ANALYSIS OF LIFTING FORCES OF PNEUMATIC GRIPPERS WITH 3D PRINTED JAWS

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Abstract - Pneumatic grippers are essential components in industrial automation, used for object manipulation in a variety of applications. Their performance is influenced by the generated clamping forces, which determine the stability and safety of the grip. This paper aims to analyze the lifting forces of pneumatic grippers with 3D printed jaws, using two additive manufacturing technologies: FDM (with PLA filament) and PolyJet (with photopolymer resin). 3D printing technology can be successfully used to manufacture custom jaws, offering comparable performance to traditional ones. The research method consisted of designing the jaws in Catia and 3D printing them, followed by their integration into pneumatic grippers. Lifting forces were measured experimentally using an LBG TC100 material testing machine and an Axis FC200 force gauge. Measurements were performed for different actuation pressures and diameters of the handled workpieces. The results showed that 3D printed jaws made of photopolymer resin generated higher lifting forces than those made of PLA, due to superior dimensional accuracy. However, the resin jaws underwent plastic deformation at high pressures. We conclude that 3D printing offers a flexible and efficient solution for manufacturing custom jaws, and the choice of printing material must consider the specific requirements of the application.

Keywords: Pneumatic grippers, Clamping forces, Lifting forces, Jaws, 3D printing, Additive manufacturing, Printing Material.

1. Introduction

Pneumatic grippers are essential components in industrial automation systems, employed for gripping and manipulating a diverse array of objects across a multitude of applications, ranging from assembly lines to industrial robots [1,2]. They offer advantages such as high gripping force, rapid actuation speed, high reliability, and low maintenance costs [3,4]. The performance of pneumatic grippers is directly influenced by the generated clamping forces, which determine the stability and security of the grip [5]. A secure and stable grip is crucial to prevent damage to the manipulated objects and to ensure the efficiency of industrial processes [6].

In recent years, 3D printing technology has experienced rapid development, offering new possibilities for the rapid and customized manufacturing of components. [7]. This technology

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enables the production of parts with complex geometries and mechanical properties tailored to the specific requirements of the application. 3D printing has been successfully employed in various fields, including robotics and automation, for the fabrication of custom components, prototypes, and gripping devices. [8,9].

This study is necessary to investigate the potential of 3D printing technology in the fabrication of pneumatic gripper jaws. Currently, most jaws are manufactured using traditional methods such as machining or casting, which can be expensive and limited in terms of geometric complexity [10,11]. 3D printing offers a flexible and efficient alternative, enabling the rapid fabrication of customized jaws adapted to the shape and dimensions of the manipulated objects [12].

A review of the specialized literature has revealed several gaps regarding the study of lifting forces in pneumatic grippers with 3D-printed jaws [13]. Most studies focus on the design and optimization of jaw shape, without paying significant attention to the generated lifting forces [14]. Furthermore, there is limited information regarding the influence of the printing material on the clamping forces [15,16].

The originality of this study lies in the comparative investigation of the clamping forces generated by pneumatic grippers with 3D-printed jaws using two different technologies: FDM and PolyJet. The influence of the printing material (PLA vs. photopolymer resin) on the clamping forces will be analyzed, as well as the effect of the actuation pressure and the diameter of the gripped workpiece.

The main objectives of the research are:

- Designing and manufacturing pneumatic gripper jaws using FDM and PolyJet technologies.
- Experimental measurement of the lifting forces generated by grippers with different types of jaws.
- Comparative analysis of gripping forces as a function of printing material, actuation pressure, workpiece diameter, and gripper architecture.
- Identifying the key factors that influence the performance of grippers with 3D-printed jaws.

2. Types of Pneumatic Grippers

Pneumatic grippers are classified based on the motion of their jaws and the number of jaws. The most common types are presented below.

2.1 Pneumatic Grippers with Parallel Jaws

These grippers have jaws that move parallel to the gripper body. They are the most widely used due to their simple construction, intuitive operation, and the wide range of objects they can manipulate. They can be used in applications such as part assembly, material handling, and loading/unloading of machine tools (Figure 1).

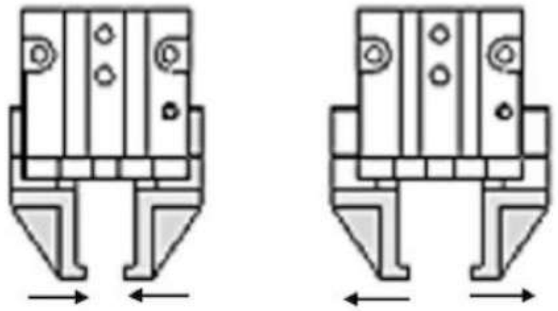

Figure 1: Parallel pneumatic gripper in closed and open position [16]

3.2 Pneumatic grippers with angular jaws

In these grippers, the jaws move radially, opening and closing around a central pivot point. They are suitable for confined spaces and for manipulating objects with complex shapes. They are used in applications such as handling electronic components, sorting products, and packaging (Figure 2).

Figure 2: Angular pneumatic gripper

2.3 Pneumatic Grippers with 3 Jaws

These grippers have three jaws that open and close towards the central axis. They are ideal for manipulating round or cylindrical objects, offering greater gripping force and better centering. They are used in applications such as manipulating tubular parts, fixing spherical objects, and gripping bottles or jars (Figure 3).

Figure 3: Pneumatic grippers with 3 jaws

Each type of pneumatic gripper has specific advantages and disadvantages, and choosing the most suitable type depends on the application requirements (Table 1).

Table 1. Advantages and disadvantages

Gripper Type	Advantages	Disadvantages
Parallel Jaws	Simple construction, wide range of applications	Lower gripping force for round objects
Angular Jaws	Suitable for confined spaces, handling complex objects	More limited range of applications
3-Finger Grippers	High gripping force, precise centering	Less versatile for irregularly shaped objects

3. Design and Fabrication of 3D Printed Jaws

To study the clamping forces of pneumatic grippers, custom jaws were designed and manufactured using 3D printing technology.

The jaws were designed for a 18mm diameter part/specimen.

3.1 Jaw Design

The design of the jaws was carried out in the CAD/CAM Catia environment, taking into account the assembly drawings of the grippers provided by the manufacturers. The geometry of the jaws was adapted to ensure a secure and stable grip of the cylindrical parts used in the experiments (Figure 4).

The profile of the jaws on one side is in accordance with the gripper's fixing surface and the other side, in contact with the specimen, a cylindrical part, has a prismatic profile.

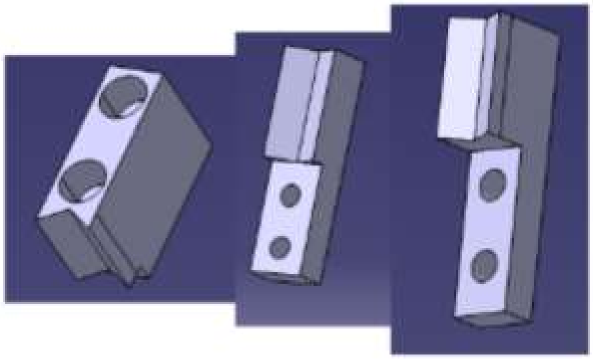

Figure 4: The designed jaw for each used pneumatic gripper

3.2 Jaw Fabrication

The fabrication of the jaws was carried out through two 3D printing methods, which are presented below.

- ***FDM Method (Fused Deposition Modeling)***

This method utilizes a thermoplastic filament that is extruded through a heated nozzle and deposited layer by layer to create the desired shape. The material used was PLA Ingeo 3D870, a biodegradable filament with good mechanical properties, easy to print. The 3D printer used for printing the PLA jaws was the i3 Metal One model, with a printing volume of 200 x 200 x 200 mm and a printing accuracy of 0.1-0.3 mm (Figure 5 and Figure 6).

For the PLA specimens, the layer height was set to 0.1 mm, and for the resin specimens, it was 0.016 mm, as defined by the respective printing machines. A 100% infill density was used for all printed parts.

Figure 5: i3 Metal One3D Printer [17]

Table 2 presents the mechanical properties of the PLA Ingeo 3D870 filament used for 3D printing the gripper jaws.

Table 2. Mechanical Properties of PLA Ingeo 3D870 Filament

Mechanical Properties	Standard	Value	Unit
Tensile Strength	ASTM D638	40	MPa
Tensile Modulus	ASTM D638	2,865	MPa
Flexural Strength	ASTM D790	73	MPa
Flexural Modulus	ASTM D790	2,414	MPa
Izod Impact Strength	ASTM D256	233	J/m

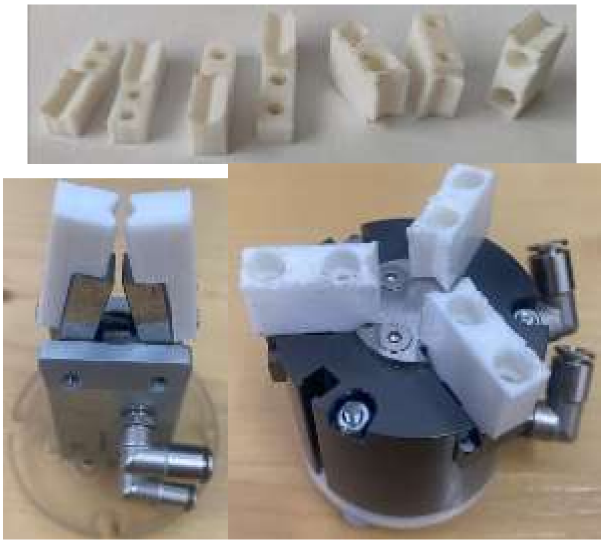

Figure 6: The PLA jaws printed on the i3 Metal One 3D printer and attached to the grippers

- ***PolyJet Method***

This method employs a liquid photopolymer resin that is jetted onto a build platform and cured under UV light. The material used was Fullcure 720, a transparent resin with excellent mechanical properties and very fine printing resolution. The 3D printer used for printing the resin jaws was the Objet Eden 350V model, with a printing volume of 350 x 350 x 200 mm and a printing resolution of 16 µm (Figure 7 and Figure 8).

Figure 7: Objet Eden 350V 3D Printer [18]

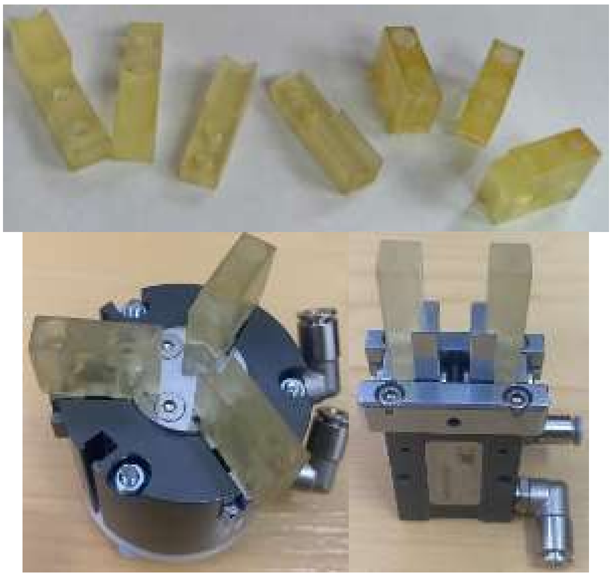

Figure 8: Resin jaws printed on the 3D printer Objet Eden 350V and attached to the grippers

Both 3D printing methods enabled rapid and precise fabrication of customized jaws, tailored to the experimental requirements.

4. Experimental Methodology

To study the lifting forces of pneumatic grippers with 3D-printed jaws, a dedicated experimental setup was designed and implemented.

4.1 Experimental Test Setup

The experimental setup consists of three main components:

- The pneumatic actuation system for the grippers provides compressed air at the desired pressure.
- The LBG TC100 material testing machine, used to generate the tensile force required for measurements and the constant actuation speed.
- The Axis FC200 force gauge, which records the clamping force values.

The pneumatic diagram of the gripper actuation system illustrates how compressed air is supplied and controlled to operate the pneumatic grippers used in the experiment (Figure 9)

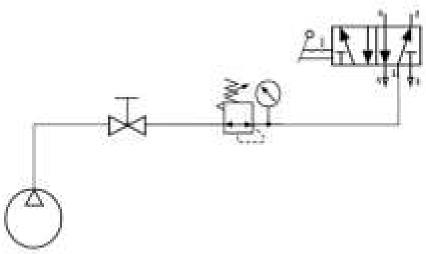

Figure 9: Pneumatic Actuation System Diagram

4.2 LBG TC100 Material Testing Machine

The LBG TC100 is a universal testing machine with a load capacity of 100 kN, used to measure the mechanical resistance of materials. In this experiment, the machine was used to generate a vertical translation movement, simulating a tensile force on the gripper (Figure 10).

Figure 10: LBG TC100 Material Testing Machine

Table 3 presents the technical characteristics of the LBG TC100 material testing machine used in the experiment.

Table 3. Technical characteristics of the LBG TC100 material testing machine

Characteristics	Value
Load Capacity	100 kN
Resolution	0.01 kN
Class	0.5
Maximum Speed	350 mm/min
Minimum Speed	0.1 mm/min
Return Speed	350 mm/min
Stiffness frame	120 kN/mm
Crosshead Travel (without accessories)	1100 mm
Crosshead Travel (with tensile heads A009-A100)	390 mm
Column Spacing	390 mm
Weight	375 kg
Dimensions (width x depth x height)	820 x 605 x 218(mm
Operating Temperature	+10 °C / +35 °C
Relative Humidity	10% / 80%
Power Supply	240V 1ph 50Hz - T
Max Power Absorbed	850 VA

4.3 Axis FC200 Force Measuring Device

The Axis FC200 is a force gauge capable of recording up to 1000 measurements per second. It was used to measure the lifting force exerted by the gripper on the workpiece (Figure 11).

Figure 11: Axis FC200 Force Measuring Device

Table 4 shows the technical specifications of the Axis FC200 force gauge used in the experiment.

The dynamometer is used due to its higher measurement accuracy compared to the material testing machine (material testing machine resolution 0.01 kN, dynamometer resolution 0.05 N, a 200x precision).

Table 4. The technical specifications of the Axis FC200 force gauge

Characteristics	Value
Model	FC200
Maximum force measured (weight	200N (-20kg)
Reading graduation	0.05N
Accuracy	±0.1% F.S.
Maximum overload	+20%
Operational temperature	-10 - +40 °C
Units	N, kgf, lbf, ozf, g, lb, oz, kg
Display	graphical LCD 61x34mm, mass indication digits height 7mm
Measurement speed	regulated max 1000 measurements/s
Measuring functions	maximal value measurement, serial measurement, measurement in time

Measurements memory	RAM 6 400 measurements, microSD card slot; optional RAM memory expansion to 72000 measurements or 26000 with date + time
Interfaces	RS232C, USB, clock; options: trigger IN, transporter OUT (for the function)
Software	AXIS FM program
Power supply	internal accumulators NiMH: 4x1,2V 2700mAh + supply: ~230V 50Hz/12V; 1,2A
Working time with accumulator	~30h (~25h with backlighting)
Gauge plunger	11mm, M6x8mm
Dimensions	215x98x41mm
Weight	350g (without accumulator and sensor)

4.4 Grippers used in the Study

For the experiments, commercially available grippers were chosen with similar dimensions and designs based on pneumatic cylinders with comparable diameters.

Table 4. Commercially available grippers

Gripper	Pneumatic cylinder diameter	Weight
	[mm]	[kg]
Metalwork P2-16	16	0.112
Metalwork P7-16	16	0.145
Camozzi CGC 050	30	0.210

Analyzing the ratio of maximum lifting force to gripper mass, we observe the following data summarized in the table below.

Table 5. The ratio of maximum lifting force to gripper mass

Gripper	Jaw	Maximum lifting Force Fl	Weight M	Fl / M
		[N]	[g]	
Metalwork P2-16	PLA	24	112	0.21
Metalwork P7-16	PLA	6.1	145	0.04
Camozzi CGC 050	PLA	75	210	0.35

The analysis shows that the 3-jaw gripper has the highest force-to-weight ratio. However, from a financial perspective, the 3-jaw gripper is the most expensive. Compared to the P7-16, the P2-16 is 42% more expensive, and the CGC050 is 207% more expensive.

Considering costs, the 2-jaw gripper offers superior advantages. For design purposes, this type of gripper (with parallel jaws) can be considered the preferred choice.

4.5 Experiment Procedure

The experiment involved measuring the lifting forces generated by pneumatic grippers equipped with 3D-printed jaws, at various actuation pressures and for different workpiece diameters.

S275 steel was used to manufacture the specimens, which had diameters of 17 mm, 18 mm, and 19 mm. The contact surface of the test piece with the jaws was finished to a surface roughness of Ra = 1.6 µm.

The grippers were mounted on the material testing machine, and the workpieces were secured in the jaws. The actuation pressure was adjusted using the pneumatic system, and the lifting force was measured with the Axis FC200 force gauge (figure 12).

For each experimental configuration (gripper type, jaw material, actuation pressure, workpiece diameter), multiple measurements were taken to ensure repeatability of the results.

Figure 12: The experimental setup and the specimen between the jaws (in case of parallel gripper)

5. Results and Discussions

Following the experiment, the lifting forces generated by the pneumatic grippers with 3D-printed jaws were measured, using different pressure configurations and workpiece diameters. The data obtained was centralized in tables and analyzed to identify the key factors influencing the performance of the grippers.

5.1 Gripper with Parallel Jaws

Table 6 and figure 13 presents the maximum clamping forces recorded for the gripper with parallel jaws (Metalwork P2-16 with an inner piston diameter of 16 mm), depending on the jaw material, actuation pressure, and workpiece diameter.

Table 6. Maximum Clamping Forces for the Gripper with Parallel Jaws

Jaws Material	Pressure (bar)	Part Diameter (mm)	Maximum Force (N)
PLA	2	17	6.8
PLA	2	18	9.5
PLA	2	19	5.3
PLA	4	17	17.2
PLA	4	18	15.65
PLA	4	19	14.2
PLA	6	17	23.95
PLA	6	18	23.8
PLA	6	19	19.15
Resin	2	19	9.25
Resin	4	19	17.9
Resin	6	19	26.6

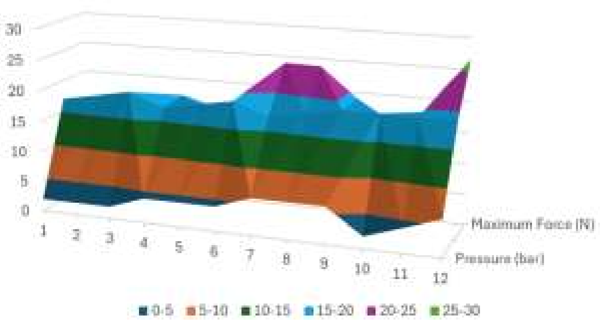

Figure 13: Maximum Clamping Forces for the Gripper with Parallel Jaws

From the data analysis, it is observed that the clamping forces increase with the increase of the actuation pressure, regardless of the jaw material or the diameter of the workpiece. It is also observed that the resin jaws generate higher clamping forces than the PLA jaws, at the same pressure and workpiece diameter. This is probably due to the superior dimensional accuracy of the resin jaws, which ensures a better contact surface with the workpiece.

5.2 Gripper with Angular Jaws

Table 7 and figure 14 presents the maximum clamping forces recorded for the gripper with angular jaws (Metalwork P7-16 with an inner piston diameter of 16 mm).

Table 7. Maximum Clamping Forces for the Gripper with Angular Jaws

Jaws Material	Pressure (bar)	Part Diameter (mm)	Maximum Force (N)
PLA	2	17	1.65
PLA	2	18	2.5
PLA	2	19	1.6
PLA	4	17	3.7
PLA	4	18	4
PLA	4	19	3.5
PLA	6	17	5
PLA	6	18	6.05
PLA	6	19	5.65
Resin	2	17	2.2
Resin	2	18	2.95
Resin	2	19	2.35
Resin	4	17	4.65
Resin	4	18	4.65
Resin	4	19	4.95
Resin	6	17	7
Resin	6	18	7.15
Resin	6	19	6.65

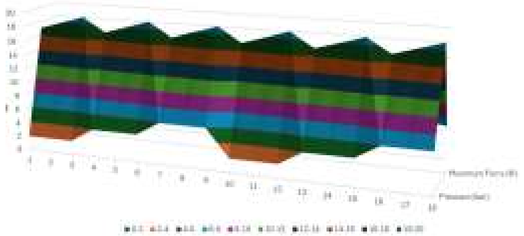

Figure 14: Maximum Clamping Forces for the Gripper with Angular Jaws

In this case as well, an increase in lifting forces is observed with the increase in pressure. Also, the resin jaws generate higher forces than the PLA ones. However, the maximum forces recorded for the gripper with angular jaws are significantly lower than those for the gripper with parallel jaws. This is likely due to the construction of the angular gripper, which limits the clamping force.

5.3. 3-Jaw Gripper

Table 8 and figure 15 presents the maximum clamping forces recorded for the 3-jaw gripper (Camozzi CGC050 with an inner piston diameter of 30 mm).

Table 8. Maximum Clamping Forces for the 3-Jaw Gripper

Jaws Material	Pressure (bar)	Part Diameter (mm)	Maximum Force (N)
PLA	2	17	22.25
PLA	2	18	27.4
PLA	2	19	24.1
PLA	4	17	43.35
PLA	4	18	47.5
PLA	4	19	47.75
PLA	6	17	75.15
PLA	6	18	64.35
PLA	6	19	72
Resin	2	17	32.45
Resin	2	18	26.05
Resin	2	19	16.8
Resin	4	17	64.85
Resin	4	18	53.6
Resin	4	19	47.05
Resin	6	17	87.35
Resin	6	18	71.4
Resin	6	19	71.9

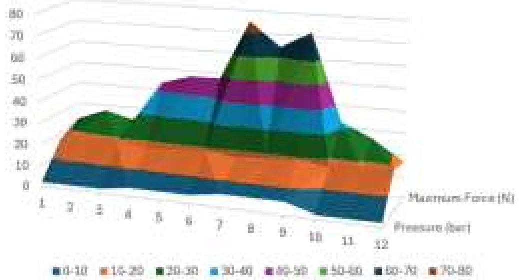

Figure 15: Maximum Clamping Forces for the 3-Jaw Gripper

The 3-jaw gripper generated the highest lifting forces, especially at high pressures. In this case as well, the resin jaws outperformed the PLA jaws.

6. Discussions

From the analysis of the results, the following conclusions can be drawn:

- The clamping forces increase with the increase in actuation pressure, regardless of the gripper type or jaw material.
- 3D-printed jaws made of photopolymer resin generate higher lifting forces than those made of PLA, due to superior dimensional accuracy.
- The 3-jaw gripper provides the highest clamping forces, followed by the parallel jaw gripper and then the angular jaw gripper.

It is important to note that, in the case of the parallel jaw gripper, the resin jaws underwent plastic deformation at high pressures (6 bar). This indicates that the choice of printing material must consider the anticipated clamping forces in the application.

The results of this study demonstrate the potential of 3D printing technology in manufacturing custom jaws for pneumatic grippers. By appropriately choosing the printing material and gripper type, optimal clamping forces can be achieved for a wide range of industrial applications

7. Conclusions

This study analyzed the lifting forces generated by pneumatic grippers with 3D-printed jaws, utilizing two additive manufacturing technologies: FDM (with PLA filament) and PolyJet (with photopolymer resin).

The main conclusions of the study are:

- The gripping forces generate lifting forces that increase with the increase in actuation pressure, regardless of the type of gripper or the material of the jaws.
- 3D-printed jaws made of photopolymer resin generate higher lifting forces than those made of PLA, due to superior dimensional accuracy.

- The 3-jaw gripper provides the highest lifting forces, followed by the parallel jaw gripper and then the angular jaw gripper.
- In the case of the parallel jaw gripper, the resin jaws underwent plastic deformation at high pressures (6 bar), which indicates the need to choose the printing material based on the anticipated clamping forces.

This study provides a comparative analysis of the lifting forces generated by pneumatic grippers with 3D-printed jaws, using two different technologies. The experimental results highlight the influence of the printing material, actuation pressure, and workpiece diameter on the clamping forces. This study demonstrates the potential of 3D printing technology in manufacturing custom jaws for pneumatic grippers.

Future research directions:

- Optimizing the design of 3D-printed jaws to maximize clamping forces and prevent plastic deformation.
- Investigating other 3D printing materials and their influence on gripper performance.
- Developing analytical and numerical models to predict the clamping forces generated by grippers with 3D-printed jaws.

Applicability of the results:

- The results of this study can be used for:
- Optimal selection of the printing material and gripper type according to the specific requirements of the application.
- Designing and manufacturing custom pneumatic grippers with improved performance.
- Optimizing industrial processes that involve object manipulation using pneumatic grippers

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