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REVIEW ARTICLE

A SYSTEMATIC REVIEW ON PNEUMATIC GRIPPING DEVICES FOR INDUSTRIAL ROBOTS

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Abstract. Based on the literature review, the article presents the analysis of approaches to classifying Gripping Devices (GDs) of Industrial Robots (IRs) and substantiates the need for systematising Pneumatic GDs (PGDs). The authors propose a classification of well-known PGDs, in which the holding force of the Manipulated Object (MO) is formed under the action of gas-dynamic effects. A general classification of PGDs with features common to all PGD subtypes is proposed: PGD type; contact type; object base type; object centring type; specialisation type; working range; availability of additional devices; the number of grippers; type of control; type of attachment to the robot. Each feature of the general PGD classification, which affects PGD characteristics, is analysed, and a usage example is given. The advantages of each feature included in the general PGD classification are also considered. For a more detailed classification, PGDs are divided into the following types: Vacuum GDs (VGDs), Jet GDs (JGDs), Combined PGDs (CPGDs). For VGD, the main distinguishing features are highlighted, which are the vacuum creation method, effect/actuator, stepwise nozzle, suction cup type, suction material type. The main distinguishing features of JGDs include using a jet of compressed air, the shape of nozzle elements, the number of nozzle elements, the direction of gas flows, type of surface of the MO. The main distinguishing features of CPGD include the type of combination and function performed. The main features are given for each classification, and the advantages/disadvantages of the most typical representatives of GDs are described. The authors identify the main development directions for GDs at the present stage of robotisation of production processes, medicine, military and space technology, etc. Based on the analysis and systematisation of literature data, the authors define the main promising areas of research that will be actively developed soon: optimisation of grippers' design, flexible grippers, additive manufacturing (3D-printing) when creating grippers, collaborative grippers, modular grippers, universal grippers, grippers based on new materials, new effects in grippers, bionic and medical grippers, simulation and rendering of the gripping process.

Keywords: gripping device, object of manipulation, industrial robot, pneumatic gripping device, vacuum gripping device, jet gripping device, combined gripping device.

Notations

BGD – Bernoulli GD;
CPG – combined PG;
CPGD – combined PGD;
EVS – elastic vertical stroke;
GD – gripping device;
IR – industrial robot;
JGD – jet GD;
JMGD – jet-magnetic GD;
JOGD – jet-orienting GD;
JPG – jet PG;
JVGD – jet-vacuum GD;
MGD – mechanical GD;
MO – manipulated object;
PG – pneumatic gripper;
PGD – pneumatic GD;
PLA – polylactic acid;
RVF – rotation vertical force;
SMA – shape memory alloy;
TPA – thermoplastic polyamide;
TPC – thermoplastic co-polyester;
TPE – thermoplastic elastomer;
TPU – thermoplastic polyurethane;
VGD – vacuum GD;
VPG – vacuum PG;
VPGD – vacuum PGD.

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Introduction

According to the International Federation of Robotics (IFR 2021), which publishes its annual reports in the *World Robotics Reports* (IFR 2020), global sales of robotic products fell by 12%, down to 373240 units worth USD 13.8 billion in 2019 (without software and peripherals) after 6 years of growth and the attainment of peak values. This decline reflects the hard times experienced by the 2 main consumer industries:

- automotive;
- electrical/electronic.

However, sales of robotic products in 2019 decreased only to the level of 2017, which is not critical for this industry (Figure 1).

Given an increasingly growing introduction of robotic products, one of the main directions of robotisation is handling operations and transport operations. The efficiency of handling and transport operations at the production site depends on the correct choice of an IR, a GD, a gripping method, and the trajectory of the object of manipulation. The choice of the gripping method and GD will depend on the features of handling operations and the MO's parameters. Therefore, the issue of classifying and reviewing GDs of IRs addressed in Koustoumpardis, Aspragathos (2004); Reddy, Suresh (2013); Long *et al.* (2020); Birglen, Schlicht (2018); Bogue (2012); Boubekri, Chakraborty (2002); Chen (1982); Fantoni *et al.* (2014a, 2014b); Raval, Patel (2016); Lien (2013); Carbone (2013); Bicchi, Kumar (2000); Wolf, Schunk (2019); Monkman *et al.* (2007); Proc' (2008) and Blanes *et al.* (2011) is of crucial importance for the scientific and engineering community focused on simplifying the GD at the design stage of the robotic cell.

Koustoumpardis and Aspragathos (2004) present the classification of GDs of IRs for gripping textiles, which is a very promising area. The presented grippers are categorised according to the gripping principles: clamping, pinching or based on pins, brush, vacuum, air jets, electrostatic, adhesive methods. The investigation of human performance and the simultaneous research on the assessment of the textiles' behaviour based on the artificial intelligence methods and the intelligent control of the grippers are proposed as research areas. However, the authors do not consider the CPGDs and manufacturers' proposals to choose a more rational method of gripping textiles at the production site.

Reddy and Suresh (2013) demonstrate that the end-effector design is a critical consideration in the application of robotics to industrial operations. The end-effector must typically be designed for the specific application. However, with the current rapid development of robotics, the GDs should be unified as much as possible, and universal grippers should be developed. Regardless of the indisputable nature of the foregoing, the authors managed to cite only one example of a positive pressure universal gripper developed by Amend *et al.* (2012). Despite many of its advantages, this gripper can only be used on solid 3D-objects and is ineffective on food and other non-rigid or brittle objects. In particular, Reddy and Suresh (2013) propose a limited classification of GDs, which does not include different types of friction gripping devices, cryogenic gripping devices, JGDs, electrostatic gripping devices and VGDs.

Detailed analysis of the mechanical flexible and anthropomorphic gripping devices is presented in Raval, Patel (2016); Bogue (2012) and Chen (1982). An overview of these articles indicates a growing tendency to using flexible grippers. This is because they are better adapted to gripping objects of different shapes. The statistical analysis of MGDs broken down by manufacturers and technical characteristics presented in Birglen, Schlicht (2018) deserves special attention. This statistical analysis allows estimating the application limits and working ranges of GDs of IRs. In particular, important research areas in terms of control and rendering of mechanical grippers are summarised by Villani *et al.* (2012); Luo, Xiao (2007, 2005); Cui *et al.* (2009) and Lippiello *et al.* (2013).

The parameters of GDs and their justification considered by Boubekri, Chakraborty (2002) and Bicchi, Kumar (2000) are part of a stand-alone study with no regard to the classical review of types of GDs. In these works, the authors focused on the parameters, the gripping method of production objects using robots, and promising research areas. Lien (2013) reviewed the GDs of IRs for gripping food to address different production types. The hygienic quality of the different methods is discussed. Finally, a qualitative evaluation of the suitability of the different methods in food handling is presented. However, the author considers only the main types of GDs and does not mention specialised grippers considered by Jørgensen *et al.* (2019), and other works.

The most extensive and detailed reviews (classifications) of GDs can be found in researches by Fantoni *et al.* (2014a, 2014b); Monkman *et al.* (2007) and Proc' (2008). The authors mainly focus on mechanical, magnetic and other types of grippers but do not make correct assumptions concerning PGs. For example, in the comparative table of gripping principles and production operations, for which they are intended (Figure 2), grippers that employ a Coanda nozzle are classified as those that use the Bernoulli principle. In fact, the operation principles of these 2 GDs have distinctive features; therefore, the gripper with a Coanda nozzle should be referred to as vacuum grippers, while Bernoulli grippers should be classified as jet grippers. A similar situation can be found in research by Monkman *et al.* (2007), mainly when a wide-range of different PGs are represented by only one type – the suction gripper (Figure 3).

Based on the analysis of the publications, it was found that no precise classification of PGs exists to date. In the best-case scenario, they distinguish between the vacuum and air-jet grippers, as Koustoumpardis and Aspragathos (2004) did. Therefore, this article aims at reviewing and developing a classification of PGDs for IRs. This will make it possible to find the best solutions for various industrial operations and choose promising research areas for PGDs. As a result of the analysis of references, it is established that now most of the publications duplicate erroneous statements about PGs in general. The classification presented for the 1st time allows to analyze the choice of PG for IRs at a new level. With the help of summarized new trends in this field will allow scientists to solve pressing problems. This allows a better understanding of the construction of pneumatic gripping systems, and their advantages and disadvantages for further research and implementation.

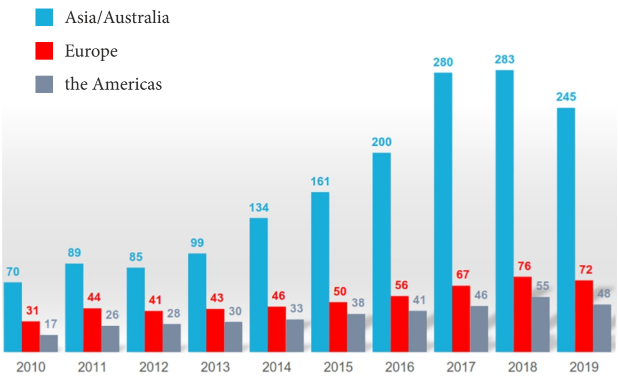

Figure 1. Annual number of installed IRs by region according to *World Robotics Reports* (IFR 2020)

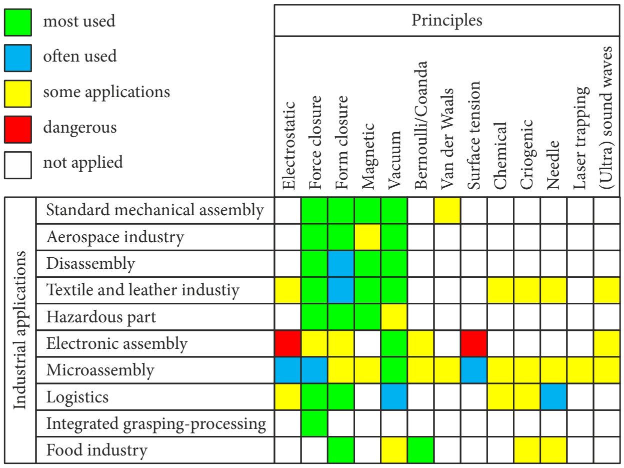

Figure 2. Grasping principles vs. applications according to Fantoni *et al.* (2014a, 2014b)

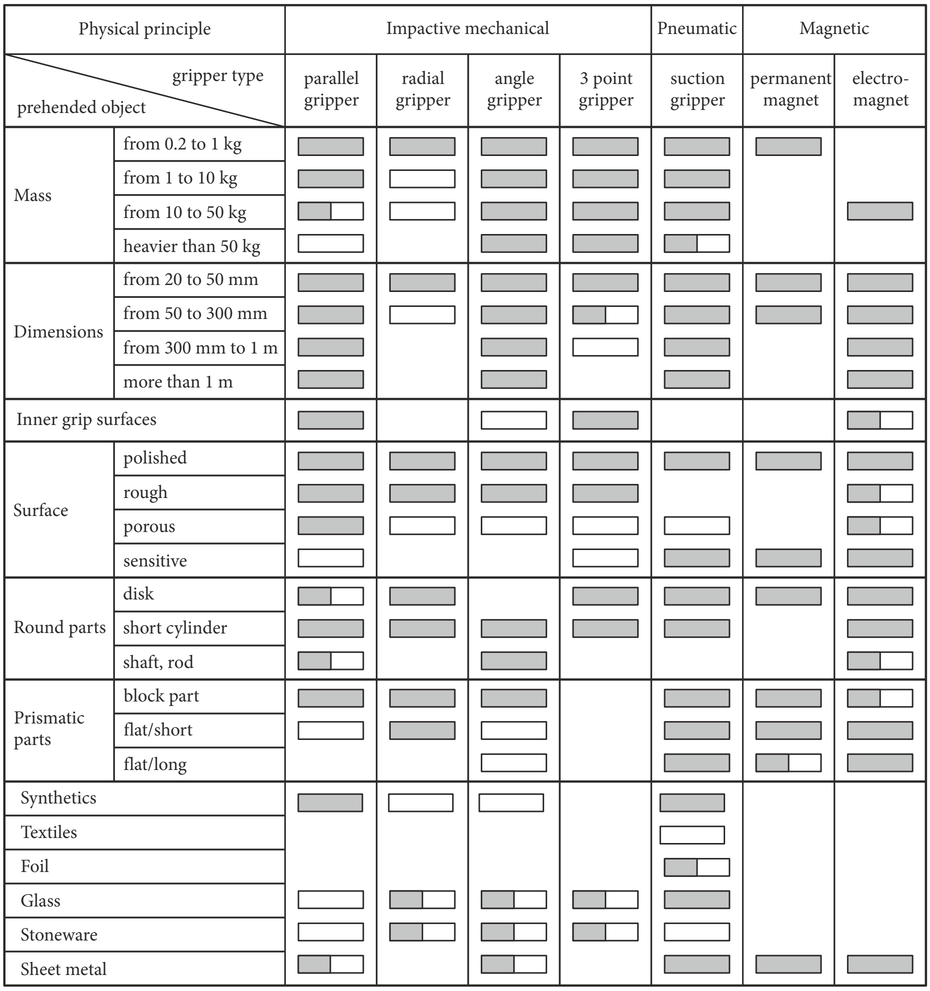

Figure 3. Rough classification of objects and the assignment of possible gripper types according to Monkman *et al.* (2007) (filled stripe – suitable; empty stripe – conditionally suitable)

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1. General classification of PGDs

The main features are identified to create a general classification of PGDs, which are common regardless of the type of PGD. Such features include:

- »» PGD type;
- »» contact type;
- »» object base type;
- »» object centring type;
- »» type of specialisation;
- »» working range;
- »» availability of additional devices;
- »» number of grippers;
- »» type of control;
- »» type of attachment to the robot.

The main feature is the type of PGD. These types of PGD include VGD, JGD, and CPGD (Figure 4).

A VGD is a device that holds an object by creating a vacuum on the object surface using a hollow working element (sucker). JGDs are devices that use compressed air as a working agent. CPGDs are devices that use different types and subtypes of PGs in their design.

According to the type of contact, PGDs are divided into 3 types (Figure 5):

- »» contact ones – the working body of the GD has a mechanical contact with the object of manipulation in a closed loop;
- »» low-contact ones – the active surface of the GD does not come into contact with the object of manipulation; friction elements or side stops are used to prevent the object from displacement;
- »» contactless (levitation) ones – the working body of the GD does not come into mechanical contact with the object of manipulation; pneumatic supports (bearings) are used to prevent the object from displacement.

The 1st type is VGD, and the last 2 types are usually JGD or CPGD (Figure 5).

According to the nature of object positioning, PGDs are divided into 2 types (Figure 6):

- »» basing;
- »» centring.

Basing PGDs determine the position of the base surface (or surfaces). These include GDs designed to grip flat objects. Centering PGDs determine the axis position or the symmetry plane of the gripped object (grippers for cylindrical objects).

Depending on the purpose, PGD can be equipped with add-ons for performing the technological operations (for example, add-ons for screwing nuts or screws, pressing parts, machining, etc.) and add-ons for controlling the object size or its presence in the GD (Fleischer *et al.* 2013; Savkiv *et al.* 2019a, 2019b).

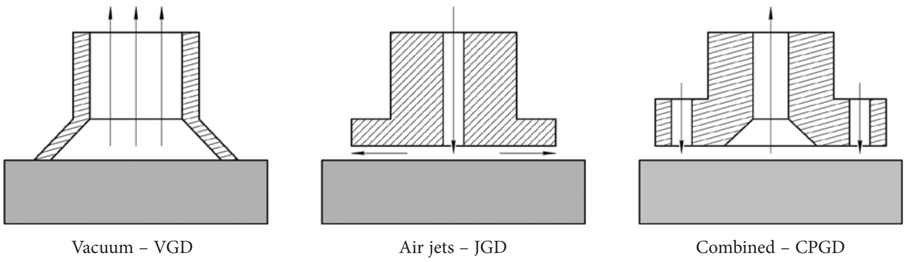


Figure 4. Schemes of operation of different types of PGDs

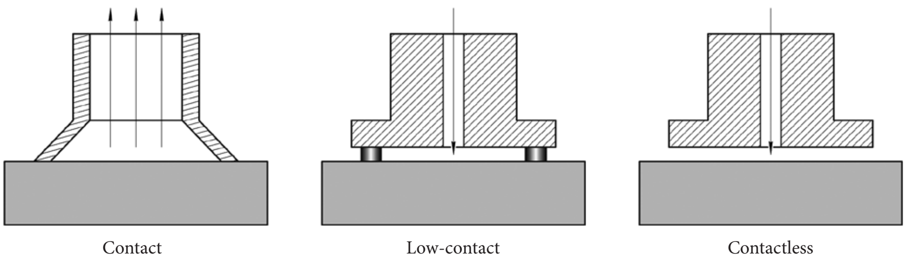


Figure 5. Schemes of the type of contact of the PGD with the object of manipulation

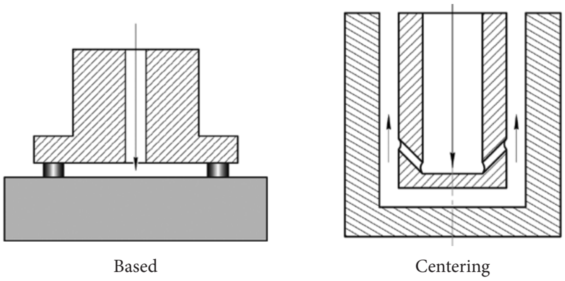


Figure 6. Schemes of the base types of the PGD with the object of manipulation

According to the specialisation type, PGDs are classified as multi-purpose, targeted and special ones. Multi-purpose PGDs are designed for gripping and holding objects by a limited range of surfaces that differ in shape or size. Targeted PGDs are adapted to gripping and holding groups of objects that have uniform structural and technological parameters. Whereas special PGDs provide for the gripping and holding of only one type of MOs. According to the operation range, PGDs are divided into 2 types (Figure 7):

- wide-range;
- narrow-range.

Wide-range PGDs can hold objects in a wide-range of gripped surface sizes and narrow-range PGDs – in a limited range, respectively.

In particular, research often focuses on the parameters of various PGDs and surface parameters of the object that affect its lifting characteristics (Gabriel *et al.* 2020). In this work, the authors introduce an experiment-based modelling method that considers the dynamic deformation behaviour of vacuum grippers in interaction with the specific gripper-object combination. In addition, we demonstrate that for these specific gripper-object combinations, the gripper deformation is reversible up to a certain limit. This motivates to allow for a gripper deformation within this stability range deliberately. Finally, the authors demonstrate the validity of the proposed modelling method and give an outlook on how this method can be implemented for robot trajectory optimisation and, based on that, enable an increase of the energy efficiency of vacuum-based handling of up to 85%.

According to the number of working positions, PGDs can be divided into single-position and multi-position ones (Figure 8). According to the type of action, multi-position PGDs are divided into 3 groups:

- sequential;
- parallel;
- combined action.

Sequential PGDs include 2-position devices that have loading and unloading positions. In each position, working elements operate independently. Multi-position PGDs of parallel action have several positions for simultaneous gripping or unloading of a group of parts. PGDs of combined action are equipped with groups of positions working in parallel. Moreover, these groups work independently of each other.

According to the control method, PGDs are divided into 3 groups:

- command (perform only commands to grip or release the object);
- programmable (relative position of the functional elements and the load capacity of such PGDs can vary depending on the program);
- adaptive (equipped with external information sensors that allow the grippers to adjust to the object parameters).

According to the type of the IR's attachment to the arm, PGDs are divided into 4 groups:

- fixed (which make an integral part of the IR's arm);
- variable (independent nodes with base surfaces for attachment to the IR);
- quick-change (base surfaces' design provides for their quick change);
- automatic-change (allow for the automatic attachment of the IR to the arm) (Figure 9).

According to all these features, a general scheme for classifying PGs was made and presented in Figure 10.

A more detailed classification of each of the main types of PGDs is discussed in the following parts of the article.

2. Classification of VGDs

VGD operate on the principle of direct suction to the MO by creating a vacuum in the volume formed by the suction cup's inner cavity and the MO surface. Despite some disadvantages, which include noisy operation, low effort of fixing MOs, short service life (especially when gripping hot products), such GDs have many advantages:

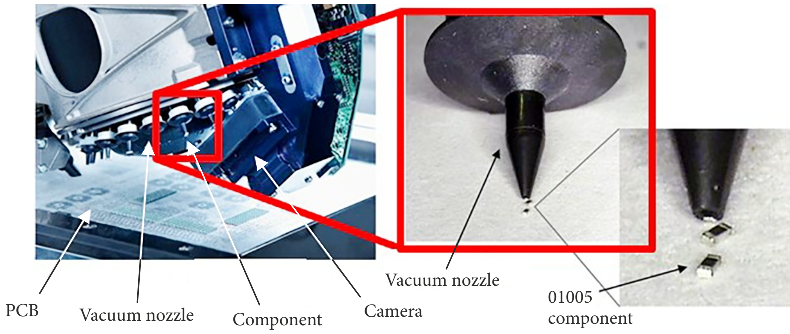
- simplicity of design, low weight;
- convenience and speed of gripping and release of products, possibility of gripping products by one surface;
- compared to MGDs, a more uniform distribution of loading on MO, which prevents damage to its surface.

VGDs are especially effective in transporting and installing of structures and products with a smooth surface made of relatively airtight material (glass, metal, stone, wood, polymeric materials, etc.). GDs consisting of several suction cups are used to grip and move bulky products to enhance their reliability. If some of them fail due to insufficiently tight contact, this will guarantee the part's retention during transportation. When gripping thin elastic plates with large suction cups, significant deformations occur, which can lead to fracture of the brittle plate material or the appearance of residual deformations if the material is sufficiently plastic. VGDs for IRs have many main features, including:

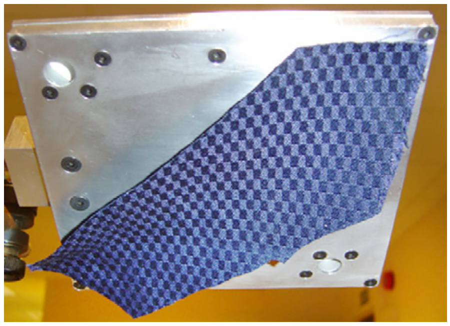
- methods of creating a vacuum;
- suction cup type;
- suction cup material.

VGD designs and their purpose depend on the method of creating air vacuum in the vacuum chamber, de-vacuation methods, etc. Vacuum can be created in suction cups using air compression when deforming working elements to the part (pumpless), increasing the volume connected to the suction chamber (piston), using vacuum generators (ejector) and vacuum pumps (Figure 11).

The performance characteristics of pumpless vacuum grippers are determined by the shape (design) of the suction cup, MO surface parameters, and movement parameters of the gripper when extruding air from under the suction cup. The operational characteristics of pumpless vacuum grippers are determined by the shape (design) of the suction cup, the parameters of the surface of the MO and the parameters of the movement of the gripper during the extrusion of air from under the suction cup.

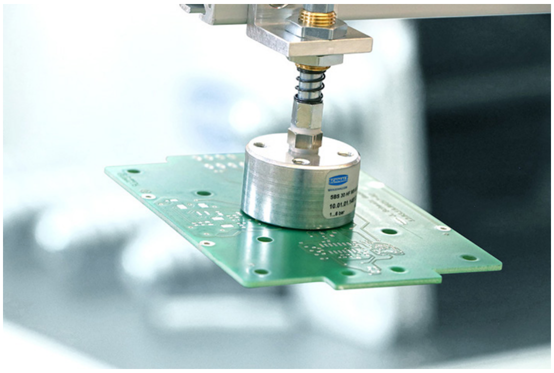


Narrow-range

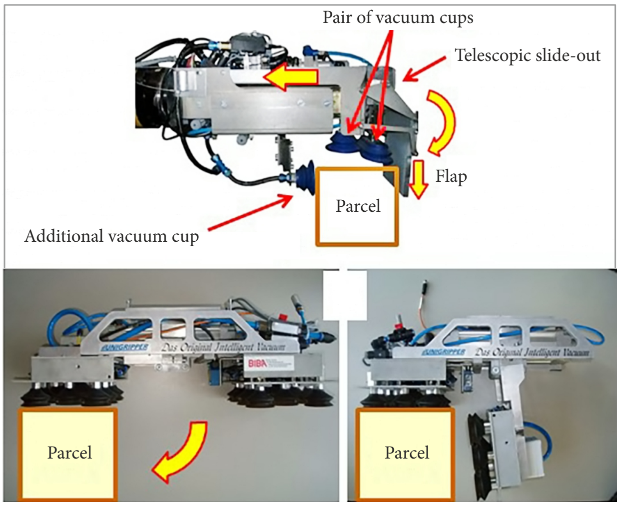


Wide-range

Figure 7. Schemes of the position types of the PGD (Pfeffer *et al.* 2011; Lien, Davis 2008)

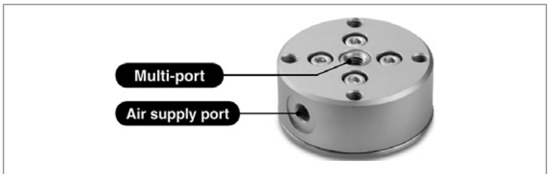


Single-position



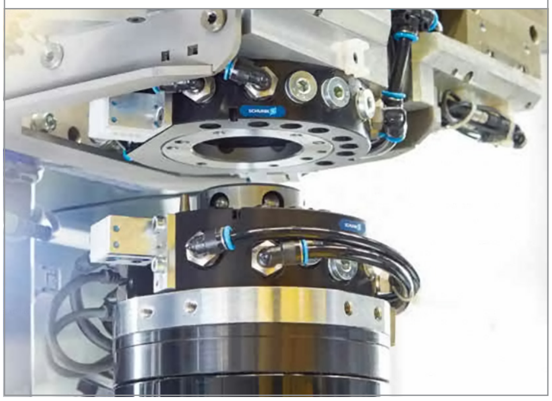
Multi-position

Figure 8. Schemes of the position types of the PGD (Schmalz 2021a; Fantoni *et al.* 2014a, 2014b)



Change

Fast-changing



Automatically-changing

Figure 9. Schemes of different types attachment to the robot (SMC Corporation 2021d; Schmalz 2021c; Schunk Inc 2021)

Depending on the method of generating a vacuum under the suction cup of the gripper, they distinguish between different effects that can provide for a vacuum. The parameters of the vacuum gripper will depend on the effect used to generate the vacuum (Figure 12).

Pumping/fan vacuum generators usually employ electrically driven units in the form of vacuum pumps, blowers with side channels, radial fans or axial fans. However, this type of vacuum generation has several disadvantages. Having a large throughput, this type of generator must suck air from the gripping system using large diameter hoses – Lien, Davis (2008); Fantoni *et al.* (2014a, 2014b); Reinhart, Straßer (2011) (Figure 13). The disadvantage of this type of vacuum generators is the need for sufficient cooling of electric motors required for their operation – Reinhart *et al.* (2010); Reinhart, Straßer (2011). There are fan vacuum generators integrated in VGD – Hernando *et al.* (2021). This solution is used for mobile systems when it is impossible to supply the airline.

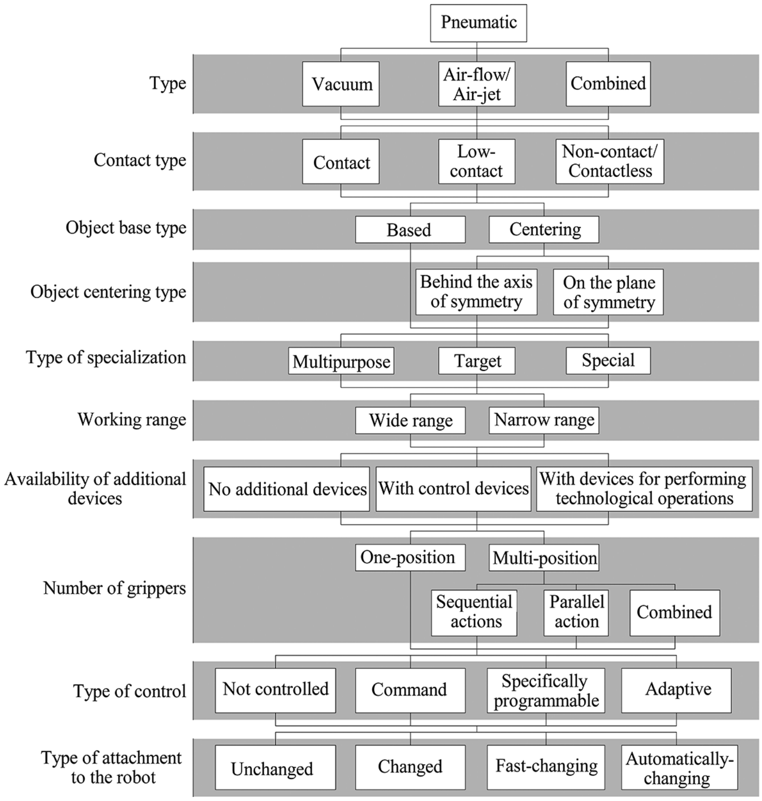


Figure 10. General classification of PGDs

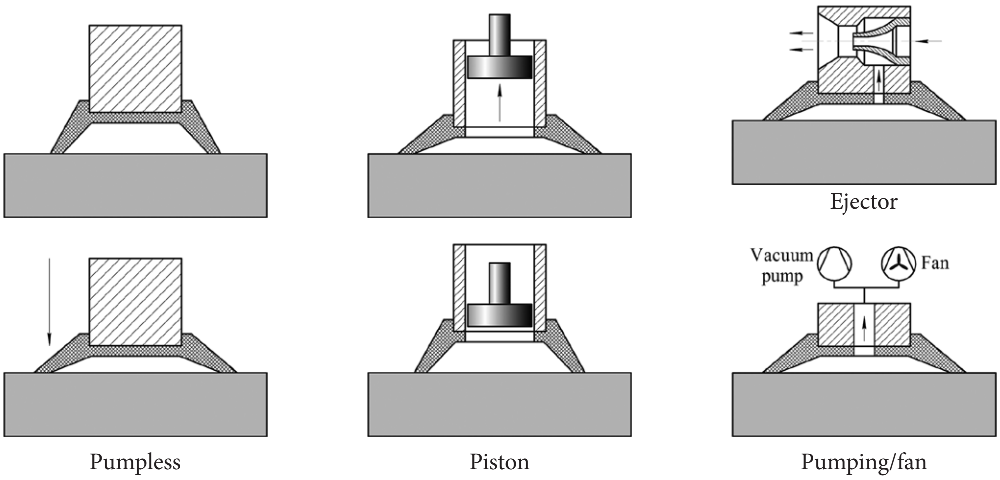


Figure 11. Methods of vacuum formation under the suction cup of the gripper

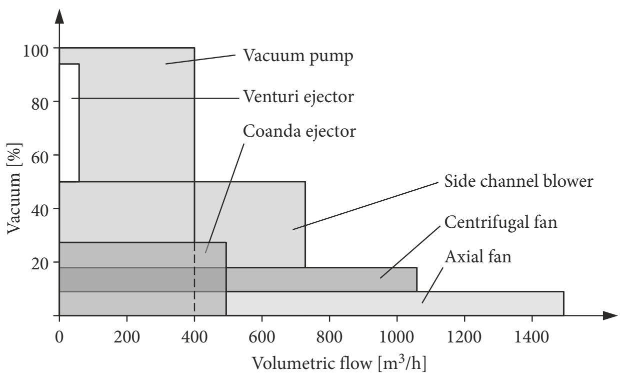


Figure 12. Different vacuum generators and their power range (Fleischer *et al.* 2016)

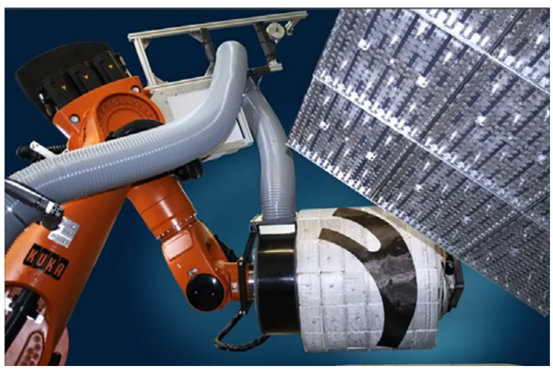


Figure 13. Vacuum gripper for contour-variant parts (Reinhart, Straßer 2011)

In particular, the Pumping/Fan vacuum generator is known for its specific feature: the loss of contact at one of the global suction points causes a decrease in pressure in the entire gripping system. This problem can be solved by using a self-activating valve system – Andersen, Christensen (2004) (Figure 14). When the suction cup is located in front of the empty zone, the airflow automatically closes the valve. Furthermore, when the suction cup is located in front of the object surface, the valve remains open, which creates a vacuum under the suction cup. Therefore, a vacuum is created only where it can grip the object of manipulation, which prevents depressurisation of the entire system. In this way, vacuum grippers can grip objects with holes and non-planar objects of manipulation.

Self-activating valve systems are also relevant for other types of vacuum grippers. In particular, Takahashi *et al.* (2013) proposed a flexible vacuum gripper with miniature lattice valves; the valves usually close and open when in contact with the object of manipulation (Figure 15).

Since the gripper is made of a flexible polymeric material, and only the valves that come into contact with the object can open to suck the surface, this gripper can hold a surface of a free shape, such as objects with steps, holes, different curvatures, and so on. In particular, the valve can switch autonomously between open and closed areas.

However, grippers with a decentralised vacuum system are usually used in GDs. Therefore, the flexibility of such exciting systems is much higher due to their adaptability. Such systems include elements that use compressed air to form a vacuum in the cup of the gripper. These elements are called ejectors. Since ejectors do not contain moving parts, they work without wear and do not require maintenance. These are the advantages of using them – Fantoni *et al.* (2014a, 2014b); Götz (1991); Hesse (2011). For jet vacuum grippers, a vacuum can be created using 2 effects (Figure 16):

- »» a Venturi ejector (Fox Venturi Products Inc 2021);
- »» a Coanda (Fleischer *et al.* 2016).

Another advantage of using ejectors for vacuum grippers is integrating ejectors into individual grippers due to their small size (Figure 17).

However, as can be seen from Figure 12, these 2 types of ejectors have opposite characteristics. In particular, the Venturi ejector (Liu 2014; Xu *et al.* 2016, 2020; Liu *et al.* 2016; Hill *et al.* 1990, 1992; Samad *et al.* 2012; Olaru 2020), provides maximum vacuum at minimum consumption, while the Coanda ejector (Wu, Li 2020; Xie 1993; Fleischer *et al.* 2013; Lien, Davis 2008; Natarajan, Onubogu 2012; Natarajan *et al.* 2018; Dumitrache *et al.* 2011; Sierra *et al.* 2017; Cîrciu, Dinea 2010; Cîrciu, Rotaru 2019), provides average values of vacuum at high consumption. Therefore, Venturi ejectors are used with vacuum grippers for smooth and uncontaminated objects of manipulation, which prevents vacuum breaking during gripping. On the other hand, Coanda ejectors are used with porous objects because vacuum breaking does not critically affect the lifting force and makes it possible to grip penetrating objects of manipulation. However, it should be noted that these statements are valid for single-stage Venturi ejectors. In particular, multi-stage Venturi ejectors (SMC Corporation 2021a) shown in Figure 18 and high-pressure Venturi ejectors, which provide a higher flow rate at a lower vacuum, are available on the market.

Less popular are also reciprocating vacuum grippers, which use a piston as a vacuum generator that increases the volume of air in the air chamber of the gripper drive, thereby providing a vacuum in the working area – Schaffrath *et al.* (2021) (Figure 19).

Design 1 (Figure 19) was developed by Freudendahl *et al.* (2019), whereas design 2 is a counterpart of what is discussed by Haines *et al.* (2014). The drive used in design 3 is described by Gümpel (2004). This design differs in terms of the selected drive and method of movement. These piston vacuum grippers can be divided into 2 subspecies according to the method of movement:

- »» variant 1 – 1, 6, 7 and 8 – according to the movement of the piston;
- »» variant 2 – 2, 3, 4 and 5 – by the movement of the membrane.

Each of the designs has its advantages and disadvantages (Figure 19). Variant 1 can work decentrally and vacuum several suction cups simultaneously, which has a positive effect on maintenance. However, in this case, the piston stroke will be very long, occupying much space. In variant 2, on the contrary, the membrane can help reduce the drive size; however, the manufacture of such structure is more expensive. A more detailed analysis of structures 2, 3, 4, 8 is presented by Schaffrath *et al.* (2021).

Each VPG has a suction cup, which plays a vital role while gripping objects of manipulation by IRs. In general, there are several types of suction cups: flat, ribbed, flat with double grips, bellows, nozzle, area, spongy, combined, special and 3D-printed (Figure 20).

From the perspective of the gripping process, flat suction cups are most flexible, which makes it possible to fix the object of manipulation tightly. Ribbed suction cups are used to dampen the blow against the object of manipulation, and when the object of manipulation is flexible and can block the air intake duct. The double-grip suction cup is used to grip objects with high roughness or protrusions to ensure a tighter fit of the suction cup and prevent depressurisation. Bellows suction cups are used for handling delicate, uneven objects of indefinite height. The flexible vertical stroke of the bellows can be used to grip an object from an uneven surface or lift it directly from a depth. A striking example of using such grippers is described by Jørgensen *et al.* (2019). In this work, the bellows suckers are selected because of the variable size of the object of manipulation and its different shape, which allows compensating the bellows (Figure 21).

The operation of the bellows can be divided into 2 stages:

- »» the suction cup is located above the object, without the action of external forces;
- »» a vacuum is created, and the object of manipulation rises, reaching a state of equilibrium.

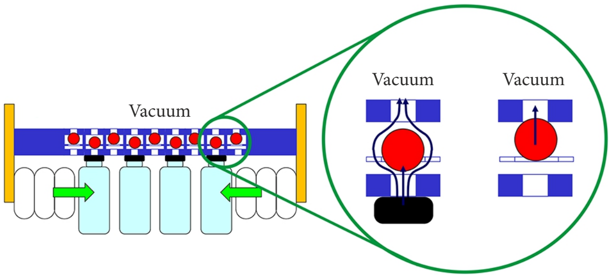


Figure 14. Self-activating valve system (Andersen, Christensen 2004)

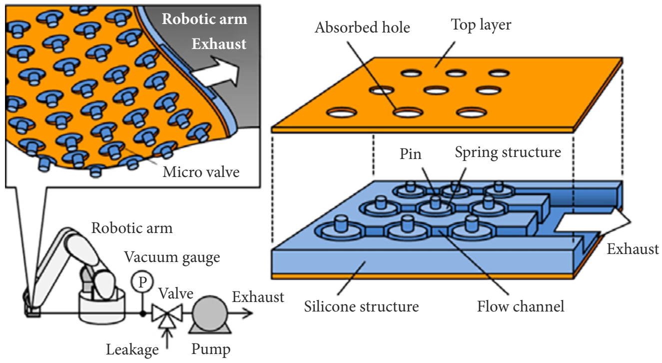
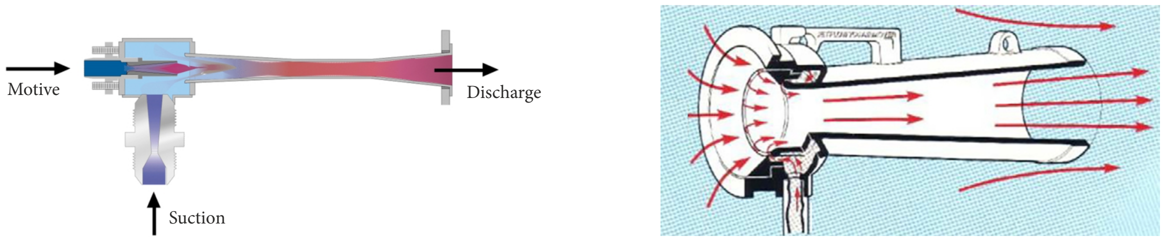
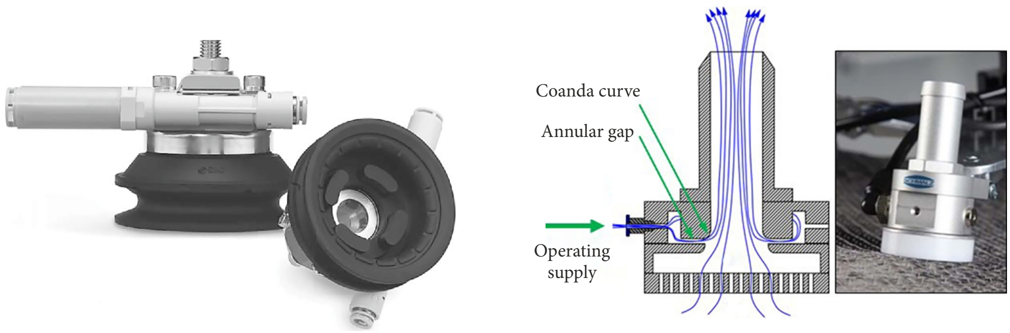


Figure 15. Concept of flexible vacuum gripper with self-directed valve (Takahashi *et al.* 2013)



Venturi Coanda

Figure 16. Types of ejectors used in vacuum grippers (Fox Venturi Products Inc 2021; Rajalakshmi *et al.* 2017)



Venturi Coanda

Figure 17. Ejectors integrated in GDs (SMC Corporation 2021c; Fleischer *et al.* 2016; Schmalz 2021b)

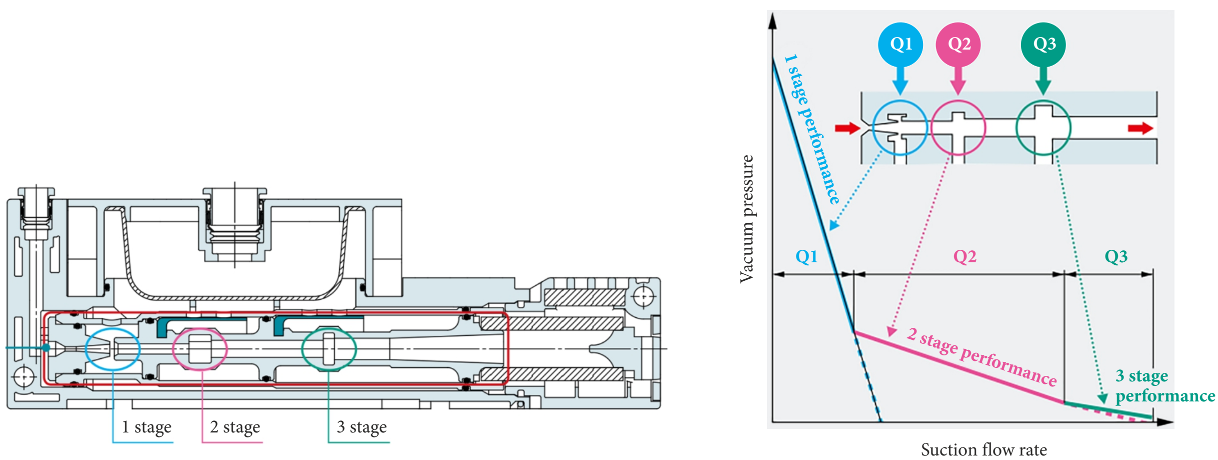


Figure 18. Multi-stage ejector (SMC Corporation 2021a)

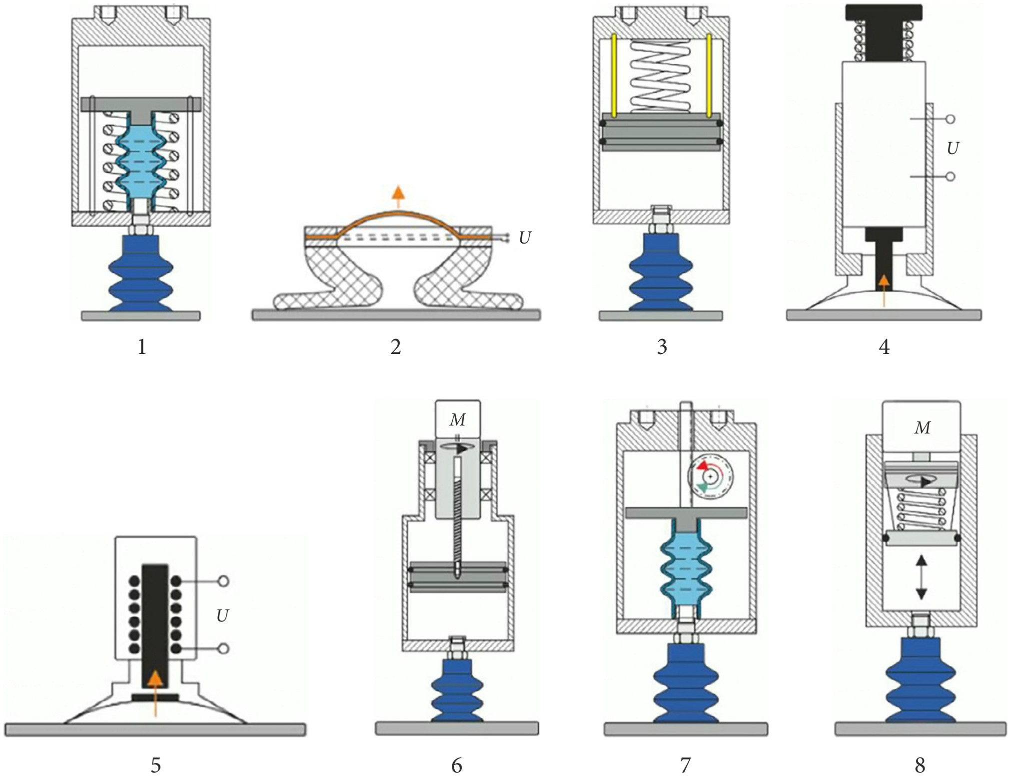


Figure 19. Possible solution variants for vacuum grippers without central compressed air supply: 1 – SMA wire; 2 – dielectric elastomer actuator; 3 – twisted nylon fibers; 4 – electric hoisting (lifting magnet); 5 – magnetic attraction of an iron plate; 6 – spindle drive; 7 – pinion-gear; 8 – winding up threads (Schaffrath *et al.* 2021)

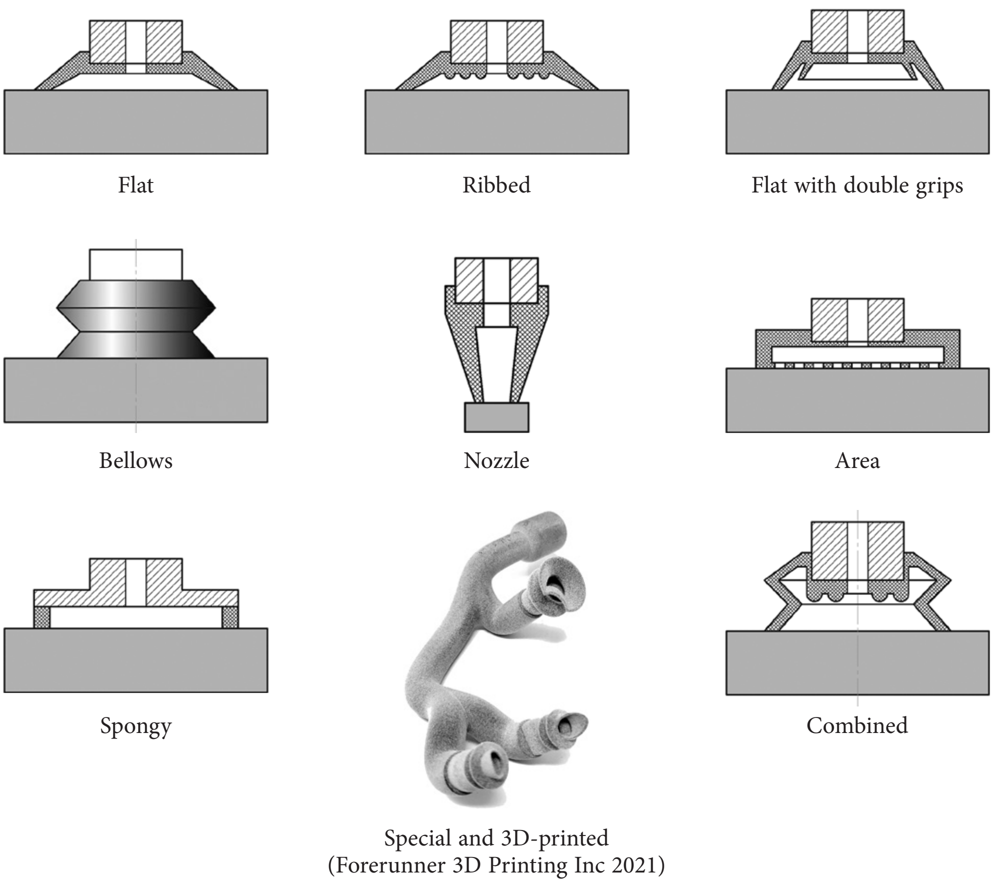


Figure 20. Designs of suction cups of vacuum PGDs

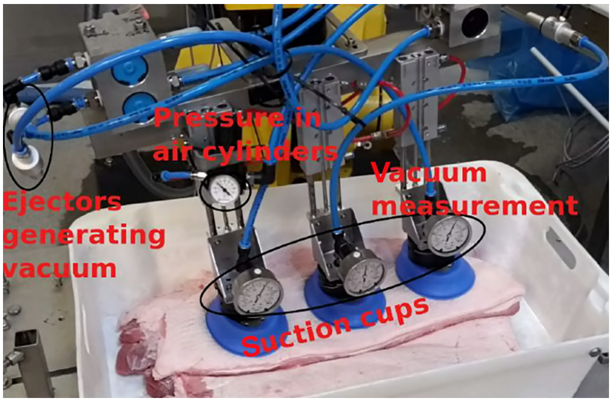


Figure 21. Use of bellows-type vacuum grippers for transportation of meat products (Jørgensen *et al.* 2019)

Nozzle suckers are used for small-sized objects of manipulation. Moreover, the nozzle diameter is also selected depending on the size of the object. Area suction cups are commonly used for gripping low-weight textile and flexible objects, where it is crucial to have a large gripping area with little force. For example, in Makarov *et al.* (2018), area suction cups are developed for gripping bags with their subsequent filling. Spongy suckers are used for gripping smooth objects such as glass, plastic, and so on. Special and 3D-printed ones are very widely used, as they are created for a specific shape and material of the object. Combined suction cups are used quite often and have a special device to ensure maximum lifting force and prevent vacuum breaking under the suction cup.

From the perspective of manipulating objects with suction cups of different designs, the main factor is deforming the suction cup during accelerations and decelerations. Such deformations may cause the object to slip and hit the gripper. Therefore, depending on the suction cup design, there are specific recommendations for their use in certain movements by the IR – Monkman *et al.* (2007) (Figure 22). In addition, many studies have been conducted to determine the optimal parameters of the movement of vacuum grippers – Al-Hujazi, Sood (1990); Mantriota (1999, 2007a, 2007b).

Another critical parameter that affects the gripper and its application is the material from which the suction cup is made. Of all the known materials used in production, the most popular is silicone, as it has all the conformity certificates concerning contact with other objects (including food). To analyse the materials of the suction cups of vacuum grippers, Jakymchuk *et al.* (2017) present Table with relevant data.

According to Table, one can choose the parameters of the suction cup material, which satisfy the technological task and provide for minimal wear of the suction cup. However, at the present stage of production and development of 3D-printing, other materials are often used for making both the grippers and suction cups. Flexible materials are typically used to provide for flexibility and compressibility under vacuum (Renganathan 2020): TPEs, TPU, TPC, TPA, soft PLA, nylon and others. However, non-flexible materials (plastics, composites, metals, etc.) are also used for making suction cups of vacuum grippers. A striking example of using solid material to minimise the price and weight of the suction cup is a metal-printed 3D-suction cup (Figure 23) – Materialise Inc (2021).

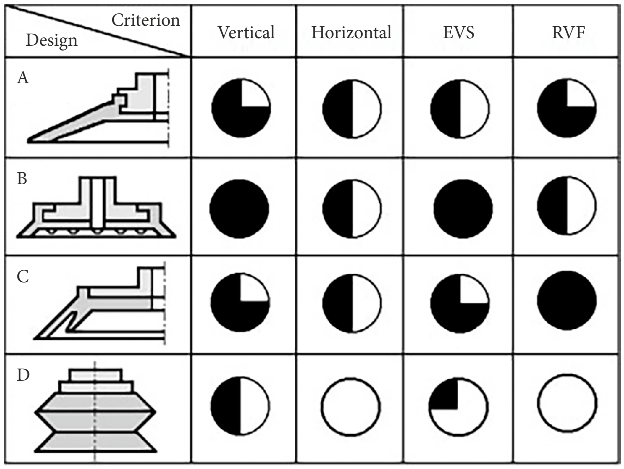


Figure 22. Application of sucker designs at specific movements (Monkman *et al.* 2007): empty circle – scarce; 1/4 – rare; 1/2 – from time to time; 3/4 – often; completely filled – very often

According to all these features, one can draw a general scheme for classifying VPGs in Figure 24.

Knowing the classification (Figure 24), advantages and disadvantages of all types of vacuum grippers, it is essential to determine the lifting force of such grippers. In the general case, the calculation of vacuum GDs is reduced to providing the lifting force, which is determined by the Equation:

$$F = S \cdot K_s \cdot \left(P_a \cdot K_a - P_r\right) \cdot K,$$

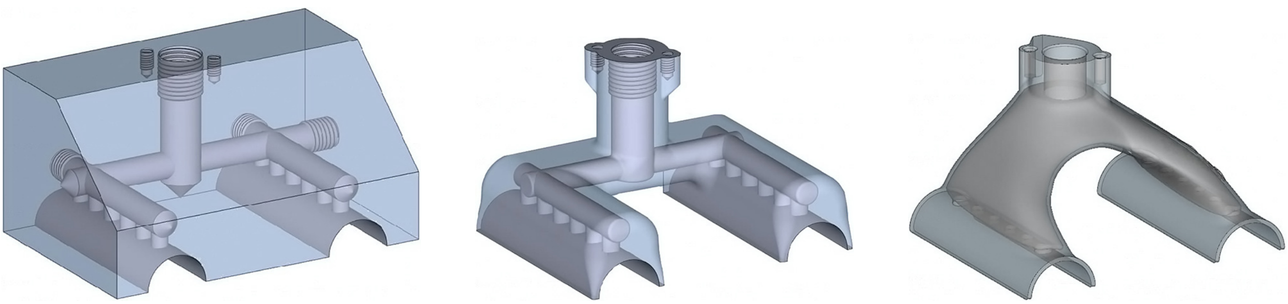
where: F is lifting force [N]; S is the area limited by the inner contour of the suction cup [m^2]; K_s is the area reduction coefficient of the suction cup due to the seal deformation (≈0.95…1.00 for the seal made of porous rubber); P_a is the atmospheric pressure [Pa]; P_r is the residual pressure inside the chamber [Pa]; K_a is the coefficient, which takes into account changes in atmospheric pressure (≈0.90); K is the lifting force reserve coefficient, which takes into account the air inflow at the point of contact between the chamber seal (suction cup) and the surface of the object of manipulation (≈1.15...1.50).

The ingress of air through the leakages in the sealing zone of the suction chamber reduces the speed and lifting force of the vacuum gripper. For certain types of VGDs with a sealing ring connected to a vacuum generator, the pressure in the inner cavity of the working chamber is taken to be equal to the vacuum pressure created by the generator. The vacuum depth in the suction chamber and the lifting force depend on the characteristics of the vacuum source.

Table. Suction cup materials and areas of their application (Jackymchuk *et al*. 2017)

Material of suction cup	Perbunan	Polyurethane	Silicon	Viton	Perbunan antistatic
Code of material	N	U	S	F	NA
Durability	++	+++	+	++	+++
Terms of use					
Food			+		
Oiled surface	+	+		+	+
High temperature			+	+	
Low temperature		+	+		
Antistatic					+
Thin films, prints			+	+	
Resistance					
Atmospheric conditions	++	+++	+++	+++	++
Ozone	+	+++	+++	+++	+
Oil	+++	+++	+	+++	+++
Fuel	++	++	+	+++	++
Solvents	++	+	++	+++	++
Acid solutions	+	+	+	+++	+
Alcohol	+++	+++	+++	++	++
Temperature range [°C]	−10…+70	−20…+60	−30…+180	−10…+200	−10…+70
Shore hardness [A]	50 ± 5	60 ± 5	50 ± 5	60 ± 5	50 ± 5

Notes: + good; ++ very good; +++ excellent.



Conventional design 3D-printing design by the customer Final 3D-printing design by materialise

Figure 23. 3D-printing metal suction cup vacuum gripper (Materialise Inc 2021)

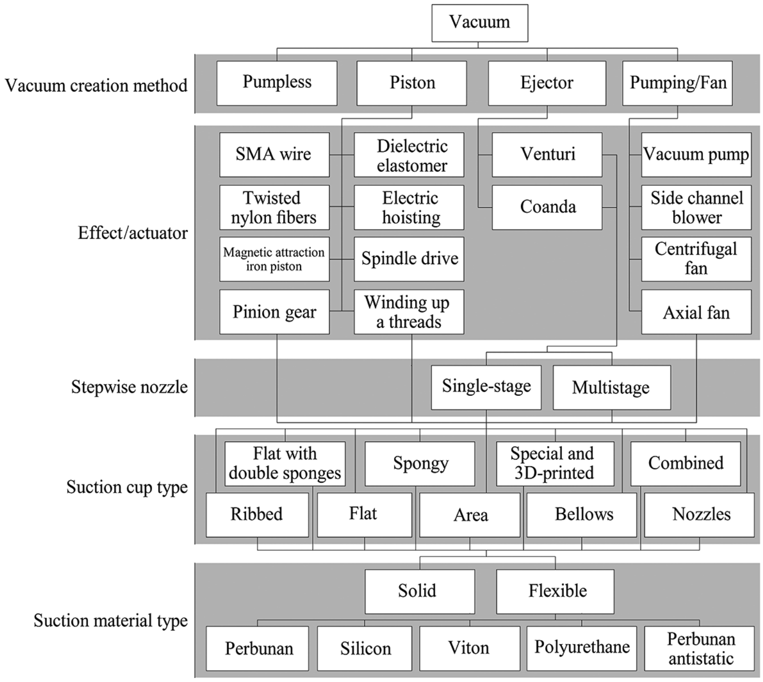


Figure 24. Classifications of VPGDs

However, when choosing the type of VPG at the current production stage, the most crucial factor is the energy cost of maintenance, which is related mainly to the parameters of the object of manipulation. In Gabriel *et al.* (2020), the authors introduce an experimental modelling method that considers the dynamic deformation behaviour of VPGs that interact with a specific combination of MOs (Figure 25).

Gripper deformation was also shown to be permissible for such specific combinations as the "gripper – object of manipulation". This allows setting the gripper deformation level within its stability range. During the previous research, the modelling method for optimising the trajectory of robots was substantiated, which will increase the energy efficiency of vacuum grippers by up to 85%. Another case of trajectory optimisation is a study presented in the research by Mykhailyshyn *et al.* (2019). The authors proposed to use the force of inertia generated during the transportation of objects for holding the MO and thus minimise the holding force of various pneumatic gripping systems. The application of this technique has reduced the energy costs of transporting objects to 69%, taking into account the cost of reorienting the object of manipulation by an IR.

3. Classification of JGDs

In recent years, various devices of jet technology have been widely used, which perform gripping, orientation, transportation and control of individual parts under the action of compressed air. Pneumatic JGDs intended for gripping and orienting parts of various configurations, materials, and weights occupy an essential place. JGD designs described by López-Arias *et al.* (2011); Park, Moon (2012); Becker *et al.* (2009); Brandt (1989); Huber (2006); Winborne *et al.* (1976) are based on the well-known lifting force effect that occurs when the airflow formed by nozzle elements by-passes flat, cylindrical or spherical surfaces. Compared with VGDs (Monkman *et al.* 2007), jet grippers have many advantages: they provide for a high-accuracy object basing; they can hold flexible, brittle and high-temperature objects; they have the best dynamic characteristics; they are structurally simple and durable. In particular, one can identify several main features for classifying JPGs:

- »» method of using a jet of compressed air;
- »» shape of nozzle elements;
- »» number of nozzle elements;
- »» directions of gas flows;
- »» surface type of the MO.

The most crucial feature of JGDs is the method of using a compressed air jet, by which 4 groups of JGDs can be distinguished (Figure 26):

- »» "nozzle with a developed end surface";
- »» ejection;
- »» vortex;
- »» support.

JGD "nozzle with a developed surface of the end face" with a nozzle axis perpendicular to the gripping plane is designed for loading parts weighing up to 1 kg and having a pronounced flat surface – Erzincanli, Sharp (1997); Armengol *et al.* (2008); Kamensky *et al.* (2019); Li, Kagawa (2014); Savkiv *et al.* (2018a, 2018b, 2019a, 2019b, 2020a, 2020b, 2020c, 2021); Maruschak *et al.* (2019); Shi, Li (2016, 2018). The jet that flows from nozzle 1 towards body 2, which is alienated from the nozzle, acts on it by the forces of viscous friction created by the flow that adheres to the body surface and the reactive repulsive force. As the distance between the nozzle end and the object surface decreases, the suction action of the jet becomes predominant in comparison with the reactive force, which reaches a maximum at a distance between the interacting surfaces $h = 0.1...0.3$ mm. To avoid lateral displacements caused by friction forces in the end plane, the object lifted to the nozzle end is fixed to the base elements protruding above the nozzle end by $h > 0.2$ mm (friction pads 3) (Mykhailyshyn *et al.* 2021), or using lateral supports. This type of JPGs with deflectors are often used to have food gripped and transported by IRs – Davis *et al.* (2008); Petterson *et al.* (2010); Sam, Buniyamin (2012).

A distinctive element of JGDs is the presence of the annular gap in the plane of their end face – Ozcelik, Erzincanli (2002, 2005); Mykhailyshyn, Xiao (2022); Ozcelik *et al.* (2003); Brun, Melkote (2006, 2009, 2012); Renn *et al.* (2008); Toklu, Erzincanli (2012); Giesen *et al.* (2013); Liu *et al.* (2017, 2019); Savkiv *et al.* (2019a, 2019b); Mechatronic Systemtechnik GmbH (2021). Load-bearing characteristics of these grippers exceed those of the previous ones; therefore, they are used for gripping parts weighing up to 10 kg. We consider a JGD design shown in Figure 26. JGD housing 1 contains a conical insert 2. The central hole's chamfer forms annular conical slit 3 at the end of the gripper. In the process of leakage from the slit, the annular conical air jet, which is forced to the surface brought to the gripper end that handles the object, flows into the gap between the housing's end surface 1 and MO 4 in the form of a flat radial flow, causing the effect of lifting due to ejection. To avoid displacement, the MO is fixed at the gripper's end face using friction forces caused by the object's contact with the friction elements, which protrude above the end face of housing 1 by $h > 0.15$ mm. In their article, Liu *et al.* (2021) demonstrated the ability to increase the load capacity of JGDs due to the ejector with a Coanda nozzle installed at the JGD's inlet. The use of JGDs in medicine has become widespread (Trommelen 2011; Ertürk, Samtaş 2019; Ertürk, Erzincanlı 2020) because these grippers can grip flexible objects such as organs and tissues during invasive operations.

However, JGDs are very costly due to their design features. Therefore, Savkiv *et al.* (2017a, 2017b, 2017c, 2018a, 2018b), Mykhailyshyn *et al.* (2017, 2018a, 2018b), propose having JGDs oriented by an IR during transport operations. They proposed a method for optimising the JGD orientation with 3 frictional elements on a straight trajectory (Savkiv *et al.* 2017a, 2017b, 2017c) and arc trajectory (Savkiv *et al.* 2018a, 2018b). The orientation was chosen to have the lifting force generated by the forces of inertia and gravity and the force of frontal air resistance, which occur when transporting objects of manipulation by an IR.

Load-bearing properties of JGDs are considered by Dini *et al.* (2009). This article discusses "nozzle with a developed surface of the end face" employed by JGDs, and a JGD design with a branched active surface of the gripper end intended for gripping leather goods (Figure 27).

The research has found that depending on the leather, microrelief and permeability type, the lifting force of each of these structures will be different. For MO with a smooth surface and low permeability, the lifting force will be greater with "nozzle with a developed surface of the end face", while for more porous and non-smooth surfaces, it is better to use G2.2 and G3.2 designs (Figure 27), depending on the case. Since "nozzle with a developed surface of the end face" and JGDs employ the Bernoulli effect to create a vacuum on the MO surface, they are often classified as one type and called BGDs.

Vortex JGDs have a much longer working range during the gripping and holding of MO – Li *et al.* (2008, 2011); Morimoto *et al.* (2010, 2011); Wu *et al.* (2012, 2013); Zheng *et al.* (2013); Blazhnov (2014); Xin *et al.* (2016); Kim, Lee (2015); Zhao, Li (2016, 2021a, 2021b); Wang *et al.* (2019); Zhao *et al.* (2019); Chandran *et al.* (2019); Konishcheva *et al.* (2020). Figure 26 shows the principle of operation of the vortex JGD manufactured by SMC Corporation (2021b). The principle of operation of the vortex JGD is that the compressed air fed through the tangential nozzles made in the gripper body enters the cylindrical chamber. Due to the tangential displacement of the nozzles to the cylindrical chamber, the airflow is swirled and, under the action of centrifugal forces, made to move along the gripper end. This generates a vacuum in the cylindrical chamber and the difference between atmospheric pressure, due to which the MO is lifted to the gripper end or friction elements. Load-bearing characteristics of vortex JGDs are less sensitive to the MO gripping (retention) distance than ejection JGDs. As a result, vortex JGDs are more often used when gripping and transporting objects with an uneven surface (boards with soldered elements, objects with holes, etc.). In addition, using this effect, vortex JGDs are used in the construction of mobile robots, Figure 28, for holding them on horizontal planes (walls, glass, etc.) – Zhao *et al.* (2018).

However, not only vortex JGDs are used for holding a mobile robot on horizontal planes. Ejection JGDs are also suitable for this purpose Wagner *et al.* (2008); Journee *et al.* (2011). The Li *et al.* (2015) compared the ejection and vortex JGDs in terms of energy efficiency and load-bearing characteristic (Figure 29). They found that in terms of deformations and stresses in the MO gripped by ejection and vortex JGDs; they are identical. From the perspective of the effect caused by MO roughness on load-bearing properties, ejection JGDs have better characteristics than vortex ones with increasing MO roughness. In terms of energy efficiency, the authors conclude that when the same lifting force is provided, the ejection JGD has a higher compressed air consumption than the vortex JGD. All authors' conclusions are correct, but it should be noted that the vortex JGD was chosen for the study and optimised by the authors themselves. At the same time, the ejection JGD was used by Festo Inc (2021a) without optimising the nozzle elements and active surface.

In addition to vortex JGDs that use air leakage from the nozzle located tangentially to the inner cylindrical surface of the gripping chamber, vortex JGDs are developed, which operate from a fan located in the gripper chamber – Li, Kagawa (2013); Rahul *et al.* (2020); Shi, Li (2020) (Figure 30).

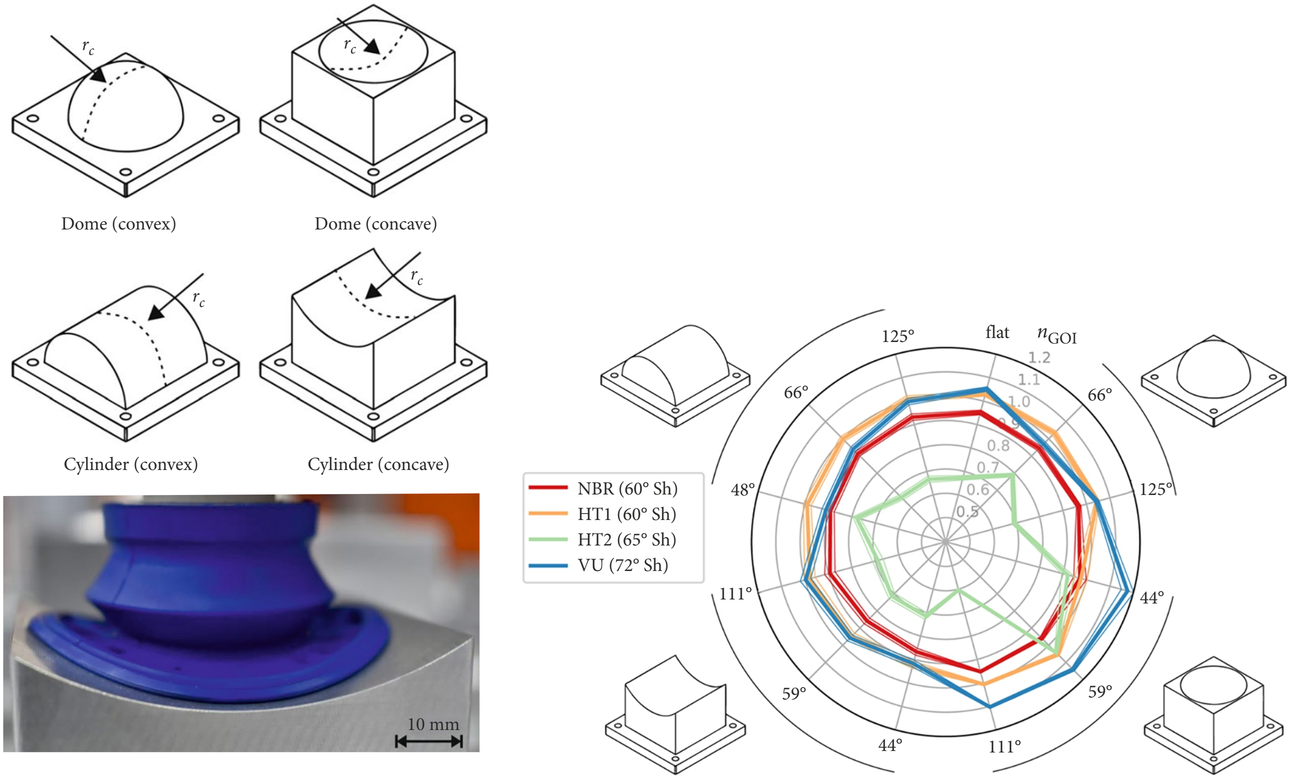


Figure 25. According to Gabriel *et al.* (2020), the object geometry influences the achievable holding force significantly

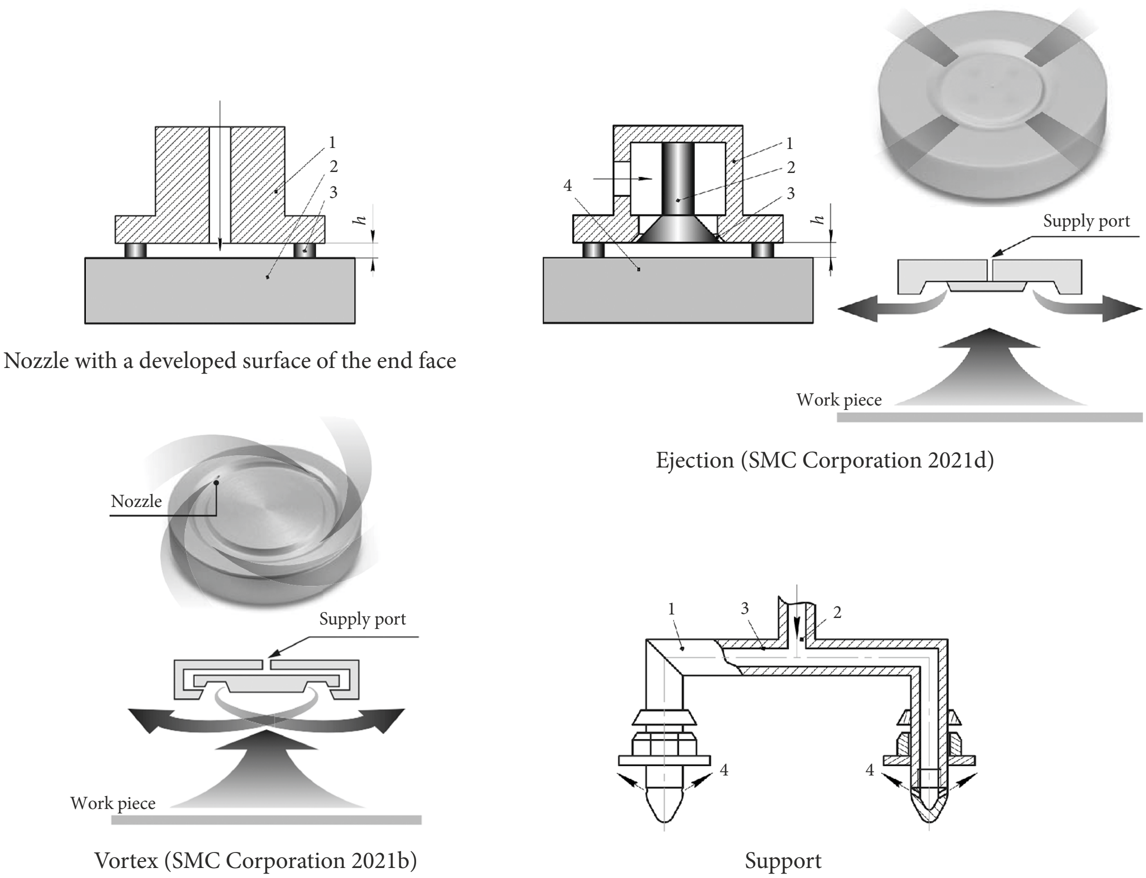


Figure 26. Types of JGDs according to the method of use

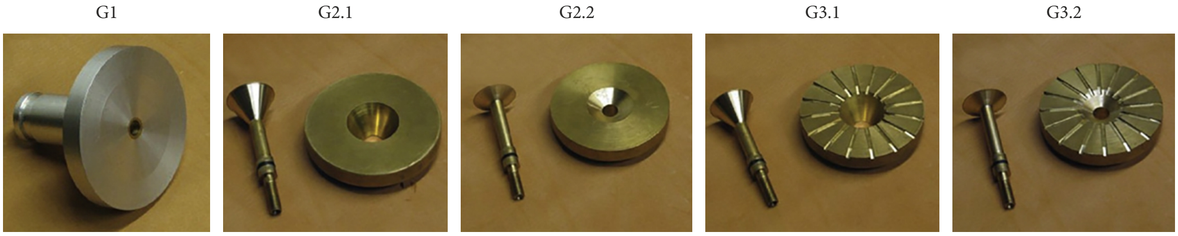


Figure 27. Designs of the studied JGD according to Dini *et al.* (2009)

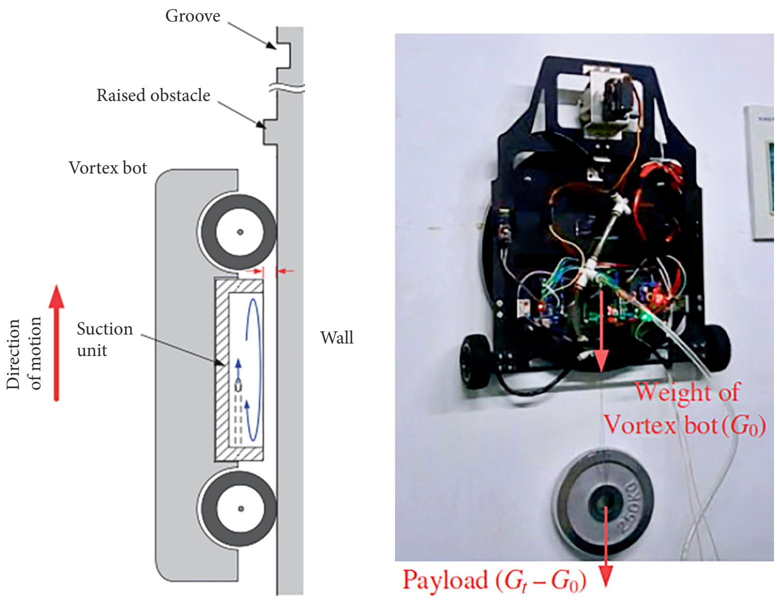


Figure 28. Use of vortex JGD to keep the mobile robot on a horizontal wall (Zhao *et al.* 2018)

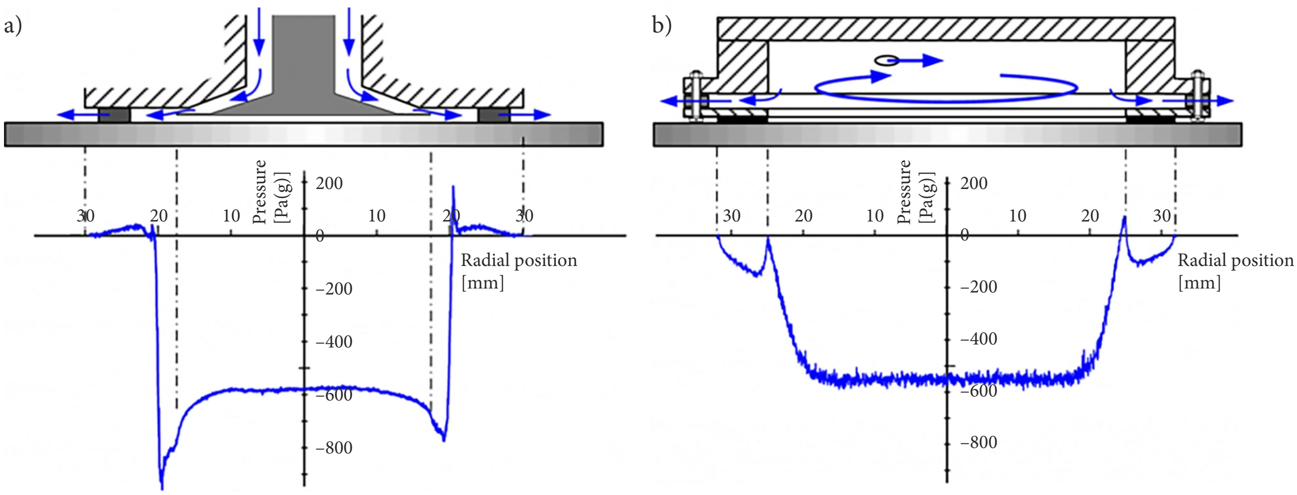


Figure 29. Power characteristics of ejection and vortex: a – Bernoulli gripper (Q = 36 L/min);
b – Vortex gripper (Q = 15 L/min) (Li *et al.* 2015)

The studies of vortex JGDs using swirl vanes suggest that they are an alternative to conventional vortex JGDs (Figure 29b) when it is impossible to bring the air line to the place where grippers are used. At the same time, vortex JGDs using swirl vanes have a lower lifting force than classical vortex grippers. This is because classical vortex JGDs have a uniform vacuum under the gripping chamber, while the vacuum generated in JGD using swirl vanes decreases from the centre to the edge of the gripping chamber.

Support JGDs described by Savin-Czeizler, Lang (1985); Edwards, Kramer (1986); Kramp (2012); Kusano (2010) and Lang, Draht (2009) are widely used in precision instrumentation, electronics and related industries when working with flat and cylindrical small-sized objects of low weight. One of the advantages of such devices is the ability to complete products or accumulate objects and combine the gripping process with the orientation process. Structurally, such devices represent a housing 1 (Figure 26), which acts as a distributor of airflow coming through the inlet channel 2 and moving through the supply channels 3 of working nozzles 4. The presented design of the support JGD is intended for gripping MO through openings: shunts, stators and rotors of variable capacity condensers, conventional and spring washers, nuts, etc. During gripping, working elements 5 are introduced into the openings of objects 6, 7, and the air stream is fed into working nozzles 4. The latter is made at an angle to the working elements 5 so that the air jets flowing from nozzles 4 press objects 6 and 7 to limiter 8. Support JGDs that serve flat objects without a through-hole may have a different design (Savin-Czeizler, Lang 1985). In any case, objects are gripped and fixed under the action of an air jet flowing at a certain angle to the working element's plane. Typically, support JGDs have highly specialised characteristics and applications; therefore, such GDs are not mass-produced but are a specific solution for gripping specific cylindrical MO.

Another special feature of JGDs is the shape of the nozzle elements, namely (Figure 31): cylindrical nozzle, slotted rectilinear nozzle, slotted open curved nozzle, slotted closed curved nozzle. Known designs of JGDs (Figure 26) most often use cylindrical or slotted closed curved nozzles. JGDs with a cylindrical nozzle or annular slot nozzle are the most technological in production.

Another essential feature of a JGD that affects the gripper's characteristics is the number of nozzle elements (Figure 32). In particular, JGDs can be single-nozzle and multi-nozzle.

A JGD uses more than one nozzle element to increase the GD's lifting force. Another reason for using multiple nozzle elements in the JGD may be providing for a more uniform lifting force on the MO surface. In addition, increasing the number of nozzle elements in the JGD allows increasing the stability of the MO retention in contactless transportation and orientation in space. For this reason, Liu *et al.* (2020) developed a JGD equipped with 4 closed curved nozzles to ensure an even distribution of forces during the gripping of flexible objects (Figure 33).

An essential feature of JGDs, which has a critical effect on the gripping of brittle and easily deformable MOs, is the direction of gas flows relative to the MO surface. There are 3 types of gas flow directions (Figure 34):

»» parallel;
»» perpendicular;
»» at an angle to the MO.

Using different directions of gas flows allows obtaining various JGD characteristics and minimising the pressure drop on the MO surface when using the parallel direction of gas flows.

Depending on the shape of the object of manipulation, JGDs are classified according to the type of gripping surface (Figure 35): JGDs intended for flat, cylindrical or arbitrary (spherical) MO shapes.

Catalogues of most companies selling pneumatic equipment contain JGDs intended specifically for gripping the MO by the flat surface. This is because gripping the MO by the flat surface is universal and is most common in production. In addition, GDs for cylindrical and other arbitrary surfaces are made for specific technological processes and are usually special. However, the article by Petterson *et al.* (2010) present research findings on using adaptive JGDs (Figure 36).

Based on all the features presented, a general scheme for classifying JGDs is presented in Figure 37.

It is noteworthy that BGD usually refers to the nozzle with a developed surface of the end face and ejection JGD. This is because the lifting force in these GDs is formed by the aerodynamic effect of lifting and is determined by Bernoulli's law. Appearance and characteristics of industrial designs "Bernoulli gripper OGGB" (Festo Inc 2021a) are shown in Figure 38.

4. Classification of CPGDs

CPGD for various handling and transport operations are becoming widespread. It should be noted that PGs are combined not only with each other but act as the principle and auxiliary grippers when combined with other types of grippers (mechanical, magnetic, adhesive and others). Therefore, a feature should be added to the classification of CPGDs – a possibility to combine with other types of grippers. Since CPGDs have all the classification properties of their types included in the combination, only distinctive features for such grippers will be included in the CPGD classification (Figure 39).

In the 1st place, we consider the CPGDs, which combine only pneumatic methods to create a lifting force – Mechatronic Systemtechnik GmbH (2021); Stühm *et al.* (2014); Savkiv *et al.* (2017a, 2017b, 2017c). A striking representative of such GDs can be a JVGD (Stühm *et al.* 2014) (Figure 40).

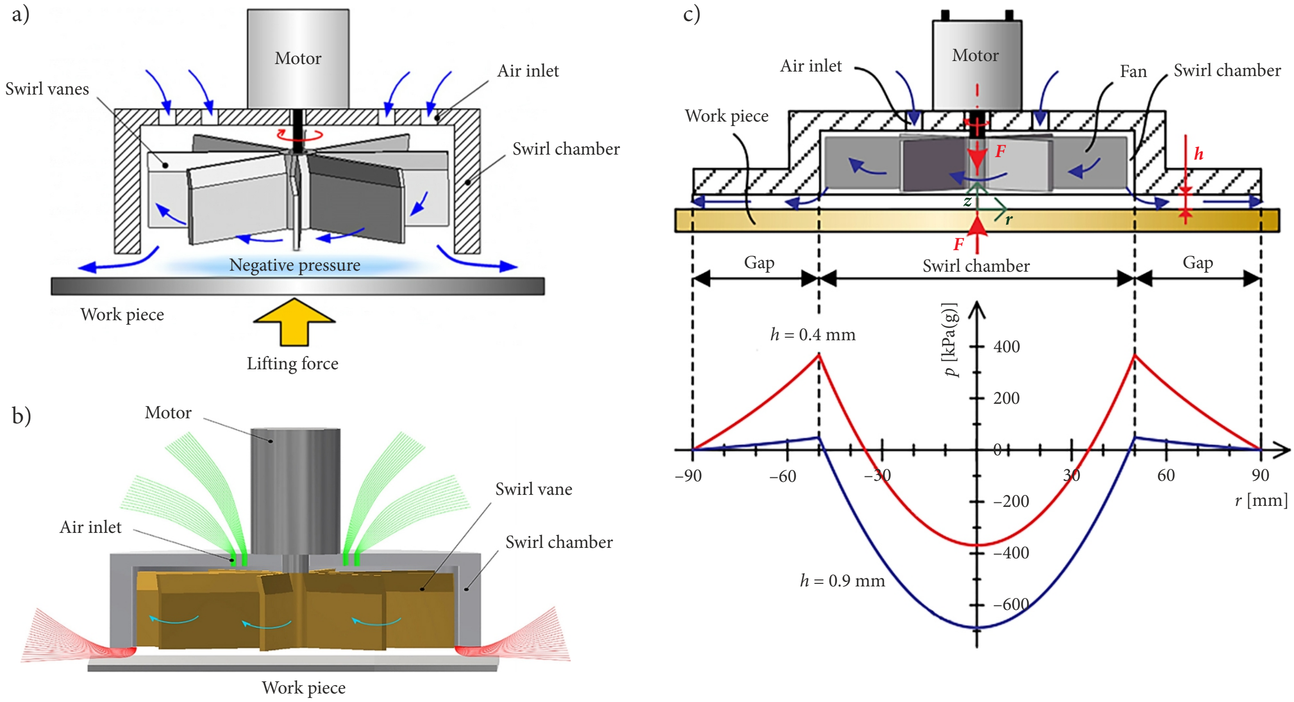


Figure 30. Vortex JGD using swirl vanes: a – Li, Kagawa (2013); b – Rahul *et al.* (2020); c – Shi, Li (2020)

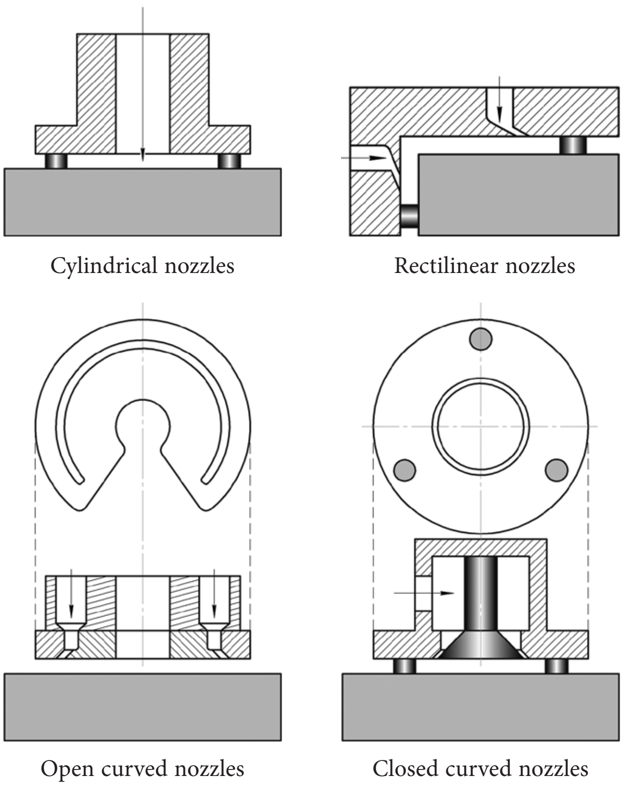


Figure 31. JGDs with different forms of nozzle elements

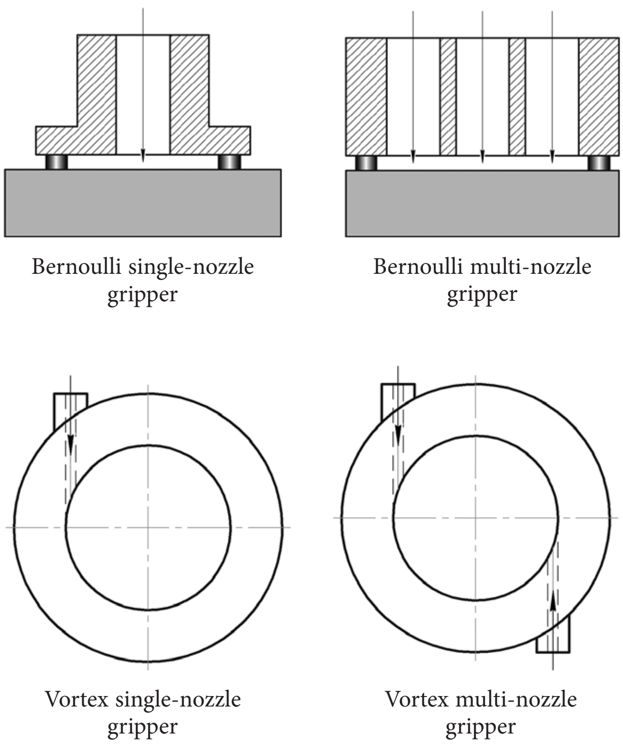


Figure 32. JGD with different numbers of nozzles, for example, vortex and Bernoulli grippers

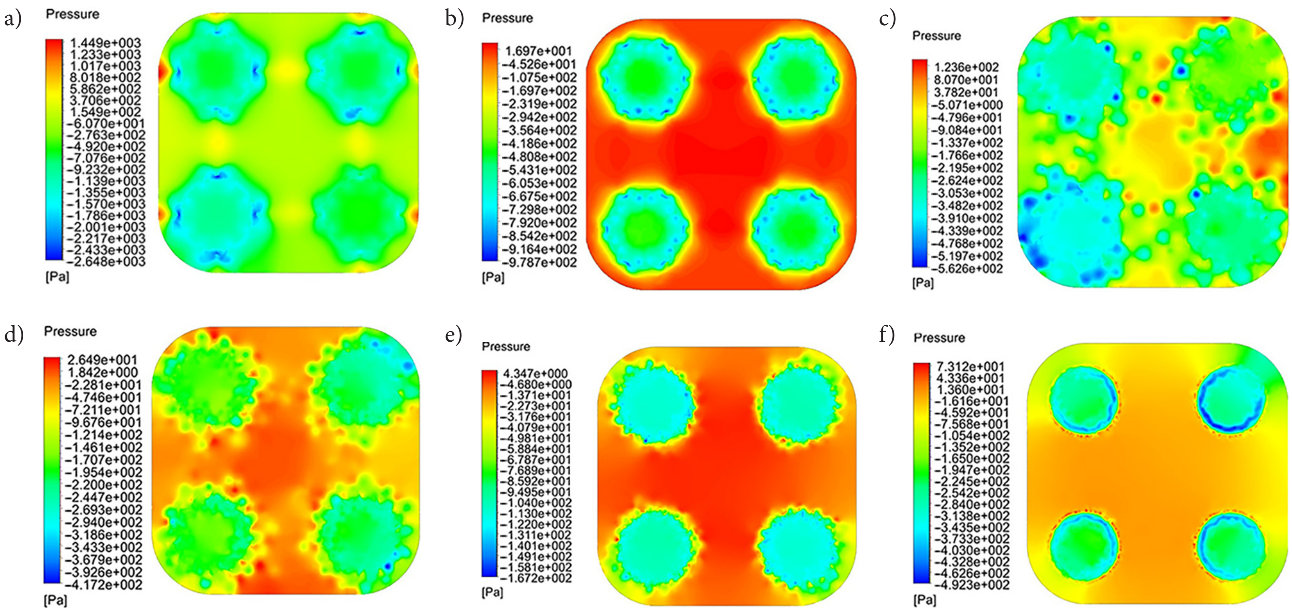


Figure 33. Pressure distribution on the contact area for multi-nozzle JGD (Liu *et al.* 2020): a – gap quantity 4; b – gap quantity 6; c – gap quantity 10; d – gap quantity 14; e – gap quantity 18; f – gap quantity ∞

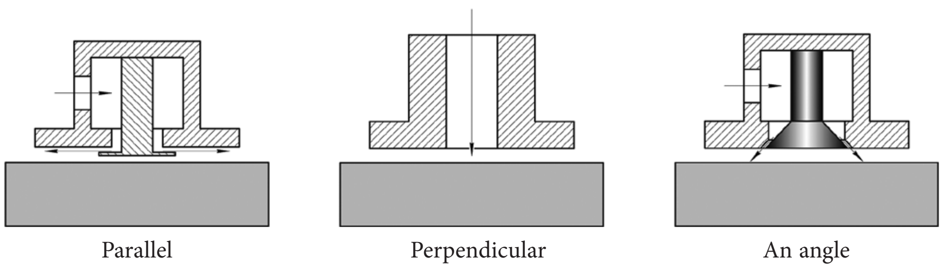


Figure 34. JGD with different directions of gas flows, on the example of BGDs

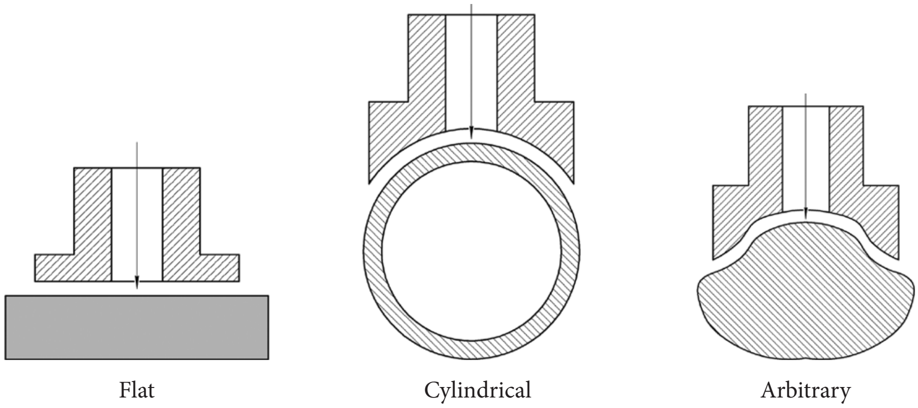


Figure 35. JGD for different types of MO surface shapes, on the example of BGDs

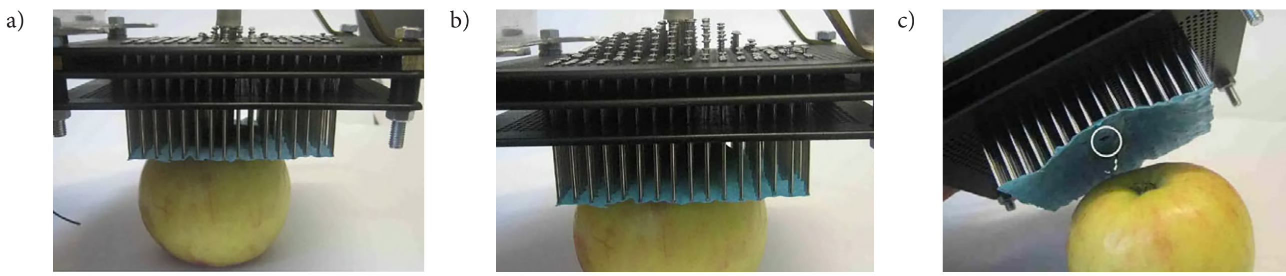


Figure 36. Adaptive JGD (Petterson *et al.* 2010): a – forming of the gripper surface by pressing the gripper against the product; b – matrix pins protrude on the top side during forming; c – the shape is locked (in the centre of the gripper, the air inlet is circled)

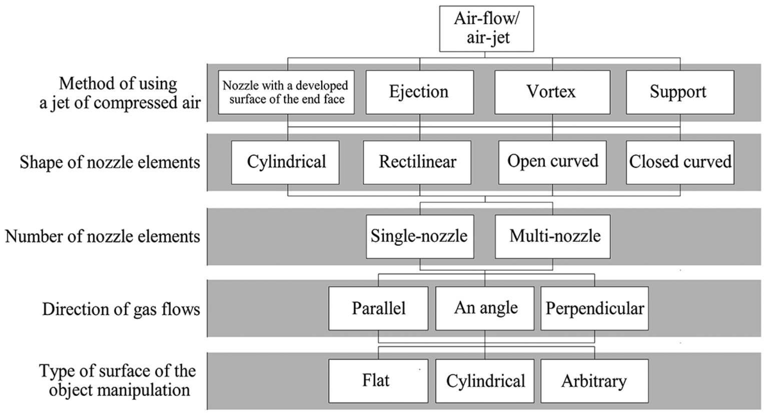


Figure 37. Classifications of pneumatic JGDs

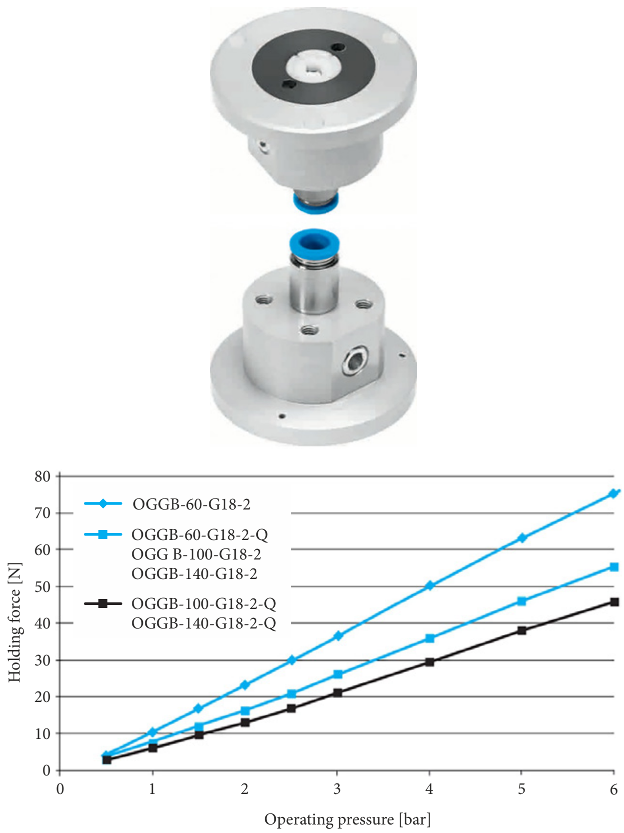


Figure 38. Parameters of Bernoulli gripper OGGB (Festo Inc 2021a)

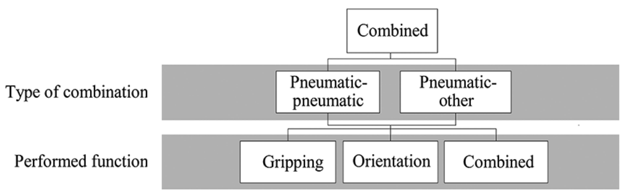


Figure 39. Classifications of CPGDs

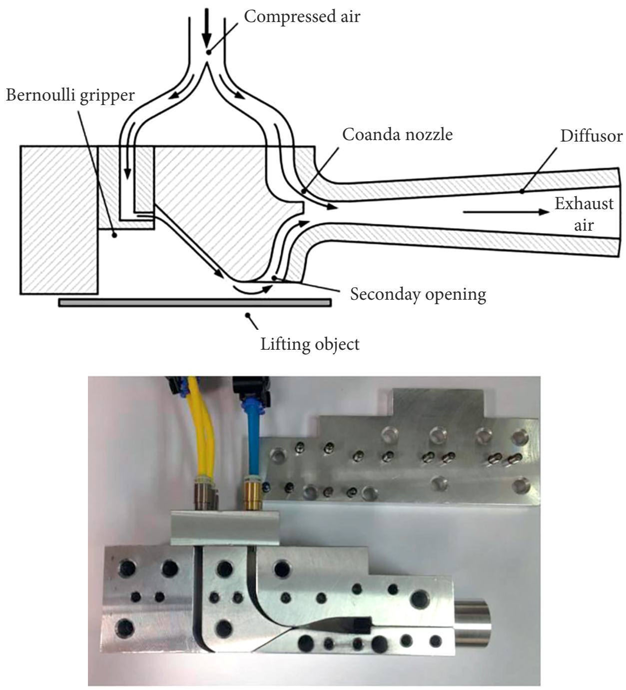


Figure 40. Principle of work jet (ejection) – vacuum (Coanda) PGD (Stühm *et al.* 2014)

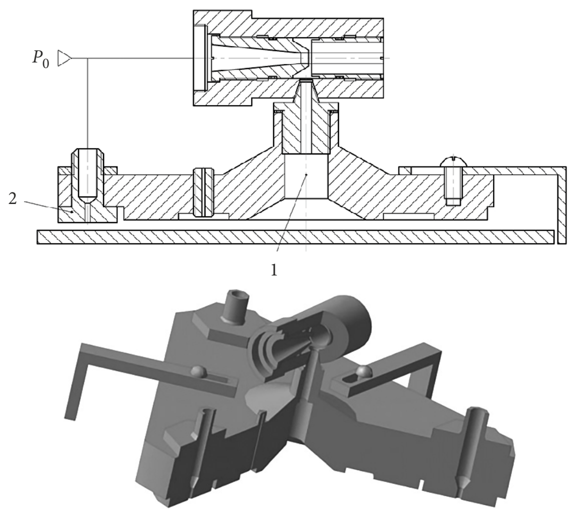


Figure 41. Principle of work jet – VPGD (Savkiv *et al.* 2017a, 2017b, 2017c)

This CPGD (Figure 40) is designed for non-contact gripping of brittle objects of manipulation, namely, elements of batteries, boards, silicon wafers, etc. Another CPGD with similar characteristics is the JVGD – Savkiv *et al.* (2017a, 2017b, 2017c) (Figure 41). It differs from other CPGDs because its main lifting force is provided by a rigid vacuum suction 1 (P_0 supply of compressed air to the ejector and grippers). In addition, 3 Bernoulli grippers 2 can grip the MO from a greater distance, thus ensuring the lack of impact during its gripping and lack of contact during its subsequent retention.

Another essential type of CPGD is a combination of PGDs and MGDs – Tawk *et al.* (2019); Derby, Lippiatt (2005); Marsova *et al.* (2020). They have many advantages, as they combine all the strengths of their main types. For example, consider a flexible mechanical-vacuum CPGD – Tawk *et al.* (2019) (Figure 42).

The main advantages of this CPGD design (Figure 42) include the initial grip of the vacuum suction cup, which allows gripping the MO from different distances without damaging it. Otherwise, all the elements would simply bend, even when pressing the MO. Another advantage of this gripper is the wide-range of flexible fingers, making it possible to grip objects of different shapes and sizes.

Compared with the gripper (Figure 42), PGs can be used in the CPGD as the main holding mechanism – Derby, Lippiatt (2005) (Figure 43).

As can be seen from the CPGD design (Figure 43), the spatula, which is driven by a pneumatic cylinder, plays the role of an auxiliary mechanism that allows separating the MO from the surface, on which the gripping occurs. Moreover, the object of manipulation is held by VPGDs.

In addition to the holding and feeding functions, CPGD may include the MO orientation functions, often performed by PGDs. For example, consider the CPGD for gripping razors from the assembly line – Michalos *et al.* (2018) (Figure 44).

As can be seen from the design of the pneumatic-mechanical CPGD (Figure 44), "manipulation module" is used to orient the razor in the gripper chamber, after which compressed air is supplied to the "|front nozzle", and MO is fed to the working area "grasping module", where the already oriented MO is gripped mechanically with a servo drive. However, there is a CPGD design in which the gripping and orientation functions are built on a pneumatic principle – Savkiv *et al.* (2012a) (Figure 45).

At the core of the patent (Figure 45) is the contactless angular orientation of objects such as bushings, short tubes, etc. The device operation envisages its preliminarily positioning under the object of manipulation 2. From pressure source 8 through air line fitting 7 and hole 6, the compressed air enters working chamber 5. Next, through a tube for injecting compressed air 12, the compressed air enters the additional working chamber 9. From nozzle 4 and additional nozzle 10, compressed air flows into the environment. At the same time, the compressed air attacks the surface of MO 2 at an angle $\alpha = 15\ldots 45°$ from additional nozzle 10. Under the action of friction force generated upon contact of compressed air with MO 2 surface, the latter begins rotating. As the distance h decreases, an elastic airbag is formed between surface 3 and MO 2. When fixation hole 17 and nozzle 4 coincide, an object of manipulation 2 is fixed in the required position for the start-up. Longitudinal groove 11 is designed to prevent the interaction between airflows coming from nozzles 4 and 10. By changing the position of bolt 16, the MO gripping angle can be changed. Thus, the proposed JOGD allows for the contactless gripping, orientation and transportation of objects such as bushings, short tubes, etc. Another possible combination is magnetic and PGDs. A remarkable representative for gripping magnetic and non-magnetic MOs is a JMGD (Savkiv *et al.* 2012b). This combination makes it possible to achieve contactless transportation of magnetic objects, which is very relevant for coated or heated MO.

Another representative of combined grippers is the bionic gripper from Festo Inc (2021b) (Figure 46). This CPGD includes elements of a flexible vacuum-enclosing gripper, and its shape resembles the tentacles of an octopus. Among its suction cups, there are 8 active suction cups, where a vacuum generator forms the vacuum, and 10 passive suction cups, in which the vacuum is generated using deforming suction cups. This CPGD has a high gripping force for capturing cylindrical objects and is usually used for this purpose.

In recent years, universal flexible gripping devices for IRs (Brown *et al.* 2010) have become very popular because they have many advantages, among which are devices for MO and a high weight-lifting capacity. Based on all the advantages of universal flexible grippers, Fujita *et al.* (2018) developed a CPGD (Figure 47), which combines a vacuum gripper with a universal flexible gripper.

The design of the universal VGD (Figure 47) allows gripping the MO, which can not be handled using conventional VPGD. This is attained due to a highly flexible vacuum suction cup, which is deformed under vacuum. Next, an external ejector or a vacuum line generates a vacuum in the gripper cavity. A gripper of this kind is very promising and can be used in many processes, which previously required various design gripping devices for a particular case.

5. Perspective directions of researches of gripping devices of IRs

Needless to say that promising research areas in the field of gripping devices of IRs will be directly related to the production tasks and promising research areas in the field of IRs. While analysing the latter research by Sanneman *et al.* (2020), we find the authors' opinion: "<…> Robotic gripping in which robots can hold or pick up or manipulate objects is still far behind human gripping capabilities. A large robotic manufacturer we interviewed described physical gripping hardware as an enormous challenge.

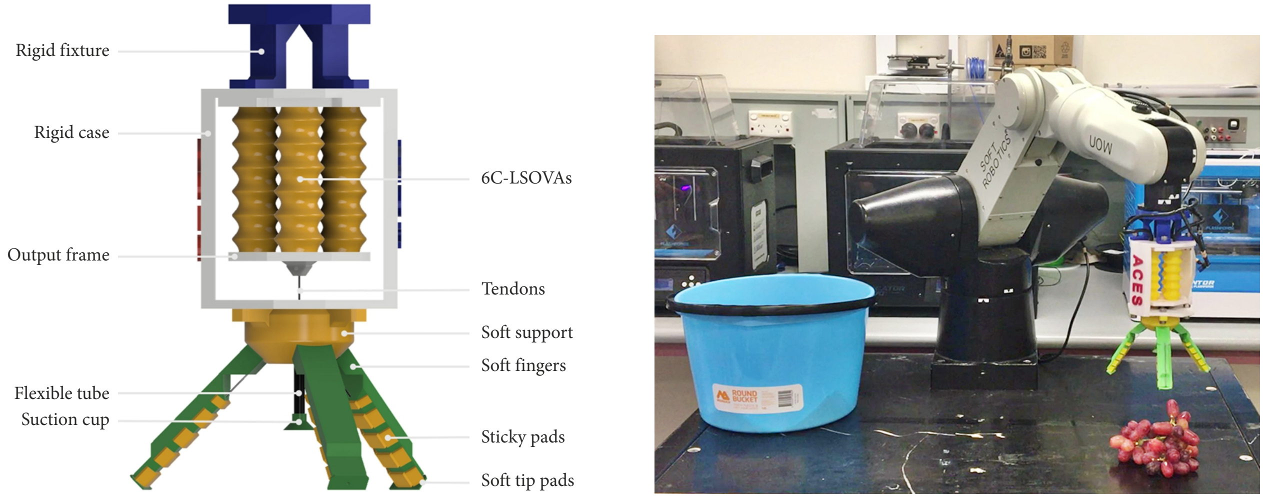


Figure 42. Flexible mechanical-vacuum CPGD (Tawk *et al.* 2019)

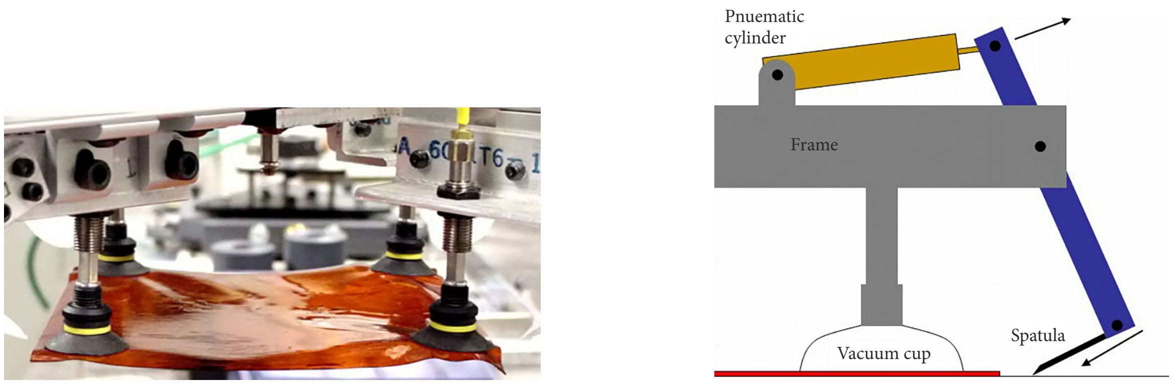


Figure 43. Vacuum-mechanical CPGD (Derby, Lippiatt 2005)

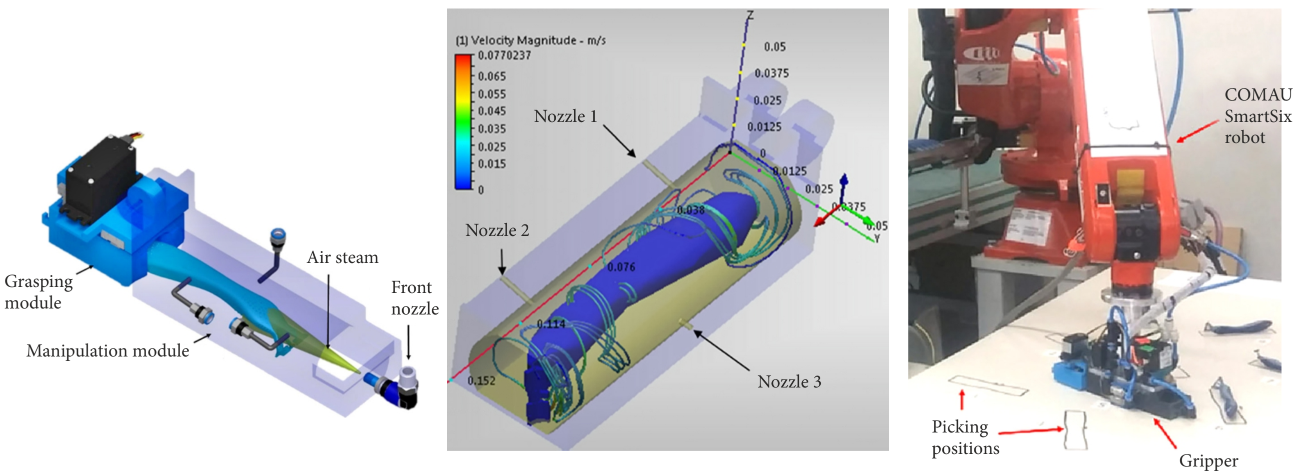


Figure 44. Pneumatic-mechanical CPGD (Michalos *et al.* 2018)

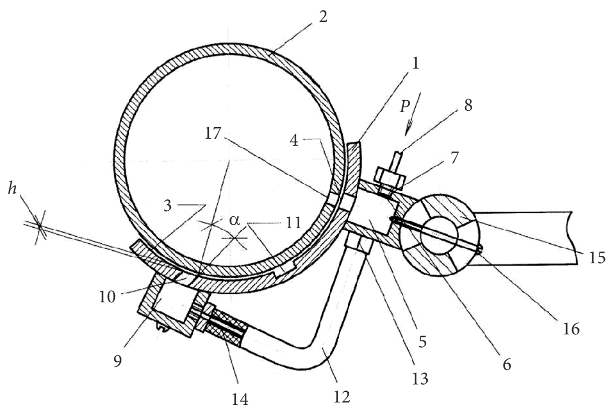


Figure 45. JOGD (Savkiv *et al.* 2012a)

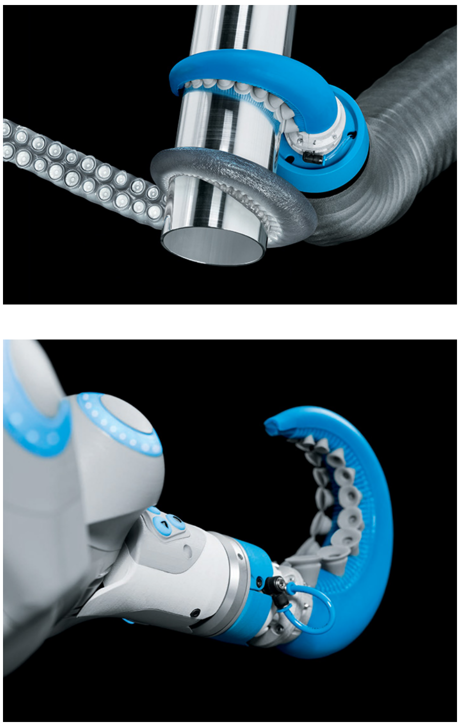


Figure 46. Tentacle gripper (Festo Inc 2021b)

Advancements in the technology, and toward improving flexibility of the hardware, cited by companies and research institutions, provided some hope that the technology may benefit from emerging innovations such as deep learning or more robust sensing systems that can improve gripping performance <…>”.

A similar opinion can be found in research by Tai *et al.* (2016). Hodson (2018) in his article formulates the main idea: “<…> Designing machines that can grasp and manipulate objects with anything approaching human levels of dexterity is 1st on the to-do list for robotics <…>”.

This statement can only confirm the general idea that robotics develops faster than gripping systems. In the conclusions to the article by Sanneman *et al.* (2020), the authors point out: “<…> Along with perception challenges, gripping remains one of the most limiting factors of automation in factories today <…>”.

Robotics now has 2 directions in terms of gripping and manipulating objects. The 1st (Figure 48), when the robot knows exactly the position of all objects in space and he needs to gripped the object in a specific place with a specific geometry. This is typical of IRs that have accurate reproducible cells for work. As a result, the accuracy and efficiency of gripping objects of manipulation are developed in this direction. That is why scientists and manufacturers of grippers are trying to optimize the design of grippers by giving them higher accuracy, multitasking or efficiency. However, it is also important for medical robots that perform operations and where you need to accurately gripping and manipulate organs or tissues of living organisms. Such trends will be accompanied by the introduction of modular solutions that will have several high-precision grippers for different tasks. In particular, the use of new materials will improve the technical characteristics of grippers devices.

The 2nd (Figure 49), when the robot is in an unknown space, has certain sensors (artificial vision and/or others), and captures without the exact coordinates of the object of manipulation and its geometry. This is typical for warehousing operations, household robots and others.

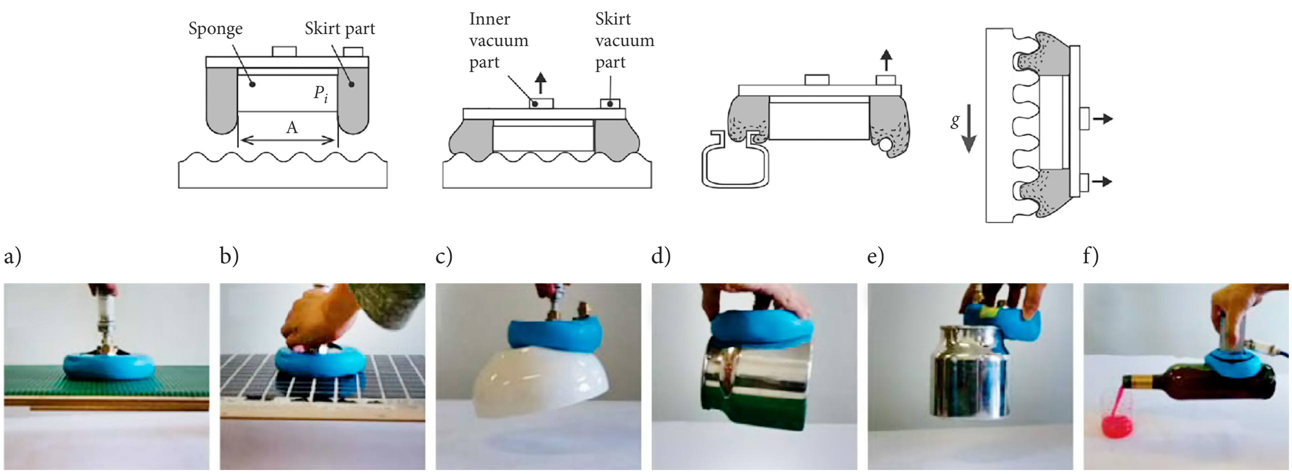


Figure 47. Universal VGD (Fujita *et al.* 2018): a – plate with an uneven surface; b – tile plate; c – bowl; d – taper can; e – grasping the edge of the can; f – filled wine bottle

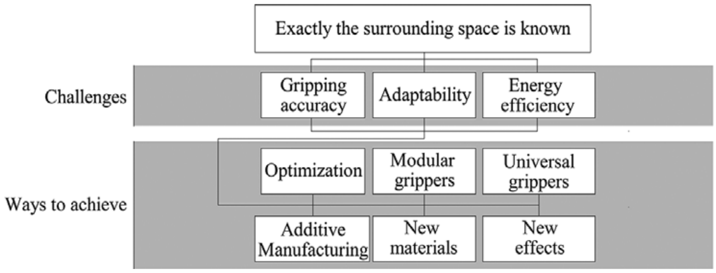


Figure 48. Challenges exactly the surrounding space is known

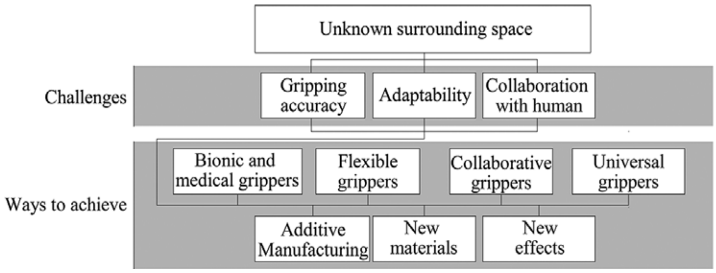


Figure 49. Callenges unknown surrounding space

Therefore, for this type of task, flexible and universal grippers are being actively developed, which make it possible to gripped the object of manipulation with a significant error in the positioning of the end-effector. In addition, the question of human safety in cooperation with the robot arises in everyday tasks, so collaborative grippers will develop and become a trend as the development of human-machine interface. This trend accompanies the introduction of new materials, effects and encourages the use of additive manufacturing to create new types of grippers.

Both of these areas will be characterized by research, accompanied by modeling and rendering of the processes of gripping and manipulation of objects. Such studies are relevant in terms of predicting the performance of grippers, optimizing their characteristics and using these models to teach artificial intelligence. Which allows to quickly develop and accumulate new knowledge in this area.

Despite the general statements, this industry is actively developing. It allows identifying some areas that are promising and have the potential of bridging many gaps with new technologies (inclusion in the list does not affect the importance of each area):

- »» optimising the designs of grippers (load-bearing characteristics, minimising energy consumption for maintenance, etc.);
- »» flexible grippers (minimising deformation of MOs and a wide-range of the gripping process);
- »» additive manufacturing (3D-printing) when designing grippers (minimising the price of grippers and the ability to reproduce structural elements that cannot be reproduced by conventional technologies);
- »» collaborative grippers (intelligent grippers with human presence sensors and the ability of educational programming);
- »» modular grippers (add flexibility in using combined designs and adapting to specific production needs);
- »» universal grippers (possibility of adapting the object of manipulation and gripping force);
- »» grippers based on new materials (using friction properties, materials with shape memory, new materials for 3D-printing);
- »» new effects in grippers (using still unexplored or unused gripping effects and principles);
- »» bionic and medical grippers (using natural forms to achieve maximum gripping efficiency);
- »» simulation and rendering of the gripping process (necessary for both researchers and designers of automated systems on the production site).

The primary purpose of all advanced research tendencies is to obtain maximum productivity and flexibility in operations performed by GDs. More problems arise when we are trying to grip MOs that could not be gripped before. Therefore, there is a tendency to use flexible grippers with unknown MOs. Moreover, special grippers have been designed lately for this type of MOs to ensure greater productivity. Given the above, it is hard to achieve maximum productivity and sufficient flexibility at the same time. This will be the next challenge faced by researchers in the future.

It is now proposed to use an anthropomorphic (human-like hand with fingers) gripper to develop a productive and flexible gripper. However, a GD of this kind has many complexities and disadvantages the scientists are trying to eliminate: complex control, complex implementation of feedback to reproduce tactile sensations, artificial vision, the difficulty of gripping thin, brittle, flexible MOs easily handled by PGDs. Therefore, combined anthropomorphic GDs with the effects of flexible, pneumatic, magnetic grippers will be produced on a large scale in the future. This will be due to the rapid development and use of artificial intelligence for MO recognition and training of robotic systems.

Conclusions

Based on the review of GDs for IRs, the task of improving the classification of PGDs is found to be relevant. In addition, it needs further development. GDs of IRs are grouped according to common functional features in the classification schemes. Therefore, the article analyzes the classifications and designs of well-known PGDs, in which the lifting force is formed under the direct static or dynamic air flow that acts on the surface of the MO. For a more detailed classification, PGs are divided into types: VPGs; JPGs; CPGs. A general classification of PGs is proposed with features that are common to all subtypes: type of PG; contact type; object base type; object centering type; type of specialization; working range; availability of additional devices; number of grippers; type of control; type of attachment to the robot. A usage example of PGDs is given along with the analysis of positive aspects of each feature of PGDs.

The analysis of publications and designs of VGDs allowed finding their main features that distinguish them from other PGs: vacuum creation method, effect/actuator, stepwise nozzle, suction cup type, suction material type. For each type of vacuum grippers, the analysis of their parameters is performed, and recommendations are given as to how they should be applied for gripping various objects of manipulation.

The analysis of publications and designs of JGDs allowed finding their main features that distinguish them from other PGs: method of using a jet of compressed air, shape of nozzle elements, number of nozzle elements, direction of gas flows, type of surface of the MO. The analysis of the main characteristics of jet grippers is made, and recommendations are given as to how they should be applied to certain types of MOs.

The analysis of publications and designs of CPGDs allowed finding their main features that distinguish them from other PGs: type of combination, performed function. Examples are given that demonstrate the main advantages and disadvantages of this type of GDs. In particular, examples of integrating additional control functions into PGs are given, along with recommendation on the orientation and performance of some technological operations, which allow improving their universal nature.

The relationship between tendencies and prospects for the development of GDs for IRs is established, and directions for improving roboticsare outlined. The opinions of the leading companies are given, which emphasize the importance of developing GDs at the present stage of mass robotization in the manufacturing industry, surgery, everyday life, prosthetics, etc. According to the data presented, a conclusion can be made concerning the basic lines of research, which will be actively developed in the near future: optimizing designs of grippers, flexible grippers, additive manufacturing (3D-printing) when developing grippers, collaborative grippers, modular grippers, universal grippers, grippers based on new materials, new effects in grippers, bionic and medical grippers, simulation and rendering of the gripping process. In addition, a detailed classification of all major types of PGs will allow engineers and scientists to clearly distinguish and find optimal solutions for the robotization of different processes.

Author contributions

Roman Mykhailyshyn and *Volodymyr Savkiv* conceived the research and were responsible for the general classification of PGDs.

Roman Mykhailyshyn classified and listed the main representatives of vacuum grippers.

Volodymyr Savkiv conducted a classification and listed the main representatives of JGDs.

Pavlo Maruschak conducted a classification and listed the main representatives of the CPGDs.

Jing Xiao and *Roman Mykhailyshyn* presented general tendencies of development of PGDs and future perspective tendencies of research in this direction.

Pavlo Maruschak, *Volodymyr Savkiv* and *Roman Mykhailyshyn* wrote the first draft of the article.

Disclosure statement

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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