Robotic Gripper Advancements and Future Directions in Order to Improve Control and Precision: A Review

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Robotic Gripper Advancements and Future Directions in Order to Improve Control and Precision: A Review

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Abstract: This study investigates the state of robotic grippers at the moment and methods that can be used to control grippers, and potential future research areas. Mainly, this research investigates an automated robotic arm directed by a microprocessor and equipped with diverse end-effectors, including vacuum, pneumatic, hydraulic, and electric grippers. The study emphasizes the embedded instructions and sensor technologies that govern gripper functions, such as object detection and force application, to ensure precision and prevent damage. By evaluating performance metrics like accuracy, speed, and capacity, the research assesses the effectiveness of these mechanisms. Addressing gaps in existing literature, this paper aims to enhance the understanding of gripper technology and its potential applications in future robotic systems.

Keywords: Robotic grippers; robot manipulator; soft gripper; hard gripper; robotic grasp; end-effector

1. Introduction

Robots were developed as a means of supplementing or replacing humans doing laborious, dirty, or dangerous tasks. Space exploration, observing radiation zones, robotic assembly lines, and minimally invasive surgery are all applications of such robots or machines. Many tasks are better performed by robotic arms than by humans today. In a general scenario, a robotic arm has a lifting capacity of about 1000 kg[1,2], repeating capabilities over 10μm[3] and the acceleration produced by it is about 15 g per 15 seconds[4]. In addition, robotic grippers are becoming more affordable while manual labour is becoming more expensive. As a result, industry, and academia have developed more advanced robotic arm and gripper systems for form-closing and force-closing applications[1]. As the work piece is directly in contact with its grippers, robotic grippers can converse with the surroundings and grasp objects, like human hands, for manipulation by humans[3,5]. Soft fabrics, microelectromechanical systems (MEMS), and synthetic sheets are currently under investigation in research aimed at improving the grasping of complicated objects[4]. The genealogy of intelligent gripper is presented in Fig. 1. The genealogy shows a progression from simple kinematic mechanisms (historical grippers) to more advanced pneumatic and electric grippers, ultimately leading to intelligent grippers that leverage sensor technology for adaptive and precise operations. This evolution highlights the trend toward increased automation and sophistication in robotic systems. Kinematic gripers are the foundational grippers that rely on basic mechanical and kinematic designs. They use simple mechanisms and are primarily focused on motion and grasping objects without any advanced sensing or feedback capabilities. Pneumatic grippers are a direct evolution from historical grippers. They operate using compressed air to generate motion, making them suitable for applications requiring fast and repetitive movements. They are widely used in industrial automation for tasks like assembly and packaging but lack advanced intelligence or adaptability. Electrical gripers are evolution from historical grippers. These grippers use electric motors or actuators to control movement.

Electric grippers are more precise and energy-efficient than pneumatic grippers and can incorporate basic feedback mechanisms for improved control. Intelligent gripper is the most advanced category in the genealogy. Intelligent grippers incorporate sensors (e.g., force, pressure, vision) to enhance functionality. They can adapt to varying object shapes, sizes, and materials, enabling them to handle complex tasks. These grippers represent the culmination of improvements from both pneumatic and electric grippers, combining actuation technologies with sensing and feedback for intelligent operation. To overcome the uncertainty in the object's mass and soft/hard properties, an intelligent gripper is developed with an embedded distributed control system. For the purpose of sequentially executing the robotic position control[6] and gripper force control functions, a communication signal is specified to incorporate both the robot arm and gripper control functions.

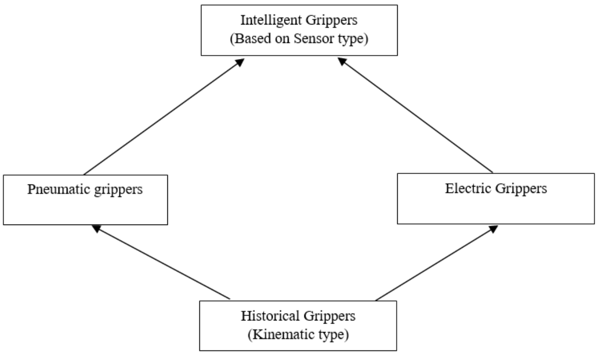

Fig. 1: Genealogy of Intelligent gripper.

A variety of materials are also being used to design grippers. In addition to piezoelectric crystals, shape memory alloys (SMA), magnetorheological fluids (MR), and carbon fiber, there are many others. The use of bio-inspired gripping mechanisms has also recently been considered as a means of solving industrial problems through nature[7]. Using grippers in automated production processes was discussed in detail[4,7]. Different gripping systems have been discussed, such as mechanical, magnetic, and artificial vacuum gripping systems[8]. A parallel manipulator gripper mechanism was discussed in[9]. The grippers in "Global adoption of robotic technology[10]" are intended for surgical applications. Aside from dual-arm manipulation, Chen[11] covered no other types of manipulation. An overview of space robots was presented in[12]. Robots used in plant production were discussed in[13]. There was only a focus on micro-contact strategies in[14]. Control schemes for end effectors were discussed in[15]. Kuka KR 1000 Titan; Dexter on the International Space Station; iRobot 510 Explosive Ordnance Disposal manipulator, and da Vinci Surgical manipulator are some examples of modern grippers[16–19]. Robotic grippers can be used in a variety of applications.

Reviewing recent research developments and discussing future design directions is essential to discussing the many developments happening in research today. Even though previous surveys have offered a broad overview of the various types of grippers, our study emphasizes applications that were not previously studied, such as grippers for deformable and delicate objects, as well as grippers for live organisms. In this study, a report on the first types of grippers, followed by the improvements made to them, and finally, the most recent technological advances in grippers. In this study, different categories of grippers currently being used in medical and industrial environments are discussed, as well as for micro and nano manipulations. A comparison of the new grippers' designs is also presented, as well as their strengths and weaknesses. The paper addresses several applications, including but not limited to medical, agriculture, micro and Nano manipulation and the future direction of trends in gripper designs, thus making it unique among other survey papers. Researchers and industry will be able to find new grasping mechanisms, their advances, as well as the challenges associated with them. Lastly, we discuss future directions and the challenges of this field.

2. Grippers with robotics applications

Industrial applications prompted the creation of the first grippers. It refers to grippers installed on a stationary platform and used for mass production. A wide variety of aspects can be considered regarding industrial grippers, including geometrical conditions of grasping, position and orientation of grasping, static equilibrium of grasped objects, and dynamic conditions of gripping[20,21]. A gripper's performance, adaptability, and flexibility are our primary concerns. In 1961, General Motors installed UNIMATE in one of their assembly plants. The piece of hot die-cast metal was grabbed using a rigid parallel manipulator[22]. The robotic gripping technology has evolved considerably since then, with different drive mechanisms being developed by many companies[23–25]. It used to be powered by hydraulic actuators or electric motors, but more recently it has been driven by electric motors, and more are being powered by piezoelectric and shape memory alloys. A gripper used in a known environment can be separated from a gripper used in an unknown environment. The main objective of the paper is to Provide a comprehensive overview of the historical development, design principles, and technological advancements in robotic grippers. Also highlight the limitations and challenges faced by existing gripper technologies, such as restricted stroke lengths, limited force capacity, and lack of adaptability. Explore the role of advanced sensors, controllers, and materials in enhancing the precision, control, and versatility of grippers for various applications, including industrial automation, healthcare, and microscale operations. Propose future research directions aimed at overcoming current limitations and addressing the growing demand for intelligent, multifunctional, and adaptive robotic grippers.

2.1 Environment-specific grippers

A gripper used in a known environment typically comes on assembly lines. A gripper can easily pick up an object because the parts are oriented in predefined orientations. A gripper can respond to input with servos, non-contact sensors, contact sensors, or a combination of these sensors. For example, hall sensors, accelerometers, photoelectric sensors, or ultrasonic sensors can be used. These sensors can detect many variables, including position, force, torque, velocity, and acceleration[26]. As part of an assembly line, these sensors can determine whether objects are being grasped or provide information to a supervisory computer, allowing it to regulate the process[27,28].

The sensors and feedback mechanisms on grippers are developed by various researchers in different ways. According to[29,30], each axis is detected using three sensors (x, y, z). Among the materials used in[31], conductive silicone is used to build the sensors. An integrated smart sensor network is presented in[32] in which each node acquires signals. In addition to the force-sensing array, recent developments have encouraged the use of artificial skin for robots[33]. Prosthetic hands can also use tactile-sensing systems[34]. To detect force triaxially, it uses a biomimetic tactile sensor. A piezoresistive rubber-based tactile sensor is presented in the study[35]. In addition to proximity sensors, grippers are equipped with an active prediction, planning, and execution system designed to intercept moving objects[36]. To acquire the object, the technology moves to the earliest grasping location close to it, then utilizes fine-motion tracking algorithms to detect the object. This reduces the distance between the object and the end effector, as it eliminates the need for continuously tracking motion during planned movements. End-effectors designed in the shell shape, so that force can be detected in any position on the body[37].

In addition, six axes can be used to determine the position and force of the contact. A launch platform can also be used to throw claw-like end-effectors. A swinging motion uses to launch the claw, while a laser range sensor measures the range of the gripper[38]. With a string attached to one end of the claw, the base is firmly fastened to the claw. The claw can run on a parabolic trajectory to its target when the tension of the string is adjusted mid-flight. The development of a minimally invasive surgical gripper has been described in the previous study[39]. By enhancing surgeons' dexterity, the design proposed is advantageous. A joystick controls the parallel end effectors of the prototype gripper. The physical movements are displayed to the user via a screen using a motion tracking system developed by Northern Digital Inc. This allows Northern Digital to determine the position and orientation of the user. The study will also examine the development of control systems[6] that will significantly enhance the performance and tracking of grippers. The tracking performance was improved by a 3-DOF parallel manipulator incorporating PID and fractional-order PID[40]. In one experiment, fractional-order controllers were used to reduce transients and steady-state errors in servo motors. Tracking was achieved using PD and H controllers on an oscillatory manipulator[41]. There was evidence that it was better than a PID controller because it used servo motors. A feedback system for underwater grippers has been developed[42]. Multi-limb grippers are used for this design, which are capable of detecting objects up to 6000 m beneath the surface. A pressure chamber test of the deep-sea gripper system at 600 bars demonstrated the system's effectiveness. The feedback for a 6-DOF electrohydraulic parallel robot was provided by six-position sensors and six servo valves in[43]. The robotic gripper was made more efficient by using decoupled-space control (DSC). Dynamic coupling[44] effects of the parallel multi-DOF robot were solved by the DSC framework, which improved the performance. Attractive grasping, or astrictive gripping, is also included among the grippers. Several types of attraction exist, including vacuum suction, magneto-adhesion, and electro-adhesion. Sheet metal fabrication was one of the first applications for astrictive grippers[45,46].

Suction grippers that are studied in a theoretical model[46]. The model is then extended with a multi-link manipulator[47]. A tightly gripped object has a softer grip than a light object and astrictive grippers are often used in the packing industry[48]. Objects that come off the assembly line are packed neatly in trays with a modular vacuum conveyor system[49]. Metal sheets that are slippery or oily can be picked up with ease using these tools[50]. During manufacturing, picking up oversized glass panes is another common application[51]. Soft drinks were packed in boxes using three robotic packing cells[52]. End-effectors were able to vacuum suction a cup of 12 soft drinks at the same time. Assembly line productivity increased by 25% after the packing robot was installed. Upon redeployment, workers were reassigned to different departments so that the final product would be of more value. For aerospace applications, a flexible assembly station was created[53].

In the manufacture of fuselages and wings for planes, changing surfaces present a large challenge. There are only 8 actuators on this assembly station that are connected to suction cup grippers. During the search for the fuselage, these are equipped with load cells, and the actuators are slowly extended. As soon as the suction cups find the part, they are activated and the heads of the suction cups are locked into place. It offers the advantage that the forces in the system can be mapped by every actuator. As excess loads will cause the process to be immediately stopped, this data can also be valuable during manufacturing processes. The speed at which workpieces can be moved is one challenge of suction cups. The gripper might lose suction if the workpiece is accelerated too quickly. Developing innovative ways to hold these objects is necessary to increase production speed. Additionally, during emergency stops, the speed at which a vehicle is decelerating can pose a challenge. The use of friction cups has been proposed as a solution. The coefficients of friction are higher in these materials, which can withstand large parallel friction forces; however, the forces of friction are weak in perpendicular directions. Adding weight, material, and costs to centralized vacuum systems adds vacuum pressure to suction cups. There is always a small amount of volume between the vacuum pump and the cup that needs to be evacuated. In many cases, miniaturizing such systems can eliminate these problems, though the amount of vacuum it creates may not be sufficient to hold the object[54].

2.2 Unknown environment grippers

The environmental conditions are often unknown to grippers performing pick-and-place applications. For grippers operating in unknown environments, various research methods have been employed, including the use of vision systems, feedback sensors, and flexible gripping mechanisms. Objects are detected using camera systems[55].

Parallel grippers, with camera systems were first developed[56]. It was designed to pick up random pieces of work from a bin. Since then, vision systems with finger resolution and enhanced computing power have been developed to improve gripping[57]. An operator needed to point inside the robot's workspace to pick up the object. The semiconductor industry has continued to improve vision systems[57]. Before large pieces of polysilicon are fused into quartz crucibles, they must be handled very carefully[58]. It is important to package these nuggets carefully before heating, as they can weigh up to 600 grams. The system is automated because the packing rules are complex. There are two scanners and an overhead photograph with charge-coupled devices (CCDs) to map the environment[59]. A modified image-based visual servo controller with a hybrid camera is being used to solve the gripper problem of autonomous mobile manipulators[55,60]. In the unstructured environment, a web camera and a stereo vision camera were used to track the object visually while measuring depth online[59].

To improve the controller's response speed, the controller combined the information and used a rule base to tune the gain. Many experiments were then conducted to validate this method. Machine vision was used to develop a vacuum gripper[61]. To calculate the best hold position and orientation, segmentation algorithms were used. Robotic vacuums then receive the data and extract the object and carry it to the desired location. For the 6-DOF gripper, a new image-based visual control system was developed[62]. In addition to limiting the risk of features leaving the field of view, the controller achieved a more linear trajectory. The movement of the human hand has also been tracked with the use of a 3D camera and inertial measurement unit[63]. An adaptive multi-space transformation was used on the hand movements while the Kalman filter was employed. As the hand moves, the gripper moves simultaneously. Additionally, 3D scanning of unknown environments has been used to study robot grippers[64]. Autonomous climbing manoeuvres were performed with the gripper. A joint absolute encoder, an inertial measurement unit, and a pressure sensor also provided feedback. Based on camera systems, grasping maps were developed[65]. Compared to offline systems, this map took 90% less time than using online and parallel computations. Afterward, both simple and complex objects were used to validate the method.

A two-finger gripper and an industrial robot arm were used to perform grasp planning[66]. There was a mapping between geometric states and logic predicates that needed to be learned. It was necessary to put the cups on a tray, then stack them on the table. Some configurations were not able to generate a plan in this case, so the approach was not entirely complete. In the event the table cannot be cleared for the generation of a plan, it would be a good idea to stack the cups. The plan generation process is currently being expanded to include other types of objects. Overall, in an unknown environment, a robotic gripper's main objective is flexibility. The challenge has been overcome in different ways. Several studies show that 3D scanning and vision feedback can be very useful. Furthermore, the gripper should be designed with a flexible mechanism, which is inherently flexible. Intelligent structures can handle part of the control task mechanically with these designs.

2.3 Fragile object grippers

A study was performed to explore the idea of picking up fragile objects with the development of end-effector sensors. The harvesting of lettuce was made possible by using an end-effector in[67]. The design contained six photoelectric sensors, a machine vision device, and a fuzzy logic controller. At a rate of five seconds per lettuce, the end-effector harvested lettuce with a success rate of 94.12%. It was designed with force feedback sensors that enclosed the hygienic food gripper[68]. The magnetic attraction allows one finger to remain stationary on the gripper while the other moves along with it. The finger is moved inside the container by an inner magnet, while the finger is moved outside by an outward magnet. The grasping of fruits was also investigated in another design[69]. A clamp and cutter were incorporated into this end-effector so that possible damage to the fruit could be avoided.

A machine vision unit is used to harvest strawberries using a similar design[70,71]. Also saw the introduction of a citrus harvester with a wide field of view camera. A similar design was presented in[72,73]. For handling sliced fruit and vegetables, an end-effector based on the Bernoulli principle was developed[74]. Airflow over the surface minimizes contact between the objects and is used to lift them. Thus, less pollution occurs and the product is less likely to be damaged. In addition to reducing surface moisture, this type of gripper lessens abrasion on the surface of the object. Food products can be handled effectively with this gripper. Mangos were tested for ripeness using accelerometers embedded in gripping fingers[75].

The robotic gripper performed well in detecting mango ripeness compared to the ripeness index. It was also developed a hybrid tomato picking end-effector with a combination of a rigid and an impactive design[76]. When leaves or stems got in the way of the gripper, it had difficulty removing tomatoes with short peduncles. An early form of this gripper consisting of four foam-padded fingers was developed in[77]. A suction cup on the tomato center helps the fingers grab the tomato once they are close together. It was able to pick tomatoes on average at a rate of 74.6 seconds per fruit with a success rate of 95.35 percent. The designer created a hybrid cherry harvesting robot that works similarly[78]. With a two-finger grasp and a tube in the center, over four degrees of freedom could be controlled. It is thought that cherry berries are harvested with their penuncles attached when using a hybrid design.

It is vacuumed to the center of the cherry with the end-effector positioned around it. Upon grasping the penuncle with the two fingers, both the cherry and penuncle detach simultaneously. The gripper of the robotic arm has been also used to measure the robot's trajectory when it collides with deformable objects[79]. Weighing the deformation of an object and comparing it with the traveling costs is the result. A similar, less computationally intensive model, using Gaussian process regression, can be used to perform FEA using the deformation models. A wheeled robot and a robot arm are then used to test the planning method. It was found that force feedback, soft grippers for fragile objects, and flexible designs are important factors to consider in robotic grippers to prevent damage to fragile objects.

2.4 Applications of medical grippers

One of the biggest problems with robotic grippers is their lack of force feedback and damaging biological tissues. Due to their intrinsic safety features and self-limiting characteristics, soft-bodied grippers are ideal for use in the medical field. This ensures safe contact with biological tissues. Soft grippers are designed for use in minimally invasive surgery for delicate and safe interaction[80]. It was reported that the design could withstand up to 1 N of force. The design is highly scalable and utilizes elastomeric materials.

Using viscoelastic force fields as controllers, a robotic gripper was created[81]. The study designed and analysed a two-finger grip control system that showed a high correlation between thumb and finger force. As a result of precision grip control, objects can be gripped based on their mechanical properties. Even though the design offered insight into adaptation to unknown precision grip dynamics, it was limited to 1-D linear gripping, and the results were not valid for nonrigid objects. Robotic grippers are also used in robotic surgery. During robotic surgery, safety and autonomy are essential to avoid possible complications and hazards such as delays in telesurgery. The application of tissue cutting led to the design and development of a star-shaped micro-gripper[82]. Researchers have demonstrated that they were capable of taking tissue samples from the skin of a live animal as well as hard-to-reach organs. Microfabrication with conventional multilayers and magnetic fields is used to manufacture the grippers.

soft robotic grippers that were designed for manipulation during minimally invasive surgery[80]. To adapt the finger shape and apply a specific amount of force, the authors used soft materials and an underactuated system. In addition to being a surgical tool, this gripper was made of soft materials to ensure user safety. Furthermore, because the soft gripper force is limited, the design is safe for surgery. Medical applications can also be achieved by using suction techniques[82,83]. As the body's largest, most delicate, flexible, and slippery organ, the bowel, this gripper was designed to offer grasping comfort. There were no definitive results on whether a manual pump or vacuum pump would be more effective for firmly grasping bowel sections with this suction method. The study described the development of a miniature robot gripper used for retraction with minimally invasive surgery[84]. In their study, they found that the gripper could generate a maximum gripping force of 5.3 N. A narrow access port is possible with the design of this gripper. Magnetic anchoring and improved dexterity of the overall platform were enhanced by brushless motors. As part of minimally invasive surgery, integrated forceps with four degrees of freedom has been developed[85]. A haptic feedback controller can measure the force involved in pulling and grasping.

For tissue manipulation, a soft pneumatic chamber gripper was developed[86]. With its grasping force three times lower than that of forceps grippers, it can grasp objects as small as two millimetres, preventing tissue damage during surgical manipulation. Medical applications were treated with a magnetically guided and actuated mechanism[87]. The grippers could be controlled both untethered and tethered using permanent magnets. A cobalt iron magnetic cobalt core is carried inside a capsule made of an electromagnetic coil. Medical grippers have become more reliable with recent advancements, making them suitable for procedures such as robotic surgery, minimally invasive surgery, and medical grippers. Novel mechanisms, high technology actuators, and the development of new mechanisms are recent developments. Force control is still one of the challenges in medical applications, despite much works dealing with the problem.

2.5 Nano- and microgrippers

Micro and nanoelectromechanical devices have been used to develop different designs and technologies for micro and nano-gripping. Microelectromechanical systems are designed to handle micro-sized objects. A wafer substrate is used in the semiconductor industry as a substrate for mounting parts[88]. Bio and nanomaterials can also be manipulated with these tools[89]. Hybrid MEMS microgrippers were developed in[90]. A hybrid microgripper based on MEMS technology has been designed in[90]. Using the arm's tip, a distance of 25µm could be deflected[91]. This has been described the invention of thermal bimetallic grippers. Using nanofabrication techniques combined with microlithography, this gripper was able to measure less than 100 nanometres in size. A microgripper that are also designed using an electrostatic linear motor[92]. With this motor, micro positions were moved with high accuracy using a scratch drive actuator. Modeling and fabrication processes were covered, as well as FEA. Using electrostatic actuation, with low electrical consumption and high precision, it is possible to integrate with integrated circuits (ICs). The gripper needles of the gripper are microfabricated to submicrometric dimensions using another method[93]. The gripping tips were made using a thin silicon-on-insulator wafer coated with SiO_2. It was capable of grasping gold spheres as small as 100 nanometres. Novel electrostatic MEMS grippers equipped with capacitive contact sensors were developed in[94]. In this case, the transverse comb differential capacitances act as a contact sensor to prevent damage. A driving voltage of 55V allows it to grip objects as low as 12 µm. The parts are also released through vibrations. SU-8 polymer was used to make microgrippers[95]. Using electro-thermal energy, it was actuated by sensors that detected the tensile force of the material. The gripper was capable of displacing up to 100µm for up to 50 cycles. It is also possible to achieve variable forces of between a few µ N and 1 MN. Researchers developed a two-fingered microhand for grasping at high rates of speed.

Researchers developed a two-fingered micro hand for grasping at high rates of speed[96]. The micro hand was capable of picking up and placing large objects of 40 to 60µ m in size in a matter of seconds. A vacuum gripper with 4 DOF robotic arms was designed with a two-camera vision system and a vacuum gripper with a vacuum[97]. As an example, design of a conventional vacuum gripper (standard dispensing needle) and a multi-lumen nozzle can be compared. Testing showed that the micro components could always be grasped by the device. However, in some cases, the micro components were not released as expected. To determine the behavior during the release of this gripper, further modelling needs to be developed. An ultra-compact gripper with polycrystalline silicon was developed[98]. The male and female parts of this ingressive gripper are connected by a snap-and-lock mechanism. As well as being shaped similar to an arrowhead, it has two hooks on its female portion. Both sections are moved by a tensile load when they snap together. A confocal Raman imaging test was performed on the assembly, which confirmed that the local peak tensile stress was around 50% of the lower bound strength with stress mapping[99]. Electrostatic grippers were developed for the micro components[100]. Besides the standard micro components, the mechanism was also capable of grasping delicate mini and micro components. Besides the theoretical models, the gripper was designed using FEM models. This machine was capable of grasping and releasing different shapes of material ranging in size from 0.3 mm to 1 mm. Nearly 100% of the grasps were found to be reliable. A microfiber array inspired by a gecko was used to develop an integrated circuit transfer robot [101]. In addition to the Gecko-inspired approach, micro wafers can be damaged by excessive pressure within vacuum grippers. The wafer is held in place on the end-effector by the friction force caused by the mass of the wafer. A square configuration of microfiber bumps has been found to have the least deformation. A rubber or stainless-steel bump can accelerate 4.155 m/s^2, but this gripper can accelerate at a pace equal to or greater than that. Liquid water layers have also been used in conjunction with concurrent grippers to secure objects[102]. Water is solidified into ice by the manipulator, which sticks to both surfaces. A submerged version was also available[103–105]. The application of microgrippers in microfabrication, micro-assembly, and micromanipulation has attracted the attention of researchers in recent years. As discussed in the literature, recent advances in micro components, specifically MEMS, have made this technology cheaper, more reliable, and easier to use.

2.6 Grippers made of soft fabric

Designing grippers that pick-up fabrics remains a challenge. Ingressive grippers were designed to accomplish this, which are also referred to as penetrating grippers. The textile industry uses them to hold fabrics, since suction cups are unable to vacuum the material because of its porosity. Moving textiles can damage the fabric's underlying structure, even if the textile is penetrated. Various textile sheets can be separated from one another using a spiked wheel[106]. An improved gripper was used in[107]. Fiber backing sheets are also removed by these grippers[108]. It is, fortunately, possible to adjust these variables on most ingressive grippers so that the material is not damaged[109]. The concept of prepegged carbon fiber sheets can also be found in[110]. As well as picking up continuous carbon fiber sheets, Trzepieciński et. al.[111] investigated the extraction of strands. Fabrics can also be gripped by suction cups[112]. During automatic or manual cutting, the fabric must not be deformed. This device had a flat surface with suction holes of 0.5 cm and positive pressure holes of 0.1 cm. The gripper lacked tactile feedback sensors, which would have improved part manipulation and handling. It is covered by[113] for this gripper in particular. A new feature has been added to suction cup grippers, which can now capture C and L-shaped profiles.

The fabric is unrolled in various stages to achieve this. The end-effector shape can also be changed to shape textiles to different geometries[114]. A cylinder was picked up and the carbon fiber textile was draped onto the contours to cure in this application[115]. Leather plies were also picked up with a flexible suction cup[116]. Due to its flexibility, this vacuum cup did not leave marks on the leather-like other commercial vacuum cups. Direct contact has been used as another method of picking up fabrics. Chemical adhesion such as glue or sticky adhesives is what is used in these constitutive grippers. In addition to using a thermal method, a surface can also be melted and adhered to an object. A permatack adhesive with a contact pad is used in the textile industry[117]. Using this method has the disadvantage of causing microfibers to stick to the fabric over time, decreasing their ability to adhere. Carbon fiber sheets also use thermal adhesion[118]. Carbon fiber sheets are thermally melted. To achieve solid bonding, the resin is melted. As a result, bonding times have been reduced since then to less than one second[119].

The chemical cure, by comparison, can take over ten seconds. It has been shown that suction grippers are effective at grasping soft fabric objects. The application of this technique is being studied through various methods, such as adhesion.

3 Kinematic design and actuators for grippers

The purpose of this section is to study the design considerations of grippers with specific purposes and applications. Various robotic gripper designs are examined in this section for their traits such as rigidity, weight, and size. When analyzing design peculiarities, two key factors are examined: a gripper's characteristics, the objects' characteristics, technology for grippers, the flexibility of grippers, and the cost. The device's transmission characteristics and grasping force, in addition to gripping force, are also studied.

3.1 Piezoelectric Grippers

Research focusing on using piezoelectric grippers for active manipulation has increased as piezoelectric materials have become less expensive[120)]. As opposed to mechanically actuated grippers, piezoelectric grippers are simple and easy to use, and they consume a low amount of electricity. Piezoelectric polymeric polyvinylidene fluoride (PVDF) was used to make some of the earliest grippers[121)]. The design was further developed, which was arranged in a rhombus shape[122)]. A piezoelectric strip can be used as a force sensor because it amplifies the force that is applied to the object. MRI-compatibility was achieved by designing a piezoelectric tweezer for use in robot-assisted surgery[123)]. With this mechanism, the tips are amplified using nested strains, which increases displacement to useful levels. The comparison of self-sensed and true tweezer tip forces showed at most a 12% average error in tip inclination and force.

The piezoelectric actuator used in gripper with (±60 V) voltage-controlled[124)]. The voltage cannot be supplied in such a manner, so a PID controller is used to achieve stability. With PID voltage controllers, micro manipulations can be done more precisely. LP controllers are substituted for the PID controllers[125)]. A piezoelectric actuator is controlled by a PI-based sliding mode controller[126)]. In addition to providing better tracking, faster responses, and higher positioning precision, the proposed controller demonstrated greater responsiveness[127)]. This provides a theoretical and experimental analysis of piezoelectric bimorphs. A variety of input voltages and signals were used, along with the transient response and frequency response. With the actuator alone, the gripper could reach objects as far as µ50 meters. Despite the various designs proposed with different control approaches, piezoelectric grippers still have significant difficulty in controlling position and maintaining stability.

3.2 Grippers with multiple fingers

The parallel gripper has been enhanced through many approaches. When multiple fingers are used, the robot can perform more motions. It was developed in[128)] that one of the first three-fingered hands surfaced. In addition, feedback sensors are integrated into[129–132)]. An end-effector was equipped with 87 touch sensors spread across its surface. Recently, engineers have studied a wide range of options for improving parallel grippers. Fiberless, flexible microactuators (FMAs) have been developed[133)]. Along the length of the gripping finger, the FMA gripper is constructed of hollow cylindrical chambers. If the positive or negative pressure is applied to the chambers, they expand or contract, bending or extending the fingers. It was possible to hold fish eggs with the model. The wire loop actuation system results in the use of an underactuated mechanism that was built without breaking it. To explore grasping capabilities, an innovative design and actuation mechanism was employed[134)].

A robotic hand was designed with three fingers and soft materials for enhanced adaptability, the gripper contains a three-fingered robotic hand[135,136)]. A variety of size and shape samples have been used to test the gripping and holding. The adaptability of the design makes it a great application for bio-inspired robot designs based on morphological computation principles. Pancakes can also be fried with multi-fingered graspers[137)]. Using the internet, two robots were instructed. They were called TUM James and TUM Rosie. Robot action plans, which encompass actions such as retrieving pancake mix, opening drawers, and transferring items, are generated subsequently. In today's way of working, we make use of 3D semantic maps to accomplish these tasks. In addition to gripping oddly shaped and unknown objects, multi-fingered grippers have many other applications. There are various actuation systems presented, including a flexible microactuator and wire loop actuation systems, though soft materials may offer better adaptability with these grippers.

3.3 Underactuated Grippers

It has been increasingly difficult to design end effectors that can grasp irregularly shaped objects. The designs of some grippers focus on mechanisms that wrap around and are underactuated. Underactuated hands were built in this case[138)]. Grapples of this type are useful for holding objects since they adapt to the object they are holding. Underactuated grippers were also developed for a similar application[139)]. The concept of contacting objects is inspired by how a chameleon shoots its tongue. An end-effector with a permanent magnet is attached to a string and loaded into a catapult. When tested, the end-effector of the catapult captured falling objects 0.7 m away 92% of the time. Due to its ability to reach objects not visible from the base, this end-effector is advantageous. While limiting the length of the end-effector, the magnet can drop behind the obstacle and loop around it to reach the target. An enveloping grasp and parallel grasp were designed, as well as a fingertip grasp[140–142]. Several cables are tensioned along with the fingers by a single actuator.

Objects can be grasped in a variety of configurations with this design. If an object is contacted by distal or proximal links, the links will flex. Pneumatic actuators were developed to solve the issue[143]. A pumping system pumps air through its outer skin. A skin's weaker side expands and bends the thicker side inward due to its thicker side. Applied to moderate pressures (<1.25 atms), the pneumatic actuator could bend up to 180 degrees. Malleable grippers are another method of grasping oddly shaped objects and deforming surfaces. The first elastic layer gripper with deforming properties was built[144]. Further, study of this in provides a model of a pair of 3 DOF fingers with soft tips[145]. By implementing such novel mechanisms, grippers can be made more autonomous and require less control effort than multi-fingered grippers. Enveloping grippers are mainly biologically inspired grippers.

3.4 Malleable Grippers

Materials that change viscosity are used in malleable grippers. Materials inside the flexible outer skin are typically electrorheological (ER) liquid, magnetorheological (MR) fluid, or pellets. In order for the outer surface to fit into the geometry of the object, it is pushed against it. Hardened inside, the object is then held by impact. It will return to a fluid state so that free movement can be accomplished after the object has been released. It is mainly used in shape-adaptable grippers that are not only soft but also strong, versatile and adaptable to different shapes and sizes. A variety of technologies have been applied to several soft grippers' designs in the literature. The flexibility of a soft grip allows it to be adapted to different shapes where a rigid grip cannot. A malleable gripper was made using ER fluid[146]. When an electric field is applied to an ER fluid, its viscosity changes. The Bingham plastic-like behaviour of the ER fluid is triggered by an electric field.

The field behaves like a liquid when the field is removed. During testing, this gripper successfully handled fragile objects like eggs. The disadvantages of using ER fluid include how energy-consuming it is as well as how arcs can form in the gripper. Granular material has been used to design a malleable gripper that is safer[147]. A vacuum is applied to the material in order to change its viscosity, and the gripper remains rigid throughout the process. Skin grippers are tested in the previous study[148]. 85% of the system is more reliable, and 25% of the system is found more error-tolerant. It was demonstrated that this vacuum could be reversed, and objects could be ejected from the mold. Now, this design has been commercialized as the Versaball[149]. Also used to pick up fruit are MR fluid grippers in[150]. Magnetic fields change the viscosity of MR fluid. There are two pouches on the ends of each arm, which contact the that hold MR fluid. Magnetic field activation changes the viscosity of the MR fluid, and the pouches conform to the fruit. It is possible to lift the fruit with low force without damaging it with this design. The advantage of this design is that the magnetic field can control how much pressure it applies to fruit on the outside. MR fluid is very expensive, so this design was not satisfactory. The flexibility of malleable grippers is greater than that of rigid grippers, but their dexterity poses a design challenge.

4 Statistics with commercially available grippers

The data can be analysed statistically once all the specifications are gathered. Table 1 presents an overview of the results of the analysis, which lists the minimum, maximum, mean, median, and standard deviation for all the selected specifications of grippers. Based on these parameters, one can define an "average" gripper of the sampled market as being 20.8 mm long, 1,020 N in force, and 3.4 kg in weight. The results, however, are noticeably different when compared with the median values. As a result, the defined median gripper consists of a stroke of only 9.5 mm, a gripping force of 320 N, and a weight of 0.6 kg. Analysing statistical data, it appears that there are differences between the mean and median values and the distribution of the data is not bell-shaped. As can be seen by a closer look, this large discrepancy is due to the fact that many specifications, especially the stroke, are biased toward smaller values. However, instead of large products, only a few intermediate devices exist, even if small grippers make up the bulk of virtually every manufacturer's.

Table 1. A statistical analysis of common specifications.

Parameters	Min.	Max.	Count	Ave.	Median	Std. Dev.
Power [W]	0.77	1840	170	239.38	82.26	355.3
Stroke [mm]	1	300	289	20.8	9.55	35.1
Weight [kg]	0.01	70	289	3.4	0.59	8.43
Force [N]	6	15400	289	1020	320	1938
Finger length [mm]	9	900	197	143.21	100	139.93
C-factor [J/kg]	0.36	28.57	289	6.91	5.68	4.98
Air cons. [cm^3/cyc.]	0.09	4600	170	163.61	13	526.64
Closing time [s]	0.01	2.3	270	0.23	0.13	0.32

It may be noted that these values are for the stroke of a single finger, following the classification method in catalogues, although the overall opening and closing range of the grippers is twice these values because two-finger grippers are considered. There are two reasons for the small stroke offered by most grippers. Firstly, it is only necessary to grasp a known workpiece with an infinitely small stroke. The fingers of a gripper can, be designed to leave an exact gap between them when closed, allowing them to grasp precisely what they are holding. This part would be released if the fingers were opened for only an insignificant amount. A certain margin of safety must be considered in practice due to factors such as positioning tolerance, accuracy, and structural compliance, as well as the use of a small but finite stroke.

Secondly, to increase production output rates, cycle times for grippers in mass production should be reduced to the greatest extent possible. Due to the fact that these grippers are commonly operated by simple 'open/close' signals rather than precise positioning, small strokes are required to grasp and release workpieces more quickly. Because of these two factors, the median gripper has a smaller stroke than the average: most grippers are small and have tiny strokes. In Figure 2 the histogram shows the frequency distribution of the gripping force of grippers, grouped in 100 N intervals. Most grippers exert a force between 0 and 400 N, with a peak at around 100 N. There are fewer grippers with higher forces, and the frequency drops significantly after 400 N. This suggests that the majority of grippers in the market are designed for lower force applications.

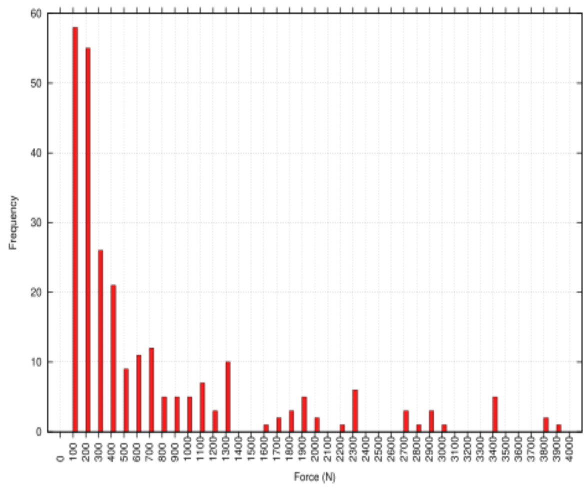

Fig. 2: Histogram for force (gripping) in 100 N bins.

In Figure 3 the cumulative frequency chart shows the total number of grippers that can exert up to a given force. The plot shows a steep increase initially, indicating that many grippers have low force capacities. The curve levels off gradually, showing that fewer grippers are available with higher force capacities. This confirms that low-force grippers dominate the market.

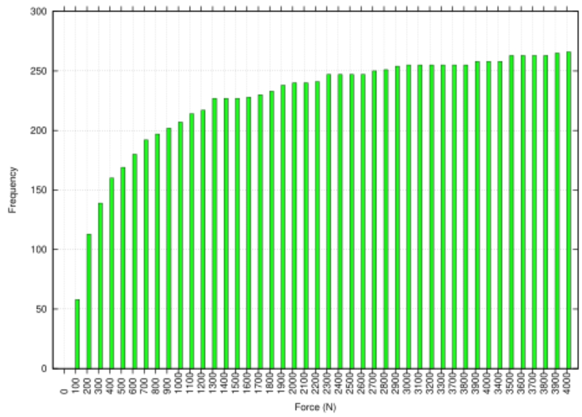

Fig. 3: Cumulative force for all instances of gripper.

In Figure 3 the histogram displays the frequency distribution of the stroke length of grippers, in millimeter intervals. The stroke length distribution is varied, with multiple peaks indicating several common stroke lengths. However, most grippers have strokes between 1 and 15 mm, suggesting a preference for shorter stroke lengths in many applications.

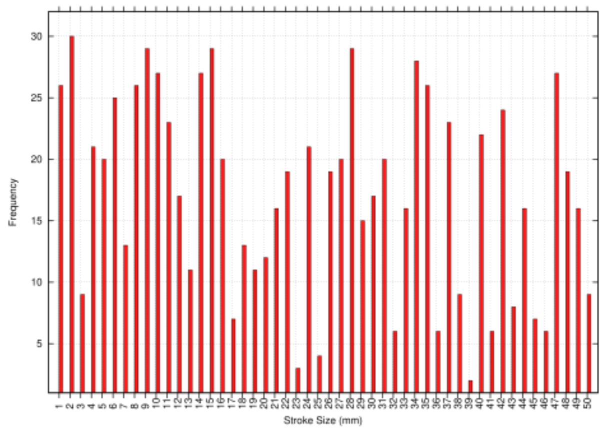

Fig. 4: Histogram for stroke length (mm).

In Figure 5 the cumulative frequency chart shows the total number of grippers with a stroke length up to a given value. The plot rises steadily, showing that a wide range of stroke lengths is available. The initial steep rise indicates that most grippers have shorter strokes, which aligns with the histogram's indication of a preference for shorter strokes.

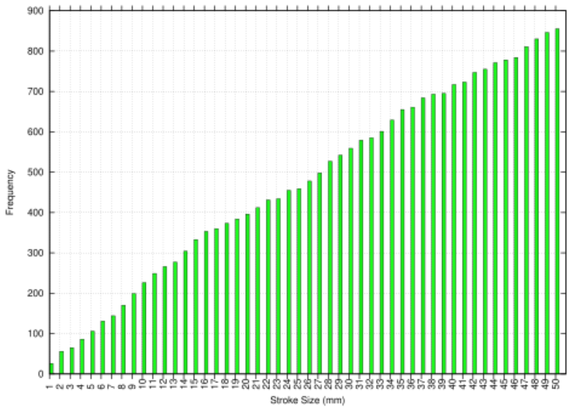

Fig. 5: Cumulative stroke length for all instances of gripper.

In Figure 6 the plot shows the normalized mean and variance for weight, stroke, power, force, and C-factor of grippers. The stroke has the widest range of variance, followed by force and power. Weight and C-factor show less variance. This suggests that while grippers can vary widely in their stroke capabilities, their weight and energy efficiency are more consistent across different models.

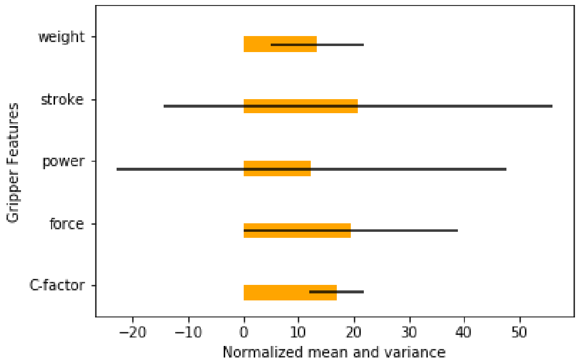

Fig. 6: Normalized mean and variance for all gripper characteristics.

In Figure 7 the plot shows the probability distribution functions (PDFs) for stroke, force, and weight of grippers. The weight distribution is skewed to the left, indicating that most grippers are relatively light. The force distribution is more balanced but still has a peak at lower values, showing a higher probability of low-force grippers. The stroke distribution is more spread out, indicating a wider variation in stroke lengths among grippers.

These figures show that most commercially available grippers are designed for low force and short stroke applications, with relatively consistent weights and energy efficiency. The data also highlight the variability in stroke length and force capabilities, reflecting the diverse needs of different industrial applications.

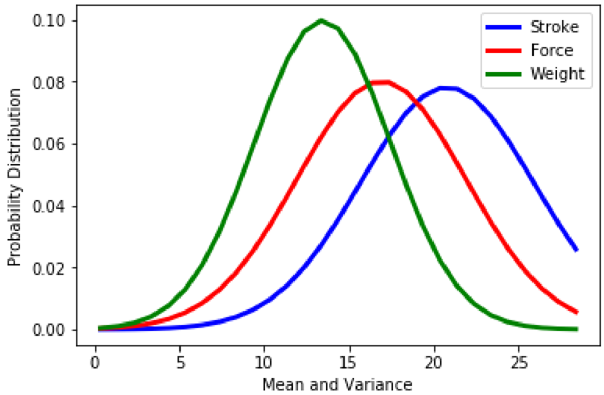

Fig. 7: Probability distribution function for three characteristics of gripper.

5. Summary

The most common values for the force of grippers in bins of 100 are shown in Fig. The median grasping force is reported to be 320 N. Its cumulative representation for all 289 grippers under study is shown in Fig. Similarly, the histogram of the stroke length of the gripper and its frequency is shown in Fig. . Fig. shows the cumulative stroke size of 289 grippers. The normalized mean and variance of all gripper characteristics is shown in Fig. . The Bell curve representing the probability distribution of three characteristics (stroke, force, weight) is shown in Fig. 7. Advantages and Disadvantages of various robotic grippers are presented in Table 2.

Table 2. Advantages and disadvantages of various robotic grippers.

Gripper Type	Advantage	Disadvantage
Vacuum gripper[26]	Highly Flexible	Some operational issue
Hydraulic gripper[45]	High force capacity	High maintenance cost
Cable driven[57]	Optimal space and weight	Control complexity
Pneumatic[39]	Small dimension and low weight	Not precise enough and high operating cost
Servo-electric[20]	Highly flexible	Low force
Multi-fingered grippers[22]	Effective in gripping small objects	Low accuracy
	Flexible gripping	Low dexterity
Piezo-electric grippers[35]	simplicity	Low accuracy
Enveloping grippers[48]	Flexible gripping	Less control

6. Conclusion

End-effectors, or grippers, have been utilized in a wide range of fields, including automotive, manufacturing, agricultural harvesting, MEMS grasping, surgical applications, and prosthetics. These grippers often rely on impactful gripping strategies, which have branched into numerous designs, such as sensor-integrated grippers, camera-enabled grippers, piezoelectric grippers, soft grippers, MEMS grippers, multi-finger grippers, underactuated grippers, elastic grippers, and multi-arm grippers. Sensory feedback plays a crucial role in enabling grippers to track and grasp objects more effectively.

While MEMS and piezoelectric grippers offer high precision, they are limited by weak gripping forces. Soft and malleable grippers can handle irregularly shaped objects but may suffer wear and tear after repeated cycles. Dual- and multi-arm grippers are replacing traditional single-arm designs for applications such as assembly lines and healthcare due to their increased versatility and efficiency.

The evolution of gripper technology has benefited from advancements in robust controllers, instrumentation, and structural design. However, most grippers on the market still share common limitations, such as small stroke lengths and limited force capacity. To overcome these challenges, this paper proposes the application of artificial intelligence (AI) to enhance current gripper technology, improving their accuracy, precision, speed, and overall effectiveness[151,152)].

7. Future Research Directions

7.1 Development of Multifunctional Grippers

Future designs could incorporate hybrid capabilities, enabling a single gripper to handle a wide range of tasks—from delicate operations like surgical procedures to heavy-duty industrial applications.

7.2 Integration with Artificial Intelligence

AI-powered grippers can leverage machine learning models to autonomously recognize object shapes, dimensions, and rigidity. These models can train robotic arms to adapt to a variety of predefined and dynamic object features, enabling real-time adjustments to gripping force and positioning.

7.3 Hybrid Grippers Combining Rigid and Soft Components

Combining the precision and strength of rigid grippers with the adaptability and gentleness of soft grippers can yield versatile solutions for handling diverse objects without damaging them.

7.4 Advanced Sensory Systems

Future grippers should include intelligent sensors capable of real-time feedback on force, texture, and object geometry. This would enable a more nuanced approach to handling objects of varying fragility and structure.

7.5 Sustainability and Longevity

Research could focus on improving the durability of soft and malleable materials to withstand repeated use while maintaining their effectiveness. Exploring biodegradable or recyclable materials could also address environmental concerns.

7.6 Miniaturization for Specialized Applications

Further advancements in MEMS-based grippers could lead to more compact designs for micro-assembly, nanotechnology, and minimally invasive surgical procedures.

7.7 Collaborative Robotics (Cobots)

Grippers designed for human-robot interaction could prioritize safety, adaptability, and ease of programming, making them suitable for collaborative tasks in industries such as healthcare, logistics, and service sectors.

In conclusion, the future of gripper technology lies in integrating advanced materials, AI-driven intelligence, and multifunctional designs to meet the increasing demands of diverse applications. By focusing on these research directions, grippers can evolve into more sophisticated, adaptable, and efficient tools, transforming the way objects are manipulated in various fields.

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