Review

State of the Art Robotic Grippers and Applications

Kevin Tai, Abdul-Rahman El-Sayed, Mohammadali Shahriari *, Mohammad Biglarbegian and Shohel Mahmud

School of Engineering, University of Guelph, Guelph, ON N1G 1Y4, Canada; ktai@uoguelph.ca (K.T.); elsayeda@uoguelph.ca (A.-R.E.-S.); mbiglarb@uoguelph.ca (M.B.); smahmud@uoguelph.ca (S.M.)

* Correspondence: mshahria@uoguelph.ca; Tel.: +1-519-824-4120 (ext. 56044)

Abstract: In this paper, we present a recent survey on robotic grippers. In many cases, modern grippers outperform their older counterparts which are now stronger, more repeatable, and faster. Technological advancements have also attributed to the development of gripping various objects. This includes soft fabrics, microelectromechanical systems, and synthetic sheets. In addition, newer materials are being used to improve functionality of grippers, which include piezoelectric, shape memory alloys, smart fluids, carbon fiber, and many more. This paper covers the very first robotic gripper to the newest developments in grasping methods. Unlike other survey papers, we focus on the applications of robotic grippers in industrial, medical, for fragile objects and soft fabrics grippers. We report on new advancements on grasping mechanisms and discuss their behavior for different purposes. Finally, we present the future trends of grippers in terms of flexibility and performance and their vital applications in emerging areas of robotic surgery, industrial assembly, space exploration, and micromanipulation. These advancements will provide a future outlook on the new trends in robotic grippers.

Keywords: robotic grippers; grasping; end effector; micromanipulators; robots

1. Introduction

The robotics industry was originally developed to supplement or replace humans by doing dull, dirty, or dangerous work. They are used in applications such as: automated assembly lines, observing radiation zones, minimally evasive surgery, and space exploration. Modern industrial robotic arms excel over humans in many tasks. They are capable of lifting 1000 kg [1], are repeatable to 10 μm [2], and are faster with accelerations up to 15 g [3]. Additionally, the cost of robotic grippers is decreasing while manual labor costs are increasing. This has encouraged industry and academia to develop more advanced robotic arms and grippers addressing both form closure and force closure [1], two of the main components of any robotic gripper. Robotic grippers, by directly being in contact with the workpiece, are tasked with interaction with the environment and grasping objects like human hands for human manipulation [2].

Advanced grasping of complicated objects is an active research area, which includes soft fabrics, microelectromechanical systems (MEMS), and synthetic sheets. In addition, grippers are being designed with different materials. This includes piezoelectric crystals, shape memory alloys (SMAs), magnetorheological (MR) fluid, carbon fiber, and many more. Recent research has also considered bio-inspired gripping mechanisms, which leverages nature to develop products that solve problems that are more industrial.

Previous papers have reviewed robotic grippers with more emphasis on specialized applications. In [3,4], the use of grippers was covered for automated production processes. Different gripping systems, such as artificial vacuum, magnetic and mechanical gripping, were discussed in [5].

In [6], only parallel manipulators gripper mechanisms were covered. In [7], grippers for surgical applications can be found. In [8], only dual arm manipulation was covered. In [9], a review of space robots was discussed. In [10], plant production robots were reviewed. In [11], only the contact strategies for micro components were examined. In [12], end effector control schemes were discussed. Some modern examples of grippers include the Kuka KR 1000 Titan; Dexter on the International Space Station; the Explosive Ordnance Disposal manipulator on the iRobot 510; and the da Vinci Surgical manipulator [13–16].

There are numerous applications of where robotic grippers can be used. This highlights the importance of reviewing the many recent developments that are occurring in research and discuss the future directions of designs and applications. This paper provides a broad perspective on the different types of grippers; our paper is especially focused on applications of grippers that have not been covered in previous survey papers including grippers for deformable and fragile objects and living organs. The earliest types of grippers in our survey are discussed along with the improvements made to them, and most importantly, the recent advancements. We discuss different categories of grippers being used for known and unknown environments, medical and industry applications, and micro and nano manipulation. We also compare new grippers' designs and state their advantages and limitations. Our paper focuses on emerging applications such as in medical, agriculture, micro and nano manipulation, new design developments in this field, and future direction of design, technologies and applications of the trending grippers' designs, which differs our work from other survey papers. We believe this paper helps researchers and industry discover newer grasping mechanisms, their advancements as well as challenges associated with them. We conclude our work by discussing the challenges and future directions in this field.

The rest of this paper is organized as follows: Section 2 covers the developing grippers organized by application, Section 3 presents different gripper designs, Section 4 discusses the future direction and discussion of robotic grippers, and Section 5 concludes the paper.

2. Applications of Robotic Grippers

2.1. Grippers for Industry

The earliest grippers were first developed for industrial applications. They are commonly defined as grippers used for mass production purposes that are mounted on a stationary platform. The industrial grippers can be studied through different aspects such as geometrical condition of grasping, position and orientation of grasping, static equilibrium of grasped object, and dynamic conditions [17,18]. We mainly focus on the performance, adaptability and flexibility of the grippers.

The first industrial robot was the UNIMATE installed in a General Motors assembly plant in 1961 [19]. This was a rigid parallel manipulator that grasped hot pieces of die cast metal. Since then, many companies have embraced robotic gripping technology and have developed different drive mechanisms [20–22]. These were typically driven by electric motors or hydraulic actuators, but more recently piezoelectric and shape memory alloys are being used for actuation.

Industrial grippers can be split into different categories such as grippers used in known environments and grippers used in unknown environments.

2.1.1. Grippers for Known Environments

Grippers that are used in known environments typically have parts that come on an assembly line. The parts are positioned in predefined orientations, which make it easier for the gripper to pick up the object. These grippers can use servos, non-contact, contact, or a combination of sensors for feedback. Sensors can include hall sensors, accelerometers, ultrasonic, or photoelectric sensors to name a few. This can be used for detecting many variables such as: position, force, torque, velocity, and acceleration [23]. These sensors prove useful in many situations such as detecting whether objects are being grasped, or by providing information to a supervisory computer to control an assembly line

process. Two examples of commercialized grippers are the Schunk DPG-plus and the Robotiq 2-Finger Gripper [24,25].

In academia, grippers are prototyped with many different types of sensors and feedback mechanisms. In [26,27], three sensors are used to detect deflection in each axis (*x*, *y*, and *z*). In [28], the sensors are built from materials such as conductive silicone. In [29], sensor feedback is integrated into a smart sensor network where each node performs signal acquisition. New developments have also encouraged the use of a capacitive force sensing array for the artificial skin of a robot [30]. Tactile sensing systems have also been incorporated into prosthetic hands [31]. It uses a biomimetic tactile sensor, which is capable of triaxial force sensing. In [32], a novel tactile sensor is presented using flexible piezoresistive rubber.

Proximity sensors have also been mounted on grippers that use an active prediction, planning, and execution system for intercepting moving objects [33]. It moves to the earliest pregrasping location close to the object and the proximity sensors utilize a fine-motion tracking algorithm to pick the object. This removes the need for continuously tracking the motion of the objects during the planned movements and it reduces the distance between the object and end effector.

A shell shaped end-effector is designed in [34] where the force can be sensed on any position of the body. The position and force of the contact can also be measured in six axes.

There are also claw like end-effectors that can be thrown using a launch platform. In [35] the claw is launched using a swinging motion while the range is measured by a laser range sensor. One end of the claw is attached to the base by a string. The tension of the string is adjusted midflight, which allows the claw to fly in parabolic trajectories to the target.

In [36], a minimally invasive surgical gripper was developed. The proposed design is advantageous as it enhances the surgeons' dexterity. The prototype gripper is a parallel end effector controlled by a joystick. The position and orientation is acquired from a motion tracking system by Northern Digital Inc. and physical movements are displayed using a screen in real time.

Control systems are also being studied which can significantly improve the tracking and performance of grippers. In [37], a 3-DOF parallel manipulator was designed with PID and fractional-order PID to improve the tracking performance. Servo motors were used and it was found that the fractional-order controller reduced the transient and steady state error. In [38], an oscillatory-base manipulator was tracked using H_∞ and PD controller. It used servo motors and it was found to be superior to a PID controller.

Underwater grippers with feedback systems have also been developed [39]. For this design, a multi-limb gripper with tactile sensors, which is capable of sensing objects up to 6000 m in depth. Testing the gripper system in a pressure chamber at 600 bar demonstrated the effectiveness of the deep sea system.

In [40], six position sensors and six servo valves were used as feedback for a 6-DOF electrohydraulic parallel robot. It utilized decoupled-space control (DSC) to further improve the performance of the robotic gripper. It was found that the DSC framework improved the performance by solving the dynamic coupling effects of the multi-DOF parallel robot.

Grippers also include attractive grasping, also known as astrictive grippers. This attraction can be: vacuum suction, magneto-adhesion, or electro-adhesion. Some of the earliest astrictive grippers were used for sheet metal fabrication [41]. A theoretical model of a suction gripper is found in [42]. This model is then expanded to multi-link manipulators in [43]. They are also used heavily in the packing industry as astrictive grippers have a soft grasp on both heavy and light objects [44]. This is used in a modular vacuum conveyor system to pack objects neatly in trays after they come off the assembly line [45]. They are advantageous as they can pick up slippery, oily metal sheets [46]. Another common application is picking up large glass panes during the manufacturing process [47].

In [48], three robotic packing cells were utilized to pack soft drinks into boxes. The end-effector could pick up 12 soft drinks at a time with a vacuum suction cup for every drink. Once the packing robot was installed, the assembly line was able to operate 25% faster. The workers were then redeployed to different areas of the company to add more value to the end product.

In [49], a flexible assembly station is developed for aerospace applications. A great difficulty in manufacturing fuselages and wings for airplanes are the changing surfaces. This designed assembly station consists of only 8 actuators with suction cup grippers. These are fitted with load cells and the actuators are extended slowly to search for the fuselage. Once it finds the part, the suction cups are activated and the suction cup heads are locked in position. The advantage of this holding mechanism is that every actuator can map the forces. It can also provide valuable information during manufacturing processes as excessive loads will allow the process to be stopped immediately.

Some of the challenges that suction cups have are the speeds that the work pieces can be moved at. If the acceleration of the work piece is too fast, the gripper could lose suction. To increase production speeds, more innovative methods of holding these objects must be developed. There can also be challenges associated with the speed of deceleration such as during emergency stops. A proposed solution to this is to use friction cups. They have higher coefficients of friction, which can handle large parallel friction forces; however, they have weak friction forces in the perpendicular direction. Vacuum pressure in suction cups is also an issue as centralized vacuum systems add weight, material and costs. It also could affect the suction pressure at different cups since longer tube lengths will cause performance penalties. In all cases, only the small volume between the cup and the vacuum pump need to be evacuated. Miniaturizing such systems can avoid these issues, however in many cases the amount of vacuum pressure created is not large enough to hold the [50].

2.1.2. Grippers for Unknown Environments

In many cases, grippers might be tasked for pick-and-place operations without knowing the conditions of the environment. Different design and techniques have been developed to increase the flexibility of grippers in unknown environment such as using vision systems, sensory feedbacks, and novel mechanism with flexibility in gripping.

Camera systems are used to detect the presence of objects. One of the first parallel grippers designed with camera systems was in [51]. This was built to pick up randomly oriented work pieces from a bin. Since then, increased computing power and finer resolution vision systems were developed for gripping [52]. In order to pick up the object, the operator simply had to point using their finger within the workspace of the robot.

Vision systems were further improved in the semiconductor industry [52]. Large polysilicon nuggets require very careful handling before they are fused into larger quartz crucibles. These nuggets range from 600 grams to a few grams, which need to be carefully packed before heating. Since they are packed using complex rules, an automated system is used. There is an overhead charge-coupled device (CCD) camera and two scanners to map environment.

The gripper of autonomous mobile manipulators is a problem that is being challenged using a modified image-based visual servo controller with a hybrid camera [53]. An eye-in-hand web camera was used to visually track the object in the unstructured environment while a stereo vision camera was used to measure depth information online. The controller combined the information and used a rule base to tune the gain in order to improve the response speed of the controller. This method was then validated using experiments.

In [54], a vacuum gripper was developed with machine vision. Using segmentation algorithms, the best hold position and orientation was determined. The data is then relayed to the robotic vacuum to pick up the object and move it to the desired location.

In [55], a new image-based visual servo controller was created for a 6-DOF gripper. The controller was able to achieve a more linear trajectory and reduced the risk of having image features leave the field of view.

Human grasping has also been investigated where a 3D camera and inertial measurement unit was used to track the movements of a human hand [56]. It incorporated a Kalman filter and an adaptive multispace transformation on the movements of the hand. The gripper would then move in tandem with the hand.

Mobile robot grippers have also been studied using 3D scanning of unknown environments [57]. The gripper was used for autonomous climbing maneuvers. Feedback was also provided by an inertial measurement unit, joint absolute encoders, and pressure sensors.

In [58], grasping maps were developed using camera systems. The map in this configuration utilized online and parallel computations to reduce the time by more than 90% compared offline systems. The method was then validated in a physical environment with both simple and complex objects.

In [59], grasping planning was conducted using a Kinect RGBD camera system, a two fingered gripper, and an industrial robot arm. It required a learned mapping between geometric states and logical predicates. The task was to find the cups on the table, stack them, and put them on a tray. The approach in this case was not entirely complete as some configurations were not able to generate a plan. If there were issues with generating a plan, a proposed solution would be to remove one of the cups off of the table and stack the rest. This work is being continued to execute plan generation on different types of objects.

In summary, the main objective of robotic grippers in unknown environment is flexibility. Different approaches have been addressed to overcome this challenge. It is discussed that 3D scanning and vision feedback are shown to perform well. The other objective is novel mechanism design, which provides flexibility to the gripper inherently. These designs can partly take care of controller task by intelligent structures mechanically.

2.2. Grippers for Fragile Objects

With the improvement of end-effector sensors, the idea of picking up fragile objects was explored. In [60], an end-effector was designed for harvesting lettuce. This design included a machine vision device, six photoelectric sensors and a fuzzy logic controller. The designed end effector was able to harvest lettuce at a rate of 5 s per lettuce with a success rate of 94.12%.

In [61], an enclosed hygienic food gripper was designed with force feedback sensors. One finger on the gripper is stationary while the other finger moves by magnetic attraction. The actuator is placed inside with an inner magnet while an outer magnet moves the finger on the outside of the container.

Another design was investigated which grasped fruits [62]. This end-effector was built to incorporate both clamping and cutting to avoid possible damage to the fruit. A similar design is used to harvest strawberries, which uses a machine vision unit [63].

In [64], a citrus harvester was also designed with a large field-of-view camera. Similar designs were presented in [65,66].

A Bernoulli principle type end-effector was designed for handling sliced fruit and vegetables [67]. It allows the objects to be lifted using the airflow over the surface to minimize contact. This then reduces the probability of cross-contamination and damage to the produce. Another benefit of using this type of gripper is to reduce the amount of surface moisture on the object. This gripper was built and was found to be feasible in handling food products.

A robotic gripper was used in [68] to assess the firmness of mangos, accelerometers embedded in the gripper fingers were used to test the ripeness of mangos. Results were compared to the ripeness index of mangos, and the robotic gripper proved effectiveness to do this task.

A hybrid tomato picking end-effector was also developed using a combined impactive and astrictive design [69]. This was capable of removing tomatoes with short peduncles, however the gripper had difficulties when there were leaves and stems in the way. In [70], a similar gripper was developed which consists of four fingers padded with foam to reduce damaging the fruit. Once the fingers close, it brings the tomato to the center where there is a suction cup, which assists the grip. It was capable of picking tomatoes at an average rate of 74.6 s per fruit with a 95.35% attachment success.

A similar hybrid cherry harvesting robot is designed in [71]. It utilized a 4 DOF gripper, a 3D vision sensor, and a two fingered grasp with a vacuum tube in the center. The purpose of utilizing a hybrid design is that cherries are harvested with the penuncle attached. The end-effector is positioned

around the cherry and the base is vacuumed to the center. The two fingers then grasp the penuncle and both the cherry and the penuncle detach simultaneously.

Deformable objects have also been studied where the robotic gripper evaluates the robot trajectories when colliding with objects [72]. It weighs the object deformation and compares it to the travel costs. The deformation models can be used to perform FEA, and a similar lower computationally intensive model is presented using Gaussian process regression. The planning method is then tested using a wheeled robot and a robot arm.

As different approaches were explored in robotic grippers for fragile objects, it is discussed that the force feedback is a key element as well as flexible designs such as soft grippers not to harm the objects.

2.3. Grippers for Medical Applications

In use of robotic grippers in surgery, one of the main issues is the lack of force feedback and damaging the biological tissues. Soft bodied grippers are very suitable in the medical field based on their self-limiting and intrinsic safety features, which provides safe interaction with biological tissues.

In [73], a soft gripper design is developed for delicate and safe interaction in minimally invasive surgery. As reported, this design could enforce maximum force of 1 N. They used elastomeric material and discussed that their design is easily scalable.

A robotic gripper with viscoelastic force fields control was developed in [74]. A two finger with precision grip control design was designed and analyzed in this work and they showed that thumb and finger force are highly correlated. Precision grip control provides adaptation capabilities which helps to grip objects based on their mechanical properties. Although this design gave insight on the ability to adapt to unknown precision grip dynamics, the design is limited to linear 1-D gripping and no result was reported for performance of gripping of nonrigid objects.

Robot-assisted surgery is another application of robotic grippers. In robotic surgery safety and autonomous control is essential because of injurious result of uncertainties and disturbances such as time delay in tele-surgery.

In [75] a star shaped micro-gripper was designed and developed with the application of tissue excision. By performing experiments within a live animal they showed that these developed micro-grippers are capable of excising tissue samples from real organs and hard to reach places inside a body. These grippers are fabricated using conventional multilayer microfabrication and actuated with magnetic field.

A design of a soft robotic gripper for manipulation in minimally invasive surgery was presented in [73]. In this design, the authors used only soft materials and an under actuated system to adapt the finger shape and apply a specific amount of force. This gripper was considered a surgical tool and it was made of soft material for safe interactions. In addition, such soft gripper designs are safe for surgery due to limited soft gripper force.

Suction techniques can also be used in medical applications [76]. This gripper was designed to grasp the bowel, which is a large, delicate, flexible, and slippery part of the body. This suction method was found to be capable of firmly gripping bowel sections: however, it is not known whether a manual pump or vacuum pump would be more optimal.

A miniature robotic gripper was designed in [77] for retraction tasks in minimally invasive surgery. They showed that the gripper can generate a maximum gripping force of 5.3 N. The design of this gripper allows performing within a narrow access port. They integrated brushless motors to enable additional degrees of freedom by magnetic anchoring and improving dexterity of overall platform.

In [78] a 4 degrees of freedom surgical forceps integrated with force sensor is developed for minimally invasive surgery. The pulling and grasping forces can be measured for haptic feedback control. Their design was experimentally validated for the open-source surgical robot platform Raven-II.

In [79] a soft pneumatic chamber gripper device was designed for tissue manipulation. This gripper can pick up objects up to 2 mm with a gripping force of three times smaller than the grip force of forceps grippers, which prevents tissue damage during surgical manipulation.

In [80] a magnetically guided and actuated milli-gripper was developed for medical applications. It was shown than using permanent magnets they were able to control the grippers in both tethered and untethered configurations. This design is an integrated capsule of an electromagnetic coil with a soft magnetic cobalt iron core and a magnet.

Recent advancement in medical grippers made them more reliable to be used in applications such as robotic surgery, minimally invasive surgery and medical grippers. The recent improvements are designing novel mechanisms, developing and employing high tech actuators. Although many works have addressed force control problem in medical application, the challenge of force control still persist.

2.4. Micro and Nano Grippers

Different designs and technologies have been developed for micro and nano gripping by employing advancements in micro and nano electromechanical devices.

MEMS were developed to grip micro-sized objects. These have been used in the semi-conductor industry where parts are assembled on a wafer substrate [81]. They are also used for manipulating bio- and nano-materials [82].

A hybrid MEMS microgripper was designed in [83]. It utilized an electrostatic comb drive microgripper with an integrated vacuum tool. The tip of the arm was able to deflect 25 μm and it was able to pick up objects ranging from 100 μm to 200 μm.

A thermal bimetallic actuation gripper was also developed in [84]. The design of this gripper was unique as it combined nanofabrication techniques with conventional microlithography methods to create a gripper that was 100 nm and less in size.

A microgripper is also designed using an electrostatic linear motor [85]. This motor consists of a scratch drive actuator, which was able to move in micropositions with high accuracy. It was also modelled using FEA and the fabrication process is covered. The electrostatic actuation is successfully obtained with high precision and low electrical consumption, which is capable of being integrated with integrated circuits (ICs).

Another technique is utilized to microfabricate grippers to sub-micrometer dimensions [86]. The process utilized a thin SiO_2 layer of a silicon-on-insulator wafer to create the gripping tips. It was able to grip 100 nm gold spheres.

In [87], a novel electrostatic MEMS gripper with integrated capacitive contact sensor was developed. It is able to grip objects as low as 12 μm at a driving voltage of 55 V. While this is occurring, the transverse comb differential capacitances act as a contact sensor to prevent damage. It also utilizes vibrations to release the parts.

In [88], a polymer made from SU-8 was used to build microgrippers. It included tensile force sensors and were actuated by using an electro-thermal effect. Large displacements of the gripper were possible up to a maximum of 100 μm for up to 50 cycles. Variable forces are also achieved from a few μN to 1 mN.

In [89], a two fingered microhand is developed for high speed gripping. This microhand was able to pick-and-place objects 40–60 μm in size within 1 s.

A combined vacuum gripper, two-camera vision system and 4 DOF robotic gripper was designed in [90]. This design was compared to a standard vacuum gripper (standard dispensing needle) and a multi-lumen nozzle. In these tests, it was found that the grasping of the microcomponents was always successful. Releasing the microcomponents however was poor in some conditions. Further modeling for this gripper will be developed to determine the behavior during the release stage.

In [91], a miniature polycrystalline silicon gripper was built. This ingressive gripper was designed using a snap-and-lock configuration where a male and female portion would click. The male portion is shaped similar to an arrowhead while the female portion is shaped with two inner hooks. When they

snap together, a tensile load is applied to move both sections. The assembly is tested using a scanning confocal Raman imaging which confirms that the local peak tensile stress is approximately 50% of the lower bound material strength. This stress mapping is also covered in [92].

In [93], an electrostatic gripper is developed. The mechanism was able to grasp standard microcomponents and delicate mini and micro parts. It also added new theoretical and FEM models, which were justified in the design of the gripper. It was able to grasp and release different material shapes with various dimensions between 0.3 mm and 1 mm. It was found that the reliability of the grasp is close to 100%.

An integrated circuit transfer robot was developed using a Gecko-inspired microfiber array in [94]. The Gecko-inspired method is investigated as vacuum grippers can damage wafers if the pressure deforms the chip excessively. This gripper utilizes the friction force caused by the mass of the wafer on the end-effector. The four bumps of microfiber material is added in a square configuration which was found to have the least amount of deformation. This gripper was able to operate at an acceleration of 4.155 m/s^2 which is much faster than using rubber or stainless steel bumps.

Contigutive grippers have also been designed to use a liquid water layer between the manipulator and the object [95]. The manipulator freezes the water to produce ice, which adheres to both surfaces. This was also designed for submerged applications [96–98].

As discussed, microgrippers have been of an interest to researchers in recent years because of their vital application in micro fabrication, micro assembly and micro manipulation. Recent advancements in microcomponents and more specifically MEMS as discussed in the literature makes this technology cheaper, more reliable and easier to implement.

2.5. Soft Fabric Grippers

An ongoing challenge in gripper design is in picking up fabrics. In order to do this, penetrating grippers have been designed which are also called ingressive grippers. They are used in the textiles industry to hold fabrics since suction cups cannot vacuum to the material due to the porosity. Textiles however can be penetrated while being moved with minimal underlying damage to the woven structure.

One of the earliest designs used a spiked wheel, which separates different sheets of textiles from each other [99]. This was improved using a different style of gripper in [100]. These types of grippers are also used to remove backing sheets from fibers [101]. Fortunately, most industrial ingressive grippers can adjust these variables to prevent damage to the material [102].

Pre-peg carbon fiber sheets have also been grasped in [103]. Picking up continuous carbon fiber sheets has also been investigated in [104].

A suction cup gripper was additionally developed for fabrics [105]. This is difficult because the fabric is not allowed to be deformed during the automatic or manual cutting process. The end-effector consisted of a flat surface with 0.5 cm holes for suction and outer 0.1 cm holes for positive pressure. This gripper did not have tactile feedback sensors, which could improve part handling and manipulation. The model for this specific gripper is covered in [106].

There have been improvements made to suction cup grippers, which are now able to pick up C and L-shaped profiles. It is able to do this by unrolling the fabric in different stages. In addition, textiles can be shaped to different geometry due to modifications in the end-effector shape [107]. In this particular case, the carbon fiber textile was picked up around a cylinder and it was draped around contours to cure [108]. A highly flexible and moldable suction cup was also designed to pick up leather plies [109]. This flexible cup was advantageous since it did not leave imprints on the leather compared to other commercial vacuum cups.

Other methods of picking up fabrics have also been used such as direct contact. They are called contigutive grippers, which work by using chemical adhesion such as glue and sticky adhesives. This can also be done thermally as well by melting a surface to adhere to the object. For the textile industry, a permatack adhesive is used with a contact pad [110]. The disadvantage to this method is that microfibers will adhere to the surface over time, reducing the ability to stick to textiles.

Thermal adhesion is also used in carbon fiber sheets [111]. This works by thermally melting the resin in the carbon fiber sheet to achieve a solid bond. Improvements since then have lowered bonding time to less than one second [112]. This is compared to chemical curing which can take over ten seconds.

In summary, suction grippers have been shown to perform well in grasping soft fabric objects. However, different methods are being developed to employ this technique such as adhesion.

3. Design of Robotic Grippers

In this section, we study the design peculiarities of grippers with different applications and given tasks' purposes. The grippers' characteristics such as dimension, weight, rigidity, and simplicity are considered in this section for different designs of robotics grippers. The main factors that need to be considered in the study of design peculiarities are the characteristics of the gripper, the characteristics of the objects, gripper technology, flexibility of the gripper, and cost of the designs. In addition, other factors including grasping force, grasp configuration and transmission characteristics of the device are studied.

3.1. Piezoelectric Grippers

As piezoelectric materials are decreased in price, research has focused more on utilizing piezoelectric grippers for active manipulation [113]. Some benefits of piezoelectric grippers are the simplicity, the ease of use, and the low power consumption compared to mechanically actuated grippers.

Some of the earliest grippers were made out of piezoelectric polymeric polyvinylidene fluoride (PVDF) [114]. This was improved in [115] where the design was arranged in a rhombus configuration. This amplifies the force applied to the object and it allows one of the piezoelectric strips to act as a force sensor. Regardless of this, the prototype was only able to apply 1.0 N at the tip. In [116], a piezoelectric tweezer was designed for use in robot assisted surgery that is MRI compatible. It is amplified using a nested strain mechanism, which increases the displacement of the tips to useable levels. The tweezer tip position and force was shown to be within a 12% average error between the self-sensed and true values.

In [117], a voltage of ($\pm$60 V) was applied on a piezoelectric actuator. This causes unstable behavior so a PID controller was designed to supply the voltage to achieve stability. It was found that using a PID voltage controller helps with precise micro manipulations. This work is continued in [118], where a PD controller is used instead. In [119], a PI-based sliding mode controller is developed for a piezoelectric actuator. The proposed controller was able to provide better tracking, faster responses, less chatter and higher positioning precision.

Piezoelectric bimorphs have also been analyzed theoretically and experimentally in [120]. The study focused on the transient response and the frequency response with various input voltages and signals along the length of the actuator. This gripper could manipulate objects down to 50 μm with the only the actuator itself.

As discussed, although different designs were proposed with different control approaches, the main challenge that still persists is the position control and stability of piezoelectric grippers.

3.2. Multi-Fingered Grippers

Many approaches have been developed to increase the flexibility of the parallel gripper. By using multiple fingers, the available motions for the robot are increased. One of the earliest three-fingered hands was developed in [121]. They have also been integrated with feedback sensors in [122]. This design utilized 87 touch sensors that were distributed over the surface of the end-effector. Some examples multi-fingered grippers include the Robotiq 3-Fingered Hand, the IH2 Azzura Hand and the Shadowrobot Hand [123–125].

Recent end-effectors studied a wide range of possibilities to improve typical parallel grippers. In [126], a fiberless, flexible microactuator (FMA) was developed. The FMA gripper consists of hollow cylindrical chambers along the length of the gripping finger. When the chambers are subjected to a positive or negative pressure, the chamber expands and contracts which bends or extends the fingers. The model that was built was capable of holding fish eggs without breaking.

In [127], a novel design and actuation principle was implemented to explore grasping capabilities. The design consists of a three fingers robotic gripper, the fingers were made of soft materials to increase adaptability. An under-actuated mechanism has been used using a wire loop actuation system. Grasping and holding capabilities have been tested on different sizes and shapes. Due to the adaptability of this design, it is considered good application for morphological computation principles in bio-inspired robots designs.

A Chinese massage end-effector was designed in [128]. This was able to thumb knead, press, roll, vibrate, and pinch. Visual tracking was used as the patent wears a massage vest with highlighted pressure points. When the end-effector is working, the patent will set a pain threshold, which tells the robot to not to exceed the limit by using force-position control.

In [129], a DARPA ARM robot was enhanced with a framework to allow the end effector to control position and force with either visual of tactile feedback. The three fingered grasp, was capable of grasping a free tool such as a drill while accounting for the uncertainty in the hand-tool interface.

Multi-fingered graspers have also been used to fry pancakes [130]. Two robots called TUM James and TUM Rosie were sent instructions over the internet. They then generate robot action plans, which involve operations such as opening drawers, retrieving pancake mix and transferring items. These tasks are done perceptually using a semantic 3D object map of the environment. They draw from a database of 3D models, which locates and identifies the objects quickly. Multi-fingered grippers have many applications such as in grapping oddly shaped and unknown objects. Several actuation systems are presented such as flexible microactuator, wire loop actuation system; however, it is suggested that soft materials may provide more adaptability to these grippers.

3.3. Enveloping and under Actuated Grippers

Grasping oddly shaped objects has been an ongoing challenge in end effector design. Some grippers have focused on enveloping and underactuated mechanisms. This was the case in [131] where a pair of underactuated hands was built. This type of gripper is valuable due to the adaptability of the gripper to mold around the object it is holding. A similar paper in [132] also developed underactuated grippers for a similar application.

An enveloping gripper has also been modeled after the biting movement of a snake mouth [133]. The snake mouth design is capable of expanding and opening up to an angle of $150°$. The advantages of this design allowed continuous clamping of smooth edged objects. It was also able to grasp items bigger than the end-effector itself.

In [134], a bio-inspired method of contacting objects is modeled after a chameleon shooting its tongue. A permanent magnet end-effector is attached to a string, which is loaded into a catapult. During testing, the catapult end-effector was successful 92% of the time when capturing a falling object 0.7 m away. This end-effector has advantages as it can reach objects, which are not in a clear line of sight from the base. By firing the end-effector above or around the obstacle while constraining total length, the magnet can drop behind or loop round the obstacle to attach to the target.

Similar to the underactuated hands, a set of parallel, fingertip and enveloping grasps was designed in [135]. It is controlled by a single actuator, which pulls a tension cable along the fingers. This design is capable of grasping objects in multiple configurations. The links will flex based on whether the object contacts the distal or proximal links.

In [136], a pneumatic actuator was developed. It consists of an outer skin which is pumped full of air. Since one side of the skin is thicker than the other, the weaker side expands and bends the thicker side inwards. This pneumatic actuator, when subjected to moderate pressures (<1.25 atms) could bend

upwards of 180°. Other methods to grasp oddly shaped objects, which are used for deforming surfaces are malleable grippers. One of the first deforming elastic layer grippers was built in [137]. This is further investigated in [138] where a pair 3-DOF fingers is modeled with soft tips.

Enveloping grippers are mainly biologically inspired grippers and recent advancements showed that by developing such novel mechanisms we will be able to implement grippers more autonomous with less control effort compared to multi-fingered grippers.

3.4. Malleable Grippers

Malleable grippers are made from materials that change viscosity. They are typically made from using a flexible outer skin with materials inside being either: electrorheological (ER) fluid, magnetorheological (MR) fluid, or pellets. The outer surface is pushed up against the object and it molds to the geometry. The inside is then hardened to provide an impactive force to hold the object. When the object needs to be released, the inside will return to a more fluid like state to allow for free movement.

These soft grippers are mainly used in shape-adaptable grippers, which are not only soft, but they are strong and versatile as well. Several soft grippers' designs have been addressed in the literature with variety of technologies. Soft grippers can be adapted to different shapes where rigid grippers are limited.

One of the earliest malleable grippers used ER fluid [139]. The ER fluid changes its viscosity in response to an electric field. When an electric field is present, the ER fluid behaves like a Bingham plastic. When the field is removed, it behaves like a liquid. This gripper was tested and was capable of handling fragile objects such as eggs. The disadvantages are that using ER fluid requires a lot of energy and the gripper is susceptible to electric arcing.

A much safer malleable gripper was designed using granular material [140]. To change the viscosity of the material, a vacuum is applied and the gripper remains rigid. In [141], the testing and use of the skin gripper is performed. The reliability is increased to 85% and the error tolerance is increased to 25%. An added feature was that this vacuum could be reversed, and capability of shooting objects out of the mold is demonstrated. A commercialized version of this design is now called the Versaball [142].

MR fluid grippers have also been designed to pick up fruits in [143]. The MR fluid changes its viscosity in the presence of a magnetic field. The MR fluid is placed in two pouches near the end of the arms, which contacts the fruit. When the magnetic field is activated, the MR fluid changes in viscosity and the pouches mold around the fruit. With this design, the fruit can be lifted with low force without damage. An advantage to this design is that the amount of pressure applied on the outside of the fruit can vary based upon the magnetic field. This design was satisfactory, however the MR fluid is very expensive.

In summary, malleable grippers are highly flexible in grasping objects with different shapes; however, the dexterity of these grippers is still a challenge of design.

Table 1 compares the characteristics and performance of grippers with different designs that were discussed in this section.

As discussed in literature, we can compare the ability of the gripers to grasp different types of objects based on the categories of Impactive, Ingressive, Astrictive and Contigutive. As presented in Table 2, impactive grippers have been used in applications of picking up different types of objects from solid flat to oddly shaped and fragile. Astrictive grippers, similar to Impactive grippers, have been used for different types of objects more commonly for fragile and irregular objects. No results have been reported, to the best of our knowledge, regarding employing Astrictive grippers for irregular shaped objects. Ingressive grippers have been used in grasping flexible sheets and in some in MEMS assemblies. Contigutive grippers have been used in grasping solid flat objects, rigid and flexible sheets, and MEMS assemblies.

Table 1. Comparison of the ability of grippers to pick up different types of objects.

Design	Advantages	Drawbacks	Significant Application	Example of Used Material and Actuators
Piezo-electric Grippers [113–120]	Simplicity, Ease of use, Gripping small objects (down to 50 μm)	Low gripping accuracy	Micro and nano gripping	polymeric polyvinylidene fluoride (PVDF)
Multi-Fingered Grippers [121–129]	Flexible gripping for different object shapes, Gripping with force feedback	Control complexity	Grapping all shaped objects with force control	Soft materials, flexible micro actuators (FMA), wire loop actuation systems
Enveloping Grippers [130–137]	Adaptability to mold around the object	Low force control capability	Grapping oddly shaped and unknown objects	Pneumatic actuators, cable-driven under-actuated mechanisms
Malleable Grippers [138–142]	Adaptable to different shapes, reliable gripping	Low gripping dexterity	Grasping unknown and specially deforming objects	MR fluid, ER fluid, granular material

Table 2. Comparison of the ability of grippers to pick up different types of objects.

Types of Objects	Type of Grippers			
	Impactive	Ingressive	Astrictive	Contigutive
Solid Flat Objects	■	□	■	▨
Solid Curved Objects	■	□	■	□
Solid Irregular Shapes	■	□	□	□
Flexible Sheets	▨	■	▨	▨
Rigid Sheets	▨	□	■	▨
Fragile Objects	■	□	■	□
MEMS Assemblies	■	▨	▨	▨
Commonly Used	■			
Sometimes Used	▨			
Not Used	□			

4. Future Directions and Discussion

Recent developments in terms of actuators and sensors technologies as well as material science have made the grippers more reliable, faster, safer, and more robust. These advances have resulted in introducing new applications such as new locomotion for mobile climbing robots (e.g., JPL's Rock Climbing Robot), hopping robots, space satellites, underwater robots being used in exploration and pipeline repair, high speed manufacturing, and robotic surgery. These development have opened doors for new research on employing new materials and designs as well as incorporating new technologies some of which are summarized as follows:

- *Adaptive and self-adaptive grippers*: these grippers have a great potential to provide flexibility in grasping objects with different shapes in industrial systems such as Festo PowerGripper, Finger Adaptive Robotiq, SARAH in international space station.
- *Modular grippers*: they use standard components such as finger type grippers, vacuum cups, and locating pins to construct complex grippers. These grippers have been used in applications where high performance and flexibility are required such as assembly in space. They can accommodate change in physical, geometrical, chemical, mechanical properties of the objects significantly by employing different standard gripping components.
- *Reconfigurable grippers*: these grippers have the ability to change into different specified configurations and pick different objects. These grippers have applications in automotive industry and space robotics.
- *Smart material based grippers*: These grippers use smart materials for grasping objects with different shapes such as grasping by particle jamming (e.g., granule-filled bag), electrorheological (ER) fluids, Giant ER Fluid, ER fluid with electroadhesion, pneumatic actuators, and shape memory foams. Although these grippers have been used in industry for a long time, due to their simple

actuation mechanism and low weight, employing this technology for robotic grasping is still challenging because they have lower gripping forces compared to conventional grippers, they are mostly slow actuators, and there is a control problem in precision actuation of these materials. There are ongoing research to increase the gripping force and precision accuracy. Some of these include developing controllers such as repulsive force control, sliding mode control, and ANFIS controllers. It is worth mentioning that electrostatic attraction provides more dexterity since they use film like layers.

- *Novel mechanism design grippers*: These designs provide inherently flexibility with a minimum required supervision by incorporating smart mechanisms such as bionic handling assistant into the grippers. The main objective of these designs is to have high performance with less control effort.
- *Soft grippers:* Different designs of soft grippers have been developed such as electroadhesion grippers, single and multi-segment grippers, artificial muscle soft robotic grippers have been developed. These grippers have been able to mimic human's hand. Flexible, microscopic hand-like gripper can help surgeons to remotely guide surgical procedures or perform biopsies. Most of these designs utilize soft robotics and artificial skins for simpler control and passive adaptation. Soft materials enable gripping automation beyond the capacities of current technology. One of the advantages of soft robotic grippers is partially taking care of the control part by the physical properties of soft grippers unlike rigid grippers. However, introducing softness into the design of grippers requires new set of design and control principles compared to hard grippers.

There are ongoing attempts to improve grippers in two-fold: performance and flexibility. Performance indicates accuracy, speed, readability, gripping strength, robustness, and flexibility denotes variety of objects that can be grasped. Most of the challenge in this aspect is whether objects are known/unknown. When one is dealing with unknown objects, the focus is to employ flexible grippers, while in grasping known objects, the focus is on the increasing the performance. Achieving flexibility and performance simultaneously still remains challenging because increasing performance usually results in decreasing flexibility.

To increase flexibility, new develops are made: grippers with human-like fingers are one of the examples, which use control systems with feedback from the interaction between the gripper and the environment to mimic humans grasping. However mimicking human hand requires significant amount of computation and it complex in terms of control. Although development of robotic grippers to mimic human hands is still a challenge regarding sensing and actuation, the use of artificial hands in industrial and social robots will be more common in the coming years. An alternative approach is to use different designs. Some of these designs include malleable grippers, MIT gripper, which is based on jamming of granular materials, and RobotinoXT.

Performance improvement is application dependent. Increasing performance can be achieved through design of robust controllers, implementation of sensors and powerful actuators as well as physical design. In terms of sensing, researchers will continue to mimic the human gripping capabilities. Vision sensing is anticipated to evolve to increase the learning capabilities of robotic grippers with incomplete knowledge of the surrounding environment. In addition, incorporating visual feedback in the design of gripers enables them to effectively communicate with unknown environments making them robust. For actuation, artificial muscles implemented in robotic hands will have the force and stroke of a natural muscle and is capable of mimicking the mobility of human hands. This will make gripping not only easier but smarter and safer. By introducing the advancements in materials as well as technologies in sensing and actuation, it is expected that the performance and flexibility of robot grippers to be increased.

Grippers with mechanical simplicity and robustness (e.g., dual arm gripper) *versus* grippers with flexibility and adaptability (e.g., artificial hands) are two extreme objectives in robotic gripping. Simple mechanical grippers require simple control architecture and are widely used because of low price and simplicity of implementation. Besides, their applications become limited when it comes to grasping objects with force control, grasping objects with odd shapes, or specific grasping conditions. In such

applications, use of graspers with more adaptability like multi-fingered grippers becomes beneficial with the cost of control architecture complexity.

Recent advancements and applications indicate that soft grippers are one of the frontiers in the future in robot grippers for many applications. The emerging applications are mostly in industry and medical. Employing these advancements in industry will improve the performance significantly as reported; however the cost of changing the current technology and update them with the recent advancements is high. In medical applications especially in robotic surgery research is still going to provide surgeries with safe, robust and most importantly reliable mechanism.

5. Conclusions

End-effectors or grippers are very versatile components that have been used in applications such as automotive industries, manufacturing lines, vegetable pickers, MEMS grasping, surgical applications and prosthetic arms. Most of these grippers utilize an impactive gripping strategy. Since then, impactive grippers have branched into many segments including grippers that have added sensors, added cameras, piezoelectric grippers, soft grippers, MEMS, multi-fingered grippers, under actuated grippers, elastic and malleable grippers, and multi-arm grippers. Overall, grippers that have more sensor feedback tend to track and grasp objects more frequently. Piezoelectric and MEMS grippers actuate with high precision, however they do not have much grip strength. Malleable grippers can pick up many oddly shaped objects, however they may deteriorate after many cycles of actuation. Dual and multi-arm grippers are trending to replace humans in many tasks such as assembly lines and healthcare.

We discussed that how the performance of the grippers can be improved in future in different applications through robust controllers, instrumentations as well as structure design. We analyzed the implementation of human gripping capabilities on robotic grippers by employing vision sensing, incorporating visual feedback, artificial muscles, and smart and soft materials. We explored detailed advancements of performance and flexibility of robotic grippers through different designs and applications. The challenges in implementation different designs are discussed. We showed that soft, modular and adaptive grippers by utilizing different gripping components and materials can increase both performance and flexibility; however, as we argued the challenges in these improvements, introducing softness into the robotic gripper design requires set of design and control principles compared to hard grippers, and smart materials are not capable of providing strong gripping force.

This paper covered the earliest types of robotic grippers, the improvements made to them and recent advancements along with applications. We hope that by comparing and categorizing these robotic grippers under certain applications, new innovative methods can be discovered to solve real world problems present newer challenges that can be investigated to further push the boundaries in gripping mechanisms.

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