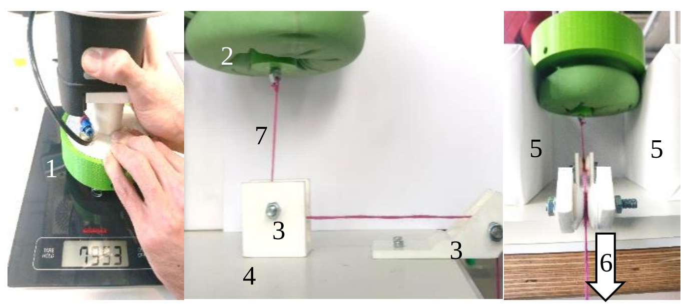

Fig. 8. Instruments used to perform the test series. 1) scale, 2) jamming-gripper 3) mounted spools, 4) stable board with vertically mounted spools, 5) two fixed bodies to protect the robot arm from the impact weight of the sand, 6) masseur the holding force with a Newton-meter, 7) string.

As shown in Fig. 9, the membrane is filled with the powder, and the weight of powder is measured. In this case, the opening diameter of the membrane is 90 millimeters. The membrane is filled to the maximum capacity with the amount of powder in 380 grams. Three different membranes, which are filled up to three different volumes (85 vol% (V1), 90 vol% (V2), and 95 vol% (V3)) are chosen. The three membranes (V1, V2, and V3) are filled with enough powder to realize the gripping of objects with the same materials.

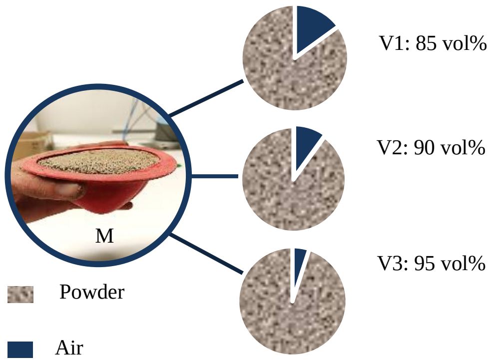

Fig. 9. Division of the capacity of the membrane involves air and powder. Three different filled volume of the membrane includes 85 vol% (V1), 90 vol% (V2), and 95 vol% (V3), M= membrane, powder as a material.

In the following, the influence of the membranes with three different filled volumes is evaluated on safe gripping and the holding force for the objects.

IV. Discussion And Result

As indicated in Fig. 7, in the first test, the six objects are selected to evaluate the ability of the gripper system for safe gripping. The three membranes with 85 vol% (V1), 90 vol% (V2), and 95 vol% (V3) filled volumes are prepared. The gripper system is connected to the arm of the Baxter robot. Then, the objects are gripped, lifted, and moved in a vertical direction to evaluate the gripping performance. The objects are gripped for ten times under the same conditions, and the success rate is measured as an indicator of the safe gripping.

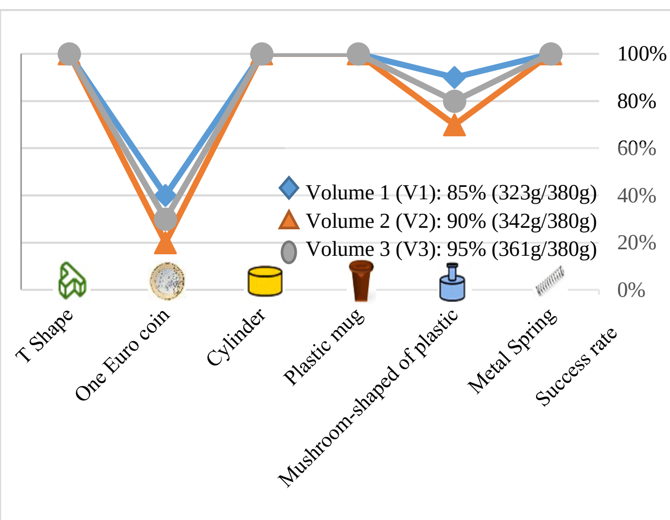

Fig. 10. The percentage of the success rate for the six objects by griping for ten times with the gripper system, the filled volume of the membrane includes 85 vol% (V1), 90 vol% (V2), and 95 vol% (V3), g=gram, the capacity of the membrane=380 gram, V1=323gram, V2=342gram, V3=361gram.

As shown in Fig. 10, the gripping of some objects, like the coin and mushroom-shaped plastic, are not always successful in all ten times of the test by using the three membranes. The results show that the performance of the grippers is satisfactory. The membrane (V1) with 85 vol% filled volume is the best performance for the coin and the mushroom-shaped plastic. The gripping of the coin demonstrates a 40% success rate, and mushroom-shaped plastic shows a 90% success rate. By gripping the objects for ten times during the test, four other objects including T-shaped wood, plastic cylinder, spring, and plastic mug are gripped with a 100% success rate. Since these four objects have a full success rate, the first test is not sufficient to evaluate the performance of the three membranes. Therefore, a second test is set up to perform the four objects as described in the following. In the second test, the four objects including T-shaped wood, plastic cylinder, spring, and plastic mug, as shown in Fig. 10, are selected to determine the required force to pull out the gripped objects. The gripper system is connected to the fixed arm of the Baxter robot. The three membranes (V1, V2, and V3) are filled with the same powder. The four objects are tested for ten times, and holding forces for them are measured. The second test is performed for the three membranes (V1, V2, and V3) under the same conditions.

A. *The Second Test for the Membrane (V1)*

The results are shown in Fig. 11. The gripper system with the membrane (V1) is gripping the cylinder better than the other objects. The maximum peak force (27.4 N) is determined when the cylinder is removed, and the minimum peak force (4.8 N) is determined when the spring is removed from the gripper System. Furthermore, it is observed that an object with a cylinder-like shape needs a higher force to be removed from the gripper.

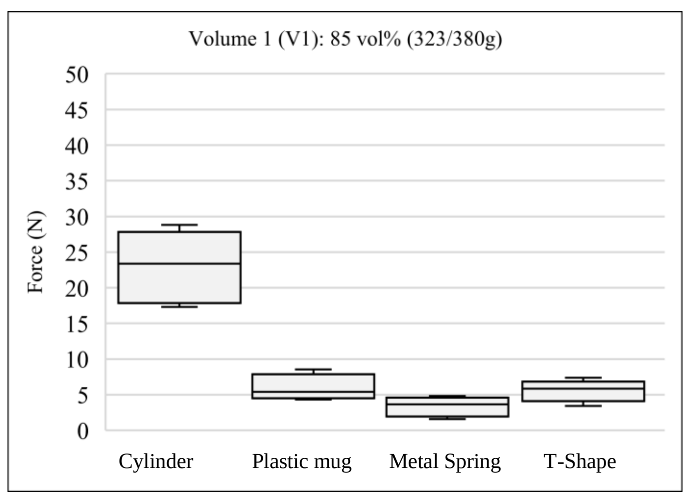

Fig. 11. The membrane (V1) with 85 vol% filled volume, the bars illustrate the required force to remove the gripped objects for ten times from the gripper system, the required forces for each object in the ten times are between the minimum and the maximum force in the relevant bars, N= Newton, g=gram, V1=323gram, the capacity of the membrane =380 gram.

B. The Second Test for the Membrane (V2)

The test for V2 is performed similarly. The results are shown in Fig. 12. The holding force of V2 compared to V1 is increasing. The maximum peak force (78.8 N) is determined when the cylinder is removed, and the minimum peak force (4.0 N) is determined when the spring is removed from the gripper system. In this case, the membrane (V2) is gripping the objects such as the cylinder, the plastic mug, and T-shaped wood better than the membrane (V1).

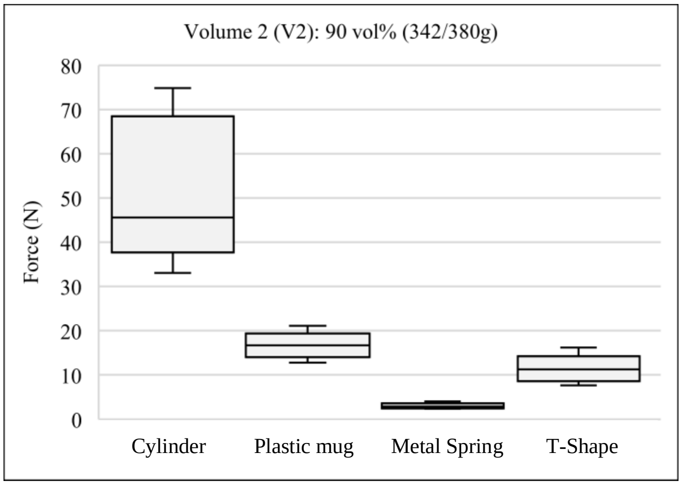

Fig. 12. The membrane (V2) with 90 vol% filled volume, the bars illustrate the required force to remove the gripped objects for ten times from the gripper system, the required forces for each object in the ten times are between the minimum and the maximum force in the relevant bars, N= Newton, g=gram, V2=342gram, the capacity of the membrane =380 gram.

C. The Second Test for the Membrane (V3)

The best gripping is achieved for the four objects by using the membrane (V3) as shown in Fig. 13. The holding force is increasing in the case of V3 compared to V2 and V1.

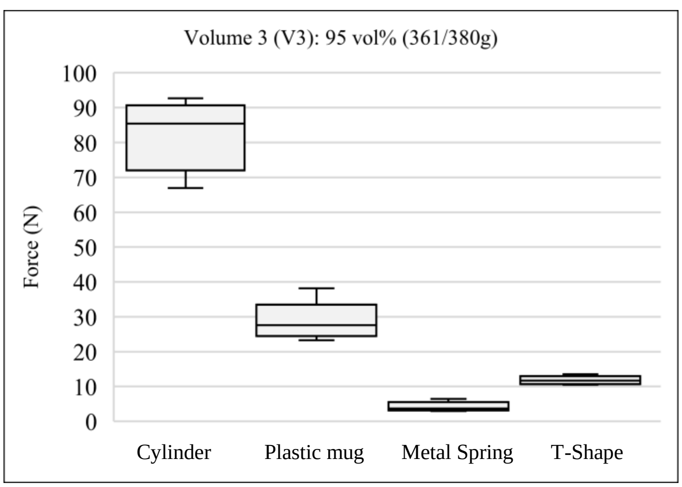

Fig. 13. The membrane (V3) with 95 vol% filled volume, the bars illustrate the required force to remove the gripped objects for ten times from the gripper system, the required forces for each object in the ten times are between the minimum and the maximum force in the relevant bars, N= Newton, g=gram, V3=361gram, the capacity of the membrane =380 gram.

In this test, the maximum peak force (92.6 N) is determined when the cylinder is removed, and the minimum peak force (6.3 N) is determined when the spring is removed from the gripper system. Therefore, the membrane (V3) is gripping these objects better than the membranes (V1 and V2). A summary of the results of the first and second tests is shown in Fig. 14 to characterize the influence of the three different filled volumes of the membranes (V1, V2, V3) on the safe gripping for the objects. The bar charts illustrate the success rate (SR) for the six objects, and the solid lines on the bars indicate the average holding force of each membrane for the four objects. As shown in Fig. 15, some of the objects are gripped by using the developed gripper system with extensible components.

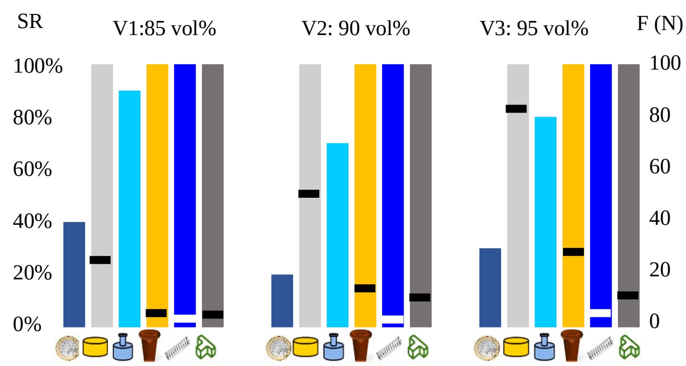

Fig. 14. The average of the safe gripping and the holding forces, the bar charts illustrate the percentage of the success rate of six objects, the solid lines on the bars indicate the average holding force for the objects expect the coin and the mushroom-shaped plastic, 85 vol% filled volume of the membrane (V1), 90 vol% filled volume of the membrane (V2), 95 vol% filled volume of the membrane (V3), F=force, N= Newton, SR= success rate.

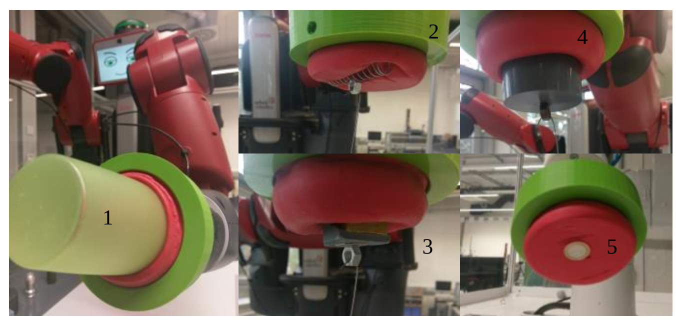

Fig. 15. The developed gripper system is gripping the objects by using the Baxter robot. 1) plastic mug, 2) spring of metal 3) T-shaped wood, 4) plastic cylinder, 5) one Euro coin

As shown in Fig. 14, the objects like the gripped cylinder require a higher force to pull out from the gripper system for all versions of the membranes (V1, V2, and V3). The highest holding force is achieved by using the membrane (V3) for the cylinder between 70 N and 90 N with an average of 82.8 N. Compared to V1 and V2, the holding force by using V3 is increasing for four objects including T-shaped wood, plastic cylinder, spring, and a plastic mug. Therefore, the membrane (V3) is the optimum filled volume of the membrane for these four objects to reach the best gripper system. The minimum holding force is achieved by using the membrane (V2) for the spring between 2.3 N and 3.8 N with an average of 2.9 N. The gripper system by using the membrane (V1) demonstrate the best performance and success rate compared to V2 and V3 for the coin and the mushroom-shaped plastic. Therefore, the membrane (V1) is the optimum filled volume of the membranes to achieve the best gripper system for gripping the coin and the mushroom-shaped plastic. Consequently, it can be inferred that the different fill volumes of the membrane play a crucial role in increasing or decreasing the flexibility of the gripper system.

V. CONCLUSION

Extensible components are designed and developed for optimizing the jamming-gripper to be user-friendly and practical. The extensible components resolve the problems of the previous versions of jamming-gripper that were developed by us such as filling the membrane with powder, installing the filter into the mechanical structure, and assembling the mechanical structure. The extensible components with a bigger entrance of the membrane provide an easy way to fill the membrane with the powder. A simple mechanism for using a commercial balloon as the membrane is achieved by using the extensible components. The structure of the extensible components provides an ability without twisting of the membrane in that for the new gripper system to pick-and-hold various objects with safe gripping. The required capacity percentage of the membrane to be filled with the powder is evaluated. Three different filled volumes of the membranes including 85 vol% (V1), 90 vol% (V2), and 95 vol% (V3) are investigated. The tests are performed for the three membranes (V1, V2, and V3). The membrane (V3) is the optimum filled volume and provide the best gripper system for objects including T-shaped wood, plastic cylinder, spring, and a plastic mug. The membrane (V1) is the optimum filled volume and provide the best gripper system for objects including the coin and the mushroom-shaped plastic. The gripper system with the membrane (V2) is gripping the objects including the cylinder, the plastic mug, and T-shaped wood better than the membrane (V1). The future research will serve to optimize the extensible components, and overall design to develop a gripper system such as the soft grippers and the vacuum grippers.

REFERENCES

[1] S. Hesse, Ed., *Greifertechnik: Effektoren für Roboter und Automaten,* 1st ed. München: Hanser, 2011.

[2] C. Blanes, V. Cortés, C. Ortiz, M. Mellado, and P. Talens, “Non-Destructive Assessment of Mango Firmness and Ripeness using a Robotic Gripper,” *Food Bioprocess Technol*, vol. 8, no. 9, pp. 1914–1924, 2015.

[3] C. Blanes and M. Mellado, C. Ortiz and A. Valera, “Review. Technologies for Robot Grippers in Pick and Place Operations for Fresh Fruits and Vegetables,” 2011.

[4] J. Bartenschlager, H. Hebel, and G. Schmidt, Eds., *Handhabungstechnik mit Robotertechnik: Funktion, arbeitsweise, programmierung*. Wiesbaden, s.l.: Vieweg +teubner verlag, 1998.

[5] J. Guo *et al.*, “Soft Pneumatic Grippers embedded with Stretchable Electroadhesion,” *Smart Mater. Struct.*, vol. 27, no. 5, p. 55006, 2018.

[6] X. Li, N. Li, G. Tao, H. Liu, and T. Kagawa, “Experimental comparison of bernoulli gripper and vortex gripper,” *Int. J. Precis. Eng. Manuf.*, vol. 16, no. 10, pp. 2081–2090, 2015.

[7] J. Oravacova', M. Matusova, and P. Kostal, “Industrial robot grippers design,” *International Journal of Precision Engineering and Manufacturing*, 2010.

[8] G. J. Monkman, S. Hesse, R. Steinmann, and H. Schunk, *Robot Grippers*. Weinheim, Chichester: Wiley-VCH Verlag GmbH & Co. kGaA, 2007.

[9] TIP/SMO, *Manufacturing: advanced robotics and intelligent automation.* [Online]Available: https://www.nist.gov/sites/default/files/documents/2017/05/09/manufacturing_adv_robotics_intelligent_automation_wp_08_11.pdf, 2011.

[10] J. R. Amend, E. Brown, N. Rodenberg, H. M. Jaeger, and H. Lipson, “A positive pressure universal gripper based on the jamming of granular material,” *IEEE transactions on robotics*, vol. 28, no. 2, pp. 341–350, 2012.

[11] C. Ho and M. Koç, “Design and feasibility tests of a flexible gripper based on inflatable rubber pockets,” *International Journal of Machine Tools and Manufacture*, vol. 46, no. 12, pp. 1350–1361, 2006.

[12] I. Zubrycki and G. Granosik, “Novel haptic device using jamming principle for providing kinaesthetic feedback in glove-based control interface,” *J Intell Robot Syst*, vol. 85, no. 3-4, pp. 413–429, 2017.

[13] E. Brown *et al.*, “Universal robotic gripper based on the jamming of granular material,” *Proceedings of the National Academy of Sciences*, vol. 107, no. 44, pp. 18809–18814, 2010.

[14] D. C. Simpson, “Gripping Surfaces for artificial Hands,” *Hand*, vol. 3, no. 1, 1971.

[15] I. Schmidt, “Flexible moulding jaws for grippers,” *Industrial Robot: An International Journal*, vol. 5, no. 1, pp. 24–26, 1978.

[16] J. Amend, N. Cheng, S. Fakhouri, and B. Culley, “Soft Robotics Commercialization: Jamming grippers from research to product,” *Soft Robotics*, vol. 3, 2016.

[17] Y. Okatani and T. Nishida, “Development of universal robot gripper using MR fluidInternational symposium on advanced intelligence systems (ISIS): Kitakyushu, Japan,” *International Conference on Soft Computing and Intelligent Systems,* 2014.

[18] J. Kapadia and M. Yim, “Design and performance of nubbed fluidizing jamming grippers,” *2012 IEEE International Conference on Robotics and Automation*, pp. 5301–5306, 2012.

[19] S. Licht, E. Collins, M. L. Mendes, and C. Baxter, “Stronger at Depth: Jamming grippers as deep sea sampling tools,” (eng), *Soft Robotics*, vol. 4, no. 4, pp. 305–316, 2017.

[20] T.G. Thuruthel, S. H. Abidi, M. Cianchetti, C. Laschi, and E. Falotico, “A bistable soft gripper with mechanically embedded sensing and actuation for fast closed-loop grasping,” *Computer Science, Robotics*, http://arxiv.org/pdf/1902.04896v1, 2019.

[21] W. Park, S. Seo, and J. Bae, “A Hybrid Gripper with Soft Material and Rigid Structures,” *IEEE Robot. Autom. Lett.*, vol. 4, no. 1, pp. 65–72, 2019.

[22] J. Shintake, V. Cacucciolo, D. Floreano, and H. Shea, “Soft robotic grippers,” (eng), *Advanced materials (Deerfield Beach, Fla.)*, e1707035, 2018.

[23] S. Reitelshofer, C. Ramer, D. Graf, F. Matern, and J. Franke, Eds., *Combining a collaborative robot and a lightweight Jamming-Gripper to realize an intuitively to use and flexible co-worker*. [Piscataway, N.J.]: 2014 IEEE/SICE International Symposium on System Integration, pp.1-5.

[24] M. Fujita *et al.*, “Jamming layered Membrane Gripper Mechanism for Grasping differently shaped-objects without excessive pushing force for search and rescue missions,” *Advanced Robotics*, vol. 32, no. 11, pp. 590–604, 2018.

[25] T. Nishimura, Y. Suzuki, T. Tsuji, and T. Watanabe, “Fluid pressure monitoring-based strategy for delicate grasping of fragile objects by a robotic hand with fluid fingertips,” (eng), *Sensors (Basel, Switzerland)*, vol. 19, no. 4, 2019.

[26] M. Fujita *et al., Eds., Variable inner volume mechanism for soft and robust gripping — Improvement of gripping performance for large-object gripping*. 2016 IEEE International Symposium on Safety, Security, and rescue robotics (SSRR), 2016.

[27] K. Harada *et al.*, “Proposal of a shape adaptive gripper for robotic assembly tasks,” *Advanced Robotics*, vol. 30, no. 17-18, pp. 1186–1198, 2016.

[28] J. R. Amend, William C. Culley, Nadia. G. Cheng, and Patrick R. Dingle, Sami M. Fakhouri, “End effector, apparatus, system and method for gripping and releasing articles and the like,” WO 2015/006613 Al, 2015.

[29] G. D. Nichilo, “Extensible gripper for clamping the head portions of plastics material plates and thermoforming apparatus used - European Patent Office - EP 1153729 A3,” EP1153729A3, 2000.

[30] H. Lipson, J. R. Amend, J.R, H. Jaeger, and E. Brown, “Gripping and releasing apparatus and method,” US8882165B2, United States US13/641,230, 2014.

[31] Rethink Robotics, *Safety & Compliance.* [Online] Available: https://www.rethinkrobotics.com/safety-compliance/2014.