Types and Applications of Soft Robot Arms and End-Effectors: A Review

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***Abstract*— Soft actuators have evolved as an inventive solution as a result of the ongoing advancements in technology and the growing demands for a safer and more efficient interaction between robots and human and natural settings. These actuators are perfect for applications that call for careful handling of fragile objects and adaptation to irregular surfaces and forms since they can move more smoothly and flexibly than typical stiff actuators. The most recent advancements in the field of soft actuators are reviewed in this study. Shape memory alloys, magnetic actuators, electroactive polymers, and pneumatic muscle actuators (PMA) are only a few examples of the various types of soft actuators. Along with highlighting the integrated structure of these actuators, we also illustrate PMA configurations such as the contraction, extensor, and bending models. Additionally, the research focuses on soft-arm robotics, or the design of robots with gripper-equipped arms. Each robot's design is explained in detail, including its purpose and the materials it was made of, as well as its size, weight, and working mechanism. The goal of the study is to provide better knowledge of the development of these technologies and their expanding use in industrial and research settings, with an emphasis on how accurate and flexible they are when interacting with their surroundings.**

Keywords—soft robot, soft actuator, PMA, soft arm, soft gripper

I. INTRODUCTION

Soft robots have demonstrated their ability to revolutionize our everyday existence[1]. Research in soft robotics has become increasingly promising, providing a new framework for creating robotic systems that are unmatched in their flexibility, adaptability, and safety[2]. Biological systems that are composed of soft materials are a common source of inspiration for soft robots. Soft robots provide a number of benefits over traditional robots, including simple gripping systems, safe human-machine contact, and adaptation to wearable technology[3][4]. Materials that are naturally malleable, flexible, and stretchable are used to build robots. Because of the reversible and changing qualities of these materials, robots can experience significant deformations without losing their structural integrity. Soft robots can adapt to a wide range of jobs and securely interact with their surroundings thanks to their great flexibility, especially in dynamic and uncertain situations[2][5][6]. Soft-material robots are safer in the event of any mishap, such as control malfunctions, human error, or unexpected robot arm malfunctions. because of its many advantages, one of them is its lightweight[7]. Created and produced in a very creative manner as opposed to being artificially put together using parallel or serial configurations of building parts, as rigid-body robots were[8]. Because soft robots may safely interact with their environment on land and underwater without endangering living things, they enable us to investigate our world[1].

Research on soft actuators has drawn more interest from the broader robotics community as the field of soft robotics grows. Soft actuators provide several advantages over rigid robots, including higher power density, increased compliance, high efficacy, acceptable efficiency, safer interaction, low cost, and simple structures[9]. Therefore, in addition to their mechanical durability, tiny soft actuators that exhibit significant deformations and respond to a variety of stimuli are essential[6]. As a result, many researchers have made creating soft actuators that meet the mechanical and control requirements of soft robots a top priority. Soft actuators, in contrast to traditional actuators, generate flexible motion by combining minute alterations at the molecular level with a macroscopic deformation of the actuator material. This may show up as a change in volume or deflection. There are various subcategories of soft actuators, including light-driven, pH-driven, electro-driven, thermo-driven, and magneto-driven. Additionally, various materials such as hydrogels, elastomers, polymers, and pneumatics[10]. Soft robots are influenced by the natural world. Natural creatures may carry out tasks in a dynamic way and use the suppleness of their bodies to interact with the outside world[11]. An exemplary case of bioinspired robotics is the octopus. According to accepted hypotheses, the octopus's unique body morphology—particularly the structure and composition of its limbs—is the cause of its improved behavior and capacity for environmental interaction. (arms). The arms' motor capabilities, in terms of both dexterity and wide range stiffness variability, significantly surpass those of any current robot. Robotics has benefited from the inspiration of the octopus arm[12]. These kinds of robotic systems are frequently constructed using soft pneumatic actuators, like the pneumatic artificial muscle (PAM), which are modeled after human muscle. The PAM is well-known for having many benefits, including a high force to weight ratio, several degrees of freedom (DoF), changeable

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stiffness, low cost, and safety for human-robot cooperation[13][14].

II. SOFT ACTUATOR

A. Shape Memory Alloy (SMA)

SMA is a particular alloy that, as shown in Fig.1 when heated, may regain its original shape after being deformed[15]. Because of its low driving voltage, large deformation, high power to weight ratio, and small weight, SMA is a good choice for actuating soft robots. Through the use of asymmetric or antagonistic SMA actuator designs, numerous soft robots powered through SMA have been created for use as locomotors and manipulators[16] SMAs are hence appropriate for technical and engineering applications across a range of domains. Certain robots, like a soft robot arm, a soft hand, and a basic gripper, can function as manipulators and do gripping tasks[17].

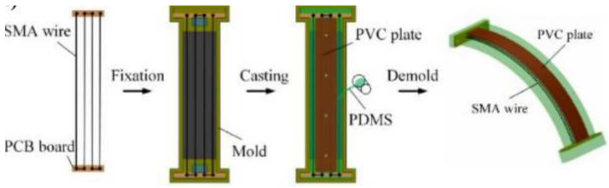

Fig.1. structure of SMA [17].

B. Magnetic actuators

Soft robots can be driven, controlled, and eased using magnetic actuators, as shown in Fig.2. They offer low cost, quick reaction, easy control, minimal input power, and non-contact actuation that may be used in a variety of media, including liquid, vacuum, and air. Note that in the presence of gradient and uniform magnetic fields, respectively, magnetic force or torque drives magnetically activated soft robots. The three types of magnetically actuated soft robots include grippers, non-bio-inspired robots, and bio-inspired robots[18].

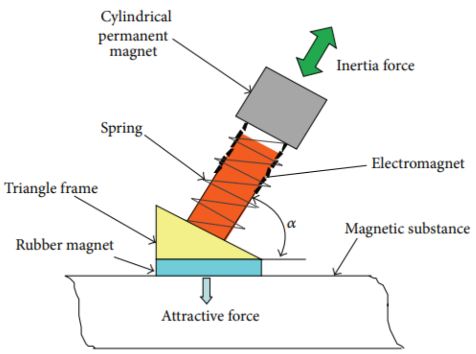

Fig.2. Structure of the magnetic actuator[19]

C. electroactive polymers (EAPS)

One significant SAM that may alter its size or shape in reaction to an external electric field is the electroactive polymer (EAP), as depicted in Fig. 3. EAPs can be classified as either ionic or electronic based on their actuation mechanisms. Examples of such actuation mechanisms include conductive polymers, ferroelectric polymers, piezoelectric polymers, electro strictive graft elastomers, dielectric polymer gels (DPGs), ferroelectric polymers, and ferroelectric polymers. The DPG exhibits exceptional electromechanical features, including low driving voltage and strong actuation strain, making it a prospective electronic EAP [20].

Fig.3. Composite ferroelectric EAP in the states of activation (left) and passivity (right) [21].

D. Pneumatic actuators

A useful and adaptable pneumatic device is a pneumatic actuator. It can function antagonistically, much like human muscles, and it can only provide traction when compressed air is used as power. A soft robot can be operated by pneumatic means, which use air pressure to create a driving force. It has the qualities of excellent flexibility, good safety, and rapid reaction time [15].

III. PNEUMATIC MUSCLE ACTUATORS (PMA)

Pneumatic artificial muscles (PAMs) are a commonly studied class of soft actuators that have been thoroughly analyzed. Numerous designs of pneumatic actuators, including those with pleated, fiber-reinforced, and braided sleeves, have been developed since the first McKibben actuator. Because PAM can be made from cheap materials that are readily available for purchase and uses readily available compressed air, it is more secure than other devices that use heat, electricity, or chemically active materials. They can realize multiple motion types, including contraction, extension, bending, and twist[9]. Notwithstanding these benefits, PAMs have a number of drawbacks that can restrict their use. In most of these PAMs, the friction between the wires of the braided sleeve results in hysteretic activity. Due to the compressibility of the air inside, the viscoelastic properties of the inner tubes, and the geometrically complex behaviors of the PAM's outer covering, they also exhibit nonlinear behavior. The primary issue with muscles, aside from these disadvantages, is displacement limits. Other forms of PAM have been developed in addition to the McKibben muscle. These include the rubbertuator from Bridgestone, the air muscle from Shadow Robot Company, the fluidic muscle from Festo (dating back to the early 1930s), PPAM (pleated pneumatic artificial muscles) from Vrije University of Brussels, netted muscles like Yarlott and Kukolj, PAM reinforced by straight glass fiber, and embedded muscles like Morin, Bladwin, Paynter Hyperboloid Muscle, Kleinwachter, and Sleeved Bladder Muscle [7][22]. Some of the pneumatic muscle types are depicted in Fig. 4.

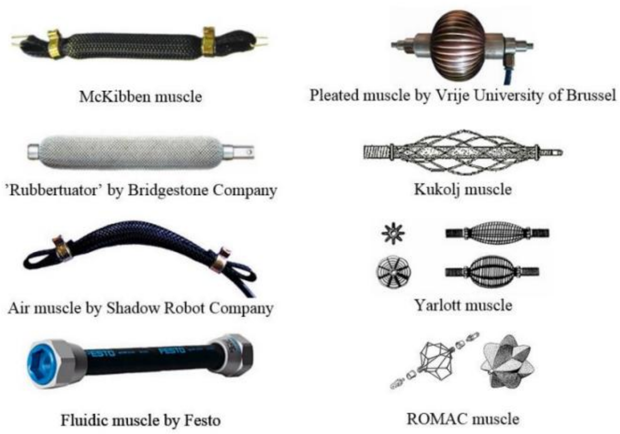

Fig. 4. Various Pneumatic Muscle Types [7][22].

A. Contraction of the Pneumatic Muscle Actuator

The muscle responsible for contraction consists of the inner tube and the braided sleeve, which have the same diameter and length. The mechanism of functioning and the contraction muscle's structure are shown in Fig. 5. At-rest actuator dimensions: length and diameter are denoted by L_0 and D_0, the angle created by the central axis and the single sleeve thread, correspondingly is represented by θ_0. As more pressure is applied, this angle gets bigger to θ_d, changing the length and diameter of the muscle to L_c and D_c. The pressure applied to the contraction muscle is represented by P_c. Also there are two aluminum caps, one of which is closed and the other of which has a port through which air can enter the muscle. [3][23][24].

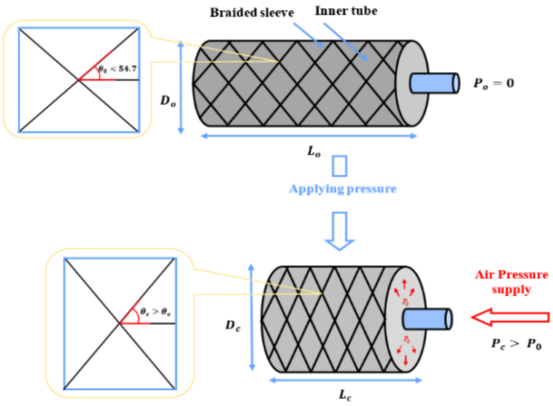

Fig.5.The structure and mechanism of the contracting muscle[23].

via which pressurized air is delivered. The suggested contracting muscle is seen at various supplied pressures in Fig. 6 [25]. In situations where the braided angle "θ" is less than 54.7, PMA contracts. Although it varies from muscle to muscle, the percentage of contraction seldom goes above 35% [14].

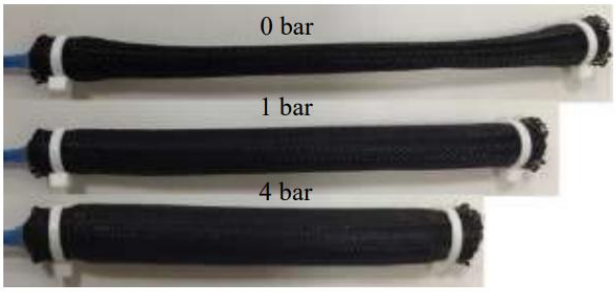

Fig.6. Muscle contraction under varying pressures [25].

B. Extensor of the Pneumatic Muscle Actuator

A longer braided sleeve is squeezed axially to match the length of the bladder, make up the extensor muscle. Consequently, there is a bigger angle than 54.7 degrees between the central axis and the sleeve thread. Similar to the contracting muscle, the muscle's two ends are sealed with a 3D-printed cap. As seen in Fig. 7, when pressure is utilized to a muscle, the angle lowers, It results in the length increasing and the diameter decreasing, producing the driving force.

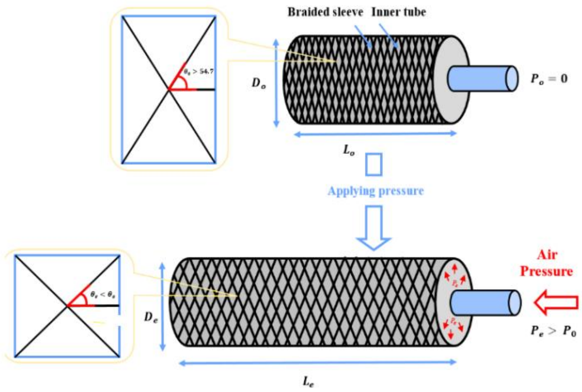

Fig.7. Extensor muscle anatomy and principle of action [23].

In this case, the actuator's resting length and diameter are denoted by L_0 and D_0, correspondingly, and the center axis and the single sleeve thread form an angle of θ_0 . This angle decreases as the applied pressure increases to θ_e , changing the muscle's length and diameter to L_e and D_e. The pressure applied to the contraction muscle is represented by P_e [23]. Fig.8. It is evident that the length of the extensor muscles increases in response to the applied pressure. Each muscle has a different amount of extension, although it is always at least 50% [26].

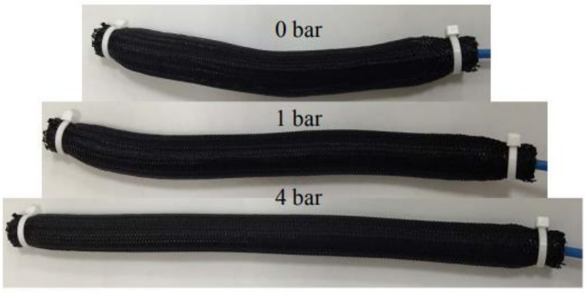

Fig.8. The Hypothesized Muscle Extensor [27].

C. Bending of the Pneumatic Muscle Actuator

By making the length of the braided sleeve equal to the length of the tube utilized inside, an artificial muscle that bends is produced. When air is pushed into a muscle, a soft rubber rod inside of it folds, allowing the muscle to contract[28].

1. bending contraction actuator

   The bending behavior of a single contraction actuator is provided by this method. high force applied to the rod causes it to shatter after multiple bending cycles. Additionally, the external stiff rod lessens the PMA's soft appearance. However, we were motivated to replicate the concept of our body for biological ideas. The human body's exterior seems soft because soft tissue, such as skin, covers the body's stiff portions, the bones. As a result, the braided sleeve and the inner rubber tube are separated by the reinforcement rod. This technique applies stress from both the covered shell and the rubber tube, which boosts the rod's longevity while achieving the biological notion. There is fewer than 54.7 degrees in the angle "θ". The SBCA using the revised construction approach is shown in Fig. 9 [28].

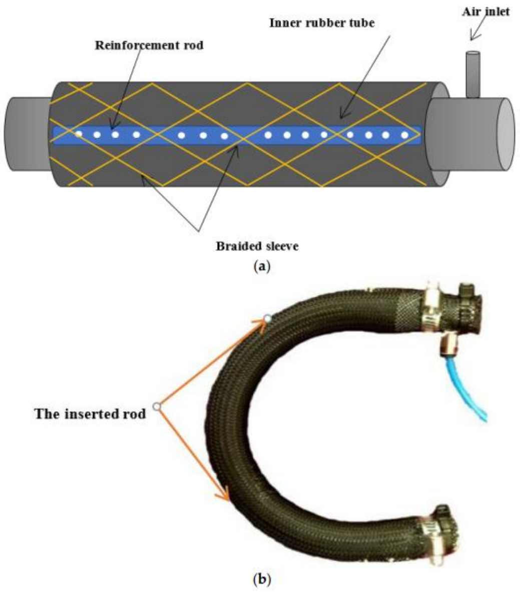

Fig.9. The self-bending contraction actuator's (SBCA) unique construction. (A) The SBCA actuator structure with the inserted rod visible. (b) The bending actuator following multiple processes [28].

2. bending extensor pneumatic

   Linearly extending McKibben artificial muscles serve as the foundation for the suggested bending extensor pneumatic artificial muscles (BEPAMs). The actuator's one side is kept at a constant length by the reinforcement of these muscles along that side. This indicates that the new actuator bends rather than stretches when under pressure. The experimental examination of several extending pneumatic muscles marked the beginning of the development of the bending pneumatic muscle. The rubber bladder used to create the prototype pneumatic muscle (M1) had a resting length of 160 mm and a diameter of 10 mm. This was covered with a braided nylon sleeve with a minimum diameter of 8 mm and a maximum diameter of 18 mm, whose length was twice that of the rubber. One of the two 3D-printed terminals at each end of the muscle was closed, while the other featured a small opening that allowed pressurized air to be injected. The actuator was able to reach an experimentally determined resting diameter of 18 mm with cable ties connecting the rubber and braid to the terminals, which is also the maximum diameter of the sleeve. "θ" is an angle bigger than 54.7 degrees. The EBPAM setup is displayed in Fig. 10 at four arbitrarily high pressures. It is evident that the actuator bends as the longer side of the actuator grows longer while the shorter side stays at a fixed length [29].

Fig.10. Various pressure levels pressurize BEPAM [29].

IV. SOFT ARM

Elephant trunks and octopus tentacles also had an influence on the soft robotic arm. Compared to rigid mechanical arms, soft robotic arms are more flexible, low stiffness, multi-degree of freedom, and safer for human interaction. It is widely used in many different fields [30]. These are a few examples of applications:

The shape sensing and motion regulating capabilities of soft robots were investigated through the construction and operation of an octopus-shaped soft arm powered by SMA coils. as illustrated in Fig. 11. Construction and composition of the soft arm. This robotic arm is 80 mm long and 26 mm in diameter. It is constructed of soft silicone gels and has gaps in the wall that are organized in a regular pattern to lessen bending stiffness. To monitor distance changes and compute body deformation during bending motions, three linear Hall sensors are mounted onto the slot surfaces as proprioceptive sensors. To simulate longitudinal artificial muscles, three groups of SMA coils are positioned onto the Hall sensors at consistent intervals. After the system determines the corresponding bending angle and bending directional angle given a planned route, the proprioceptive Hall sensors determine the present form. The soft arm's motion was controlled and its exact position was obtained using a PID controller. Experiments on one- and two-dimensional bending demonstrate how precisely the arm's shape and motion could be controlled. Because of its extremely basic structure, this soft arm segment can serve as the foundation for the construction of a multi-segmented soft manipulator or leg that can perform complicated movements during manipulation and locomotion. This soft arm's accurate deformation, affordability, and robustness make it a good option for soft robots that can interact safely, dynamically, and autonomously with people in a variety of challenging contexts. The main contributions lie in the arm's ability to gradually bend to the proper angle in less than a second and with an accuracy of less than two degrees. It is important to note that the goal of this effort was to create a soft arm that is easy to use, long-lasting, affordable, and capable of precise control of movement - rather than to precisely mimic the shape or behavior of a living octopus [16].

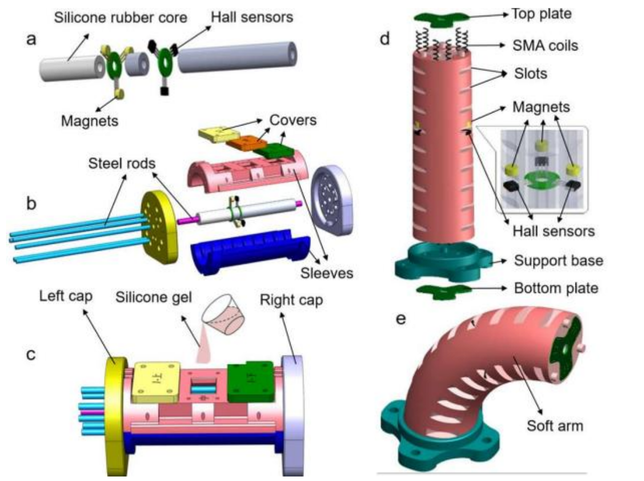

Fig. 11: Soft arm fabrication and construction. (a) A silicone rubber core holds the linear Hall sensors and related magnets in place; (b) a larger picture of the 3D-printed soft arm mold reveals the six steel rods that serve as the holes for the SMA coils; (c) silicone gel is poured into the mold to create the soft arm; (d) the SMA coils, plates, and support base are put together on the soft arm's body; and (e) the soft arm is bent. [16].

It is a difficult problem to design robotic manipulators that can carry out activities involving effective physical interaction. We created a brand-new soft robotic arm (SRA) made of elastomeric materials that was inspired by octopus arms. It has four series of interconnected pneumatic chambers that provide functions comparable to those of the octopus arms' longitudinal muscles. as illustrated in Fig. 12. An asymmetric compressive force is created when one air channel is inflated because the sequence of chambers will compress one another. In addition, the spaces between the parts will allow for some bending. Pneumatic actuators are the only means of control for this SRA; however, air pressure regulation or air channel combination can yield larger DOFs. By using the parallel control, the SRA is able to execute a sophisticated 3D motion. The main contribution lies in the ability of the gripper to change its gripping position to suit the geometric properties of an object due to the high degree of flexibility provided by the SRA with multiple degrees of freedom. The ability to rotate objects either clockwise or counterclockwise has been added using the new gripper function. We realize that using alternative robotic grippers to accomplish this purpose is difficult. Biological sampling platforms and human-machine interaction are two engineering applications where a flexible gripper may prove to be useful in general [31].

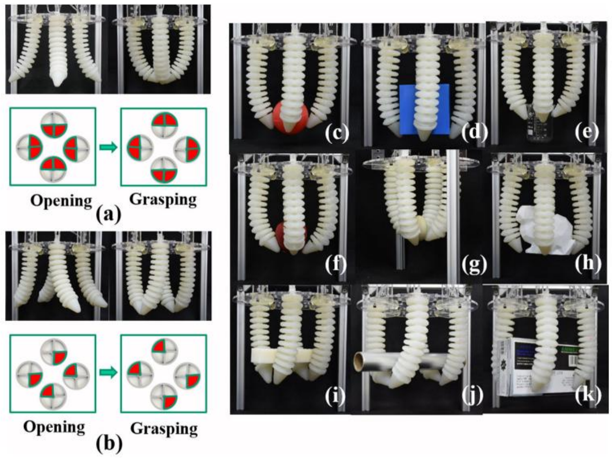

Fig. 12. The four-armed gripper's clamping hold. The four-armed gripper has two distinct modes of grasping: a) four SRAs move toward the center, and b) two pairs of SRAs move toward each other. The four SRAs are arranged as seen in the gripper's cross-sectional view. The inflated air tubes are visible in the red areas. A plastic ball is being held by C, a plastic cube box by D, a glass breakers by E, an apple by F, an egg by G, a 3D printed rabbit model by H, a lathy rectangular solid by I, an extended tube by J, and a carton box by K [31].

Recent years have seen a significant increase in research interest in soft robotic arms (SRAs) because of their affordable, numerous degrees of freedom (DoF), relative safety, and good environmental adaptation. Thus, a unique SRA that was inspired by the human arm was created; it is seen in Fig.13 and is made up of two soft extensible arms (SEAs) and a soft bendable joint (SBJ). Two nylon plates and four elastic bellows make up the SBJ. The nylon plates are 3D printed, while the SEAs and bellows are created by casting in 3D printed molds. The walls of the SEAs and bellows are 2 mm thick and hollow. With the exception of the nylon plates, the SRA is primarily made of silicon rubber (hardness: 90), and it is powered by inflating gas channels. The modular parts of the 602-mm-long SRA are serially concatenated and independently cast. Real-time data from a vision sensor system was used to construct a closed-loop model-free control system based on a PID controller. The main contribution of this arm's design is its ability to move in multiple ways because it is based on a diamond origami pattern. The flexible nature of the arm also allows for large deformations, making it useful for gripping abrasive materials such as space debris. It is also simple and inexpensive to produce [32].

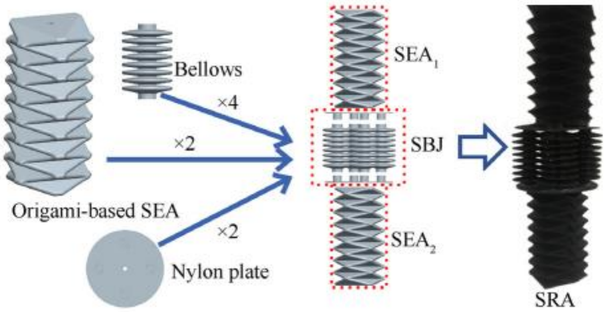

Fig.13. One SBJ and two SEAs (SEA1 and SEA2) make up SRA [32].

There has been a noticeable increase in interest in the design, modeling, and use of biologically based continuum robot arms in recent years. These robots lack a backbone, much like their natural counterparts' limbs and trunks, which belong to octopuses and elephants, respectively. which don't require any stiff joints in order to move and bend. therefore created a new continuum arm that can bend and extend using a pneumatic muscle actuator. The suggested soft arm can perform a variety of tasks, including bending, contraction, and extension. Furthermore, because of its safety features and softness, it is meant to function in close proximity to humans. The length of the soft arm, including the fixed, mid-end, free end, and end-effector bracket, is 72 cm. The material used to manufacture the actuator's fixed, mid, and free ends was created with SolidWorks 2016 and printed using a 3D printer. The caps of the actuator are composed of metal. The continuum arm uses both parts to accomplish a full bending angle of 117 degrees and an elongation quantity of 12 cm (elongation by 48%) when there is no weight applied. The continuum arm weighs 0.75 kg, which is split as follows: The end effector support weighs 0.3 g, the contractor section weighs 0.2 kg, and the extension section weighs 0.25 kg [33]. The proposed continuum arm, which can bend in all directions and extend longitudinally, is designed as shown in Fig. 14. The primary contribution is the use of self-bending actuators (SBCA) in place of conventional shrinkage actuators in order to improve bending performance and raise load-bearing capacity.

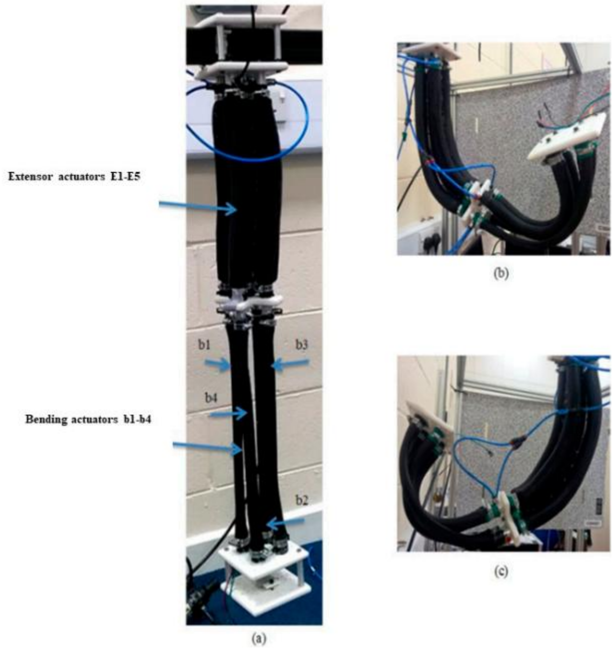

Fig.14. The adaptable multipurpose soft arm. (a) The arm in its relaxed state. Two distinct bending possibilities are represented by (b, c) [33].

In order to effectively twist around items with diameters up to 30 mm (the maximum diameter of the objects to be retrieved), a length of 370 mm was chosen. The arm is a useful tool for retrieving objects in confined spaces and under different pressure situations since it can record a gripping force of up to 3.3 Newtons, which is equivalent to 3.9 times the arm's weight in different environments [34].

Robotics' exploration and manipulation in hostile situations and intricate spaces continue to be fascinating and difficult problems. Accessing working locations can be challenging because of their potentially explosive atmosphere and the mix of high pressure, high temperature, and aggressive fluids, as shown by the oil and gas sector of the energy business. Therefore, as seen in Fig. 15, a soft arm with suction cups inspired by an octopus was built for the purpose of retrieving nonstandard things from wells, pipes, tanks, or other confined spaces during industrial production or maintenance. This is accomplished by partially mimicking octopuses' fetching and reaching motions. The solution takes care of difficult situations, such as air or oil media, restricted spaces, pressurized chambers (up to 18 bar), fluid and surface dirtiness and/or roughness.

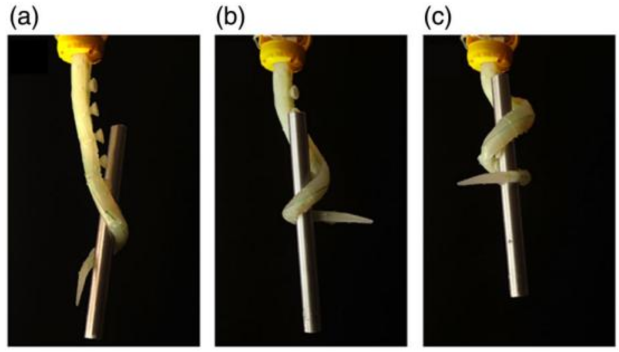

Fig.15. the suction cup-equipped arm in use: Three distinct configurations are used to grab the tubular object (steel) with a 20 mm diameter from (a to c) [34].

It is currently difficult to enable soft robots to carry out interaction activities on their own. Nonetheless, it appears that reinforcement learning policies trained on effective mechanical models can be transferred practically. Therefore, as illustrated in Fig. 16, created a 3D-printed soft robotic arm with three elliptical pneumatic chambers that can provide powerful actions by combining stretching and bending. Six rings spaced throughout the body confine the chambers, two terminals (top and bottom) limit the modules, and bolts and nuts hold the pieces together. Every module is approximately 202 mm long, with a 30 mm radius cross-section, and weighs roughly 183 g. The lengths of the top and bottom terminals are around 20 mm and 5 mm, respectively, while the pneumatic chambers are approximately 180 mm. The actuators are arranged axially, equally spaced 120° around the center, and at a radial distance of δ ¼ 20 mm from the cross-section centroid. The soft material thermoplastic polyurethane with 80 Shore A hardness (TPU 80 A LF, manufactured by BASF) was used to create the arm. It has a tensile strength of 17 MPa and an elongation at break of 471%. TPU 80 A LF was processed and process settings were established using the Ultimaker S5 (Ultimaker, The Netherlands) machine with a 0.4 mm nozzle and the slicing software Ultimaker Cura 4.11. The main contribution is that soft robotic arms can perform propulsion tasks quickly, so a closed-loop position/force controller was created, with parameters dependent on position, orientation and force. The controller achieved a satisfactory transition from simulation to reality, using pressures up to 3 N and producing an average position inaccuracy of 34 ± 14 mm and 0.40 ± 0.29 rad [35].

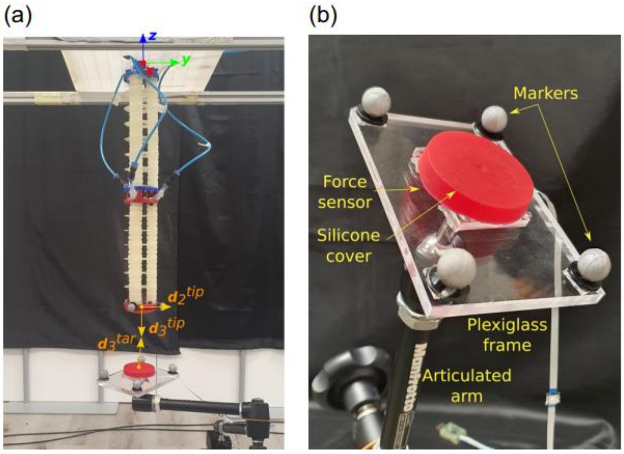

Fig.16. the actual surroundings. a) To counteract the force of gravity, the soft robotic arm is angled downward. In the robot workspace, the force sensor attached to an articulated arm is moved in various orientations and locations. b) The force sensor plate is shielded by a silicone cylinder. The centroid of the four reflecting marks on the supporting Plexiglass plate matches the sensor position [35].

A fluid structure and lack of a solid skeleton allow an octopus arm to exhibit a high degree of flexibility and freedom. These great qualities are appropriate for use when working with delicate and amorphous things. As a result, a soft robot arm that resembles an octopus arm has several applications in the fields of agriculture, welfare, and medicine. It can be used as a harvesting machine without harming crops, as a rehabilitation aid, and for safe surgery. The soft robot arm, which is essentially made up of the nerve cord and muscles, is designed to resemble the muscular arrangement of an octopus's arm using pneumatic artificial muscles, in contrast to industrial robots. The muscles are grouped around the nerve code (NC) and can be broadly classified as longitudinal muscles (LMs), oblique muscles (OMs), and transverse muscles (TMs). This artificial muscle was utilized as a Master-Slave Control and, as Fig.17 illustrates, had an initial diameter of 2.0 mm. It was also highly flexible. Only threads serve as sensors throughout the body of the slave and master machines, which lack any hard material. The system that was put in place was effective; the slave machine moved in accordance with the operator's intention, while the master machine deformed. Consequently, for simplicity, the size and configuration of the master and slave machines were intended to be the same [36].

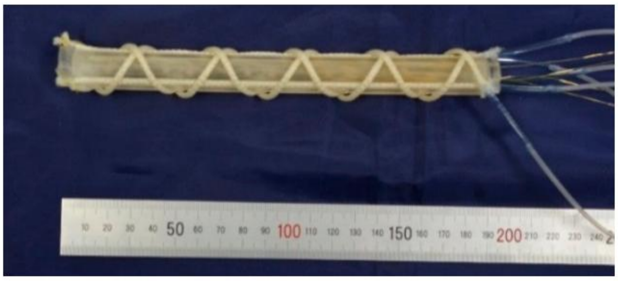

Fig.17. The soft robot arm that was created [36].

It is crucial to concentrate on the dexterity of the robots and the safe cooperation of people and robots. to provide secure human-robot communication. Therefore, for direct human–robot interaction, a modularized soft robotic arm with integrated touch sensing was built. As illustrated in Fig. 18, the robotic arm is built by joining several soft manipulator modules, each of which has three bellow-type soft actuators, pneumatic valves, and an on-board sensor and control circuit. Through the use of three-dimensional (3D) stereolithography printing, the bellow actuator may incorporate embedded organ gel channels—which are utilized to detect human touches into its thin body wall. As a result, the organ gel acts as a soft interface to discern the intents of the human operators, allowing the robot to communicate with humans and produce the manipulator's desired movements. Each manipulator module features soft string sensors that are small and compact in addition to touch sensors to sense the movements of the bellow actuators. The manipulator module may internally estimate its own posture or orientation when paired with an inertial measurement unit (IMU). additionally provide a localization technique that enables us to determine the manipulator module's approximate location and obtain 3D data about the target point in an uncontrolled setting. Compared to conventional motion capture systems, which typically require numerous cameras in a controlled environment, the suggested method is substantially easier as it only requires one depth camera in conjunction with a deep learning model. The main contribution is to invent and integrate a small and lightweight omnidirectional soft filament strain sensor that can measure linear and omnidirectional arm movements. Finally, they performed several tasks including human interaction and demonstrated the control of the soft robotic arm, which had a total mass of about 2.5 kg. The proposed system indicated that in the future, robots could be used to assist and interact with humans in our daily lives [37].

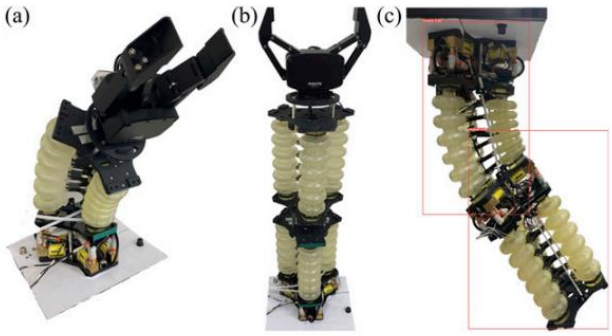

Fig.18. Bellow-type soft actuators are used to construct manipulator modules, which form the soft robotic arm. Manipulators having grippers that are (a) single-module and (b) double-module. (c) Soft robotic arm pose and motion detection [37].

The human arm is an essential tool for carrying out many duties. In order to mimic the natural design process, a modular bioinspired soft robotic arm with reconfigurable connected portions was created, as illustrated in Fig.*19*. The pneumatic tube can run within the whole length of the arm thanks to the hollow parts in the suggested design. Because it reduces the chance of entanglement in silicon tubes, this improves the operational safety provided by the arm. The link, joint, and gripper parts make up the soft robotic arm. The thermoplastic polyurethane (TPU) coated nylon fabric (N210D, Jiaxing Inch Eco-Materials, China) was utilized in each area. An airtight seal is formed between the two nylon layers when the TPU layer is melted and polymerized by high heat and cooling. This makes it possible to produce hermetically sealed bladders that don't leak when inflated pneumatically. The multi-joint arm has three link sections and a weight of 0.350 kg. The main contribution lies in the biologically inspired design of the arm and its ability to perform various motions under different stresses, in contrast to the soft arms reported in the literature. The large working area, lightweight design, and ease of fabrication are just some of the advantages of the modular arm. Finally, experiments were conducted to demonstrate the arm's ability to move various objects from one side to the other. In the future, to simulate a more realistic arm, a soft grip could be attached to the arm. The grip could facilitate complex activities such as holding and picking up various objects [38].

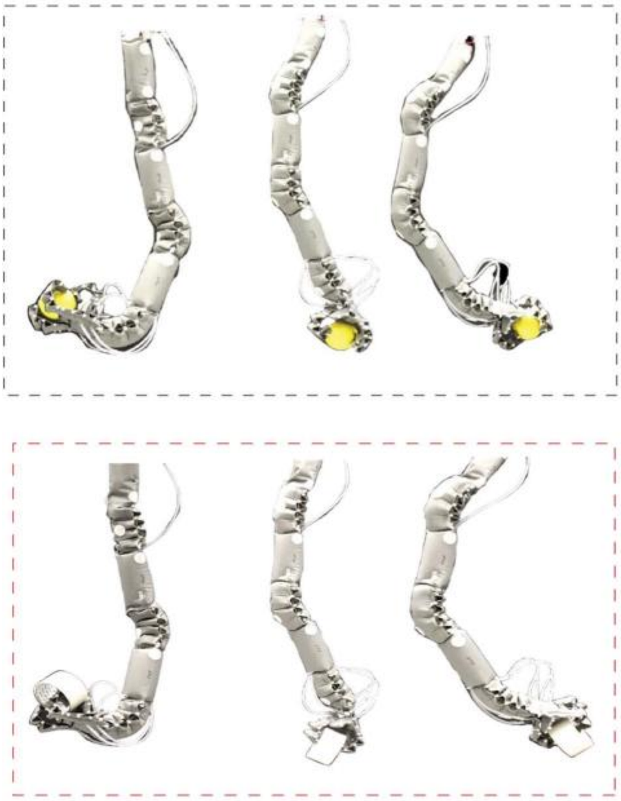

Fig.19. A modular soft robotic arm inspired by biology [38].

Without compromising no-load reach, High strokes can be achieved with many-actuator soft arms when the load and actuation pressures are similar. Using a single pressure signal and a simple actuation sequence, these arms may also perform near-constant-curvature turns and attain quasi-omnidirectionality. As seen in Fig. 2*0*, The modular arm architecture, which is made up of McKibben actuators connected to radial plates, matches the arms used to validate the reduced-order model. Polylactic acid filament was used to print the EcoFlex 00-30 tube and caps, and a polyester plastic braided sheath (McMaster #9284K2) make up the McKibben actuators. When the actuators are under pressure, they contract and produce a force and strain combination. The actuators utilized in this work had a tube wall thickness of 1 mm, a diameter of 7 mm, and a length of 230 mm at first. The primary contributions are multi-actuator arms, which can make control techniques easier to understand and more straightforward. The infrastructure needed for accurate pneumatic pressure management can be significantly reduced by choosing actuators that follow the curvature direction instead of altering the pressure ratio. The load capacity of over-actuated designs is restricted by their circumference rather than their diameter, and they increase load capacity without compromising curvature [39].

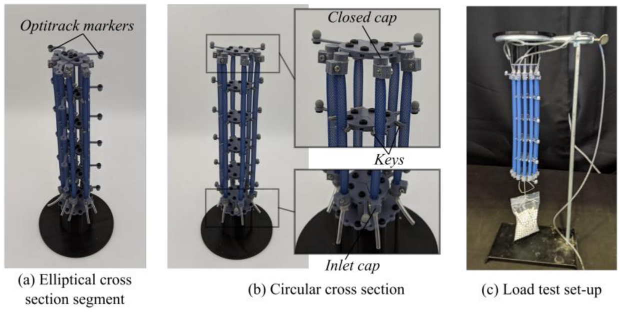

Fig. 20. Examples of arm segment prototypes include (a) an elliptical, eight-actuator segment the stress test setup includes two circular cross section segments: (b) one with six actuators and (c) one with twelve actuators. The segment's actuators were subjected to air pressure, and loads were secured to one end. [39].

V. SOFT END EFFECTOR

A key component of a robot system is the end effector, which specifies the tasks the robot is capable of performing. Nevertheless, a gripper is usually only suitable for holding one or a limited variety of objects [40]. Furthermore, controlled stiffness, controlled adhesion, and actuation gripping are all possible with soft robotic grippers. Grippers made of electroactive polymers are capable of producing strong forces and quick responses up to 12 milliseconds. Shape-memory polymers can be wirelessly actuated by thermal stimulation, although they are not able to produce strains as great as those of fluidic or electroactive actuators. Similarly, pH, humidity, solvent, light, and magnetic fields can activate soft grippers made of different stimuli-responsive polymers. The majority of these untethered stimuli cause a deformation based on an indirect volumetric change [41]. These are a few examples of applications:

suggested a brand-new, three-fingered soft robotic gripper that can conduct adaptive grasping with the least amount of system complexity. It has decoupled stiffness and shape control capabilities, as seen in Fig. 2*1*. The suggested soft fingers can adjust to the forms of items, making it easier to handle a variety of objects that are variable in size, shape, and kind. Pneumatic muscles actuate each soft gripper finger, which features an inextensible articulable backbone. Its primary contributions include its capacity to hold objects while they are being moved and directed, its ability to measure the force needed to release objects, and its ability to control stiffness, which can improve grip quality and lower the risk of handling-related damage to delicate objects. It also helps develop more appropriate and efficient robotic grippers for a variety of applications, including healthcare and agriculture [42].

Fig.21. the structure of tri-fingered soft robotic gripper [42].

We demonstrate a soft robotic gripper for the Tele-operable In-Home Robotic Assistant (TIHRA), a device for people with limited mobility, as depicted in Fig. 22. The Fin Ray Effect, which derives from the physiology of fish fins, served as the model for this gripper. The gripper fingers may be 3D printed from a number of materials, such as PLA and NinjaFlex, and are soft and triangular with rigid crossbeams that buckle and deform to adapt around items. The main contribution is that when the same force is applied, the TIHRA fingers deform 15% more than conventional fingers. The TIHRA grip (560 grams) can hold about 40% more weight than a grip with conventional fingers. The grip performed poorly in some activities, indicating a need to enhance grip strength to prevent out-of-plane twisting and bending and to increase the force the grip can exert. However, it completed other tasks effectively, demonstrating its conformability, deformability and shape[43].

Fig.22. The TIHRA gripper [43]

Based on the soft actuator, a four-finger gripper prototype was created and demonstrated exceptional grabbing capabilities in aquatic conditions, particularly for delicate and soft objects as shown in Fig. 23. Furthermore, the flexible actuator that, when deflated, can bend outward and inward. by the simulation of finite element analysis (FEA). Because the gripper may experience unanticipated vortexes and flow resistance when operating under running water, the actuator's shape might not be ideal for gripping objects underwater. They might create a suction gripper in the future that makes use of suction flows to improve grasping of small, light floating objects or suspended objects in the water. In the meantime, they collectively optimize the soft actuator's parameters to find the global optimum and maximize the acutator's bidirectional motion by experimenting with various chamber shapes [44].

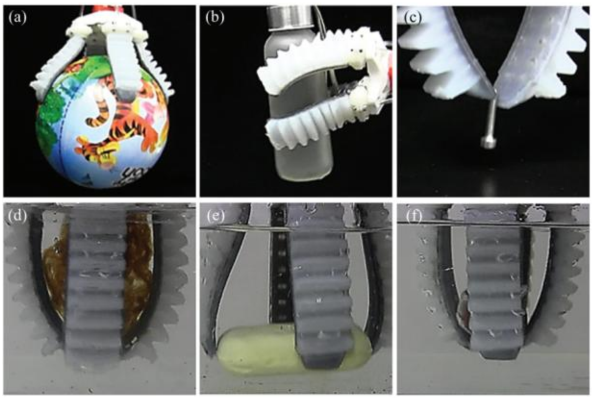

Fig.23. Findings on the soft gripper's gripping ability in aquatic settings. The gripper is capable of successfully grasping the following objects: (a) a 170 mm diameter sphere; (b) a 250 g weighted cup; (c) a 3 mm diameter screw; (d) a bundle of scaphium scaphigerum; (e) a bit of soap; and (f) a grape [44].

The suggested design incorporates a soft pneumatic gripper with soft sensor skins, as seen in Fig. 24. The gripper creates a three-dimensional tactile feedback-based model of an object by twisting things and using tactile sensing. Three soft actuator modules installed on a laser-cut acrylic frame make up the gripper. The gripper's palm serves as a central axis, around which the three actuator modules are arranged in a radially symmetrical manner. The main contribution of internal sensing technology in soft robotics is that it solves the forward motion problem of not knowing exactly where the end effectors are. These fingers are able to manipulate unfamiliar and fragile objects without causing damage. Future research may focus on improving our understanding of unfamiliar objects. Gripper fingers have a fundamental limitation on the accuracy of the resulting perception, so the size of the fingers affects the model. Rather than just using a single sensor to detect touch for perception, they could incorporate additional fingers and multiple sensor readings into different contact sequences for these more complex manipulations [45].

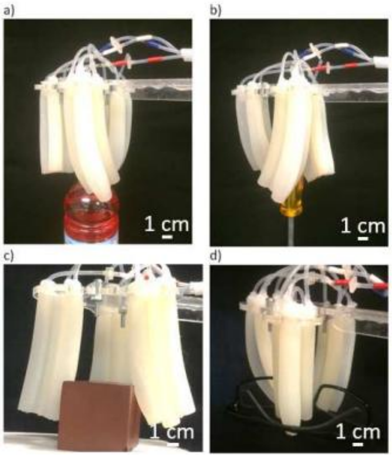

Fig.24. A variety of intricate manipulation activities can be carried out by the Fig. 25. suggested soft gripper design, such as: a) unscrewing a bottle cap, b) turning a screw driver, c) expanding its grab area to operate a larger box, and d) grasping complex forms like a pair of spectacles [45].

included both positive and negative pressures to create a soft gripper with four pneumatic elastomeric actuators, as seen in Fig. 25. This could speed up the gripper's actuation. For pneumatic actuation, this gripper just needs a basic control system. Deflate the soft actuators to open the gripper's "jaw" and approach the objects; subsequently, inflate the actuators to conform the objects being grabbed. A strategically positioned inelastic nylon tendon was employed. The gripper has a strong grasp on objects between 2 and 170 mm. The gripper's precision and error tolerance were also considerably better than those of the gripper with full length, and it was able to produce the maximum pull-off force for the corresponding object size under the ideal length. The soft robotic prototype can grasp a variety of objects with ease and at a reasonable cost. It may also have significant leverage for future industrial activities [46].

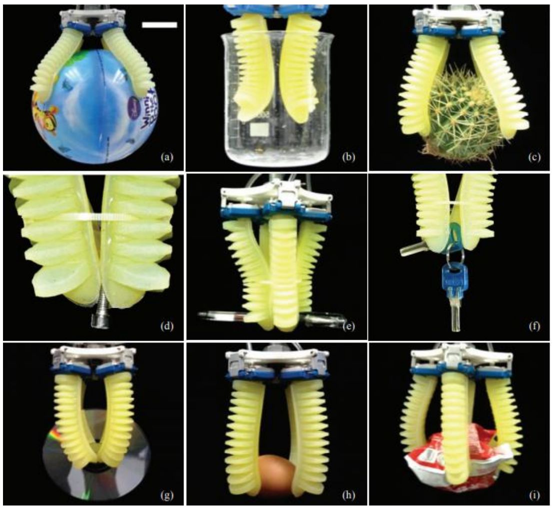

Fig.25. conclusions drawn from the soft gripper's universality. A beaker (b), a cactus (c), a screw (d) with a diameter of 2 mm, a pen (e), a chain of keys (f), a compact disk (g), a raw chicken egg (h), and a bag of milk (i) may all be held in place by the soft gripper [46].

created a three-finger soft gripper using a PMA for bending contraction. The gripper, as seen in Fig. 26, has been demonstrated to provide a wide range of grasping sizes for different item shapes and dimensions, as well as grasp strength sufficient to sustain a 1.4 kg load. Controlling the air pressure inside the fingers leads to finger closure. The primary contributions are designing two grippers in accordance with the suggested modification and altering the McKibben contraction actuator to establish a bending performance [40].

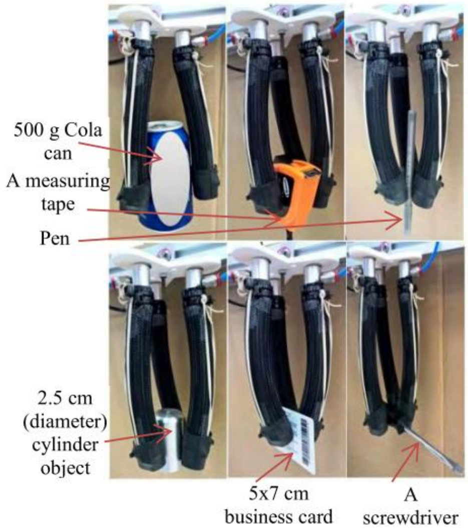

Fig.26. The three-finger gripper is able to hold multiple things. [40].

created the extension-circular gripper depicted in Fig.27 using PMA. The two primary characteristics of the extension-circular gripper are its length extension, This makes it possible to properly position the primary gripping contact area on the object that needs to be grabbed. The second characteristic is a pressurized circular PMA that can capture an object placed in the middle of it thanks to a reduction in diameter. Experimental results have demonstrated that the gripper can lift up to 10.9 kg of weight. In order to develop a high gripping force gripper, the main contributions are the construction of a circular pneumatic muscle actuator and its connection with an extensor actuator. Utilizing the circular "Orbicularis Oculi" human facial muscle, which controls the movements of the lips and eyes, this is accomplished.[40].

Fig.27. The circular gripper with extension may hold many objects [40].

created a unique robotic gripper, depicted in Fig. 28, that is capable of switching gripping modes through contact with an environment. The parallel gripper, pinching, and enveloping modes are interchangeable grasping modes. Versatile grabbing was realized by using fluid fingertips implanted in microgrippers. The passive joint in the fingertip is equipped with a torsion spring and a ratchet. Soft, stiff, deformable, delicate, small (boundary length less than 30 mm), large (more than 80 mm long), thin (less than 0.5 mm), and heavy (more than 3 kg) things are among the many varieties of graspable objects. Future research will concentrate on grasping and motion planning based on sensor data or on the best size and material design based on real-world tasks. The secret to autonomous grabbing and manipulation is to recognize and automate manually established parameters [47].

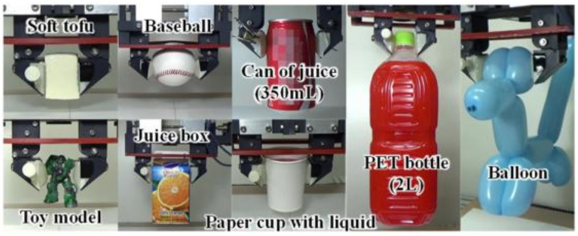

Fig.28. The robotic gripper with Multiple objects [47].

created a soft manipulator and ROV system, as depicted in Fig. 29, for grabbing seafood in shallow water. The underwater soft manipulator can move in three dimensions of space and is developed and operated under opposite-bending-extension conditions. can take the position of human divers in the safe, effective, and damage-free gathering of seafood. The primary advances include the creation of a quick reversible technique to regulate the manipulator's motion and the elimination of the requirement for human divers, which improves efficiency and safety [48].

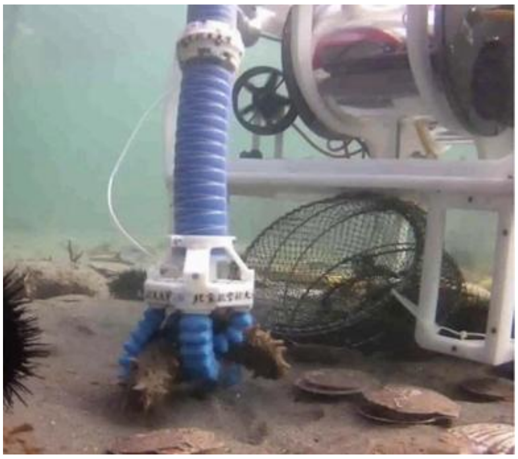

Fig.29. The underwater gripper [48].

Designing the end-effector with the human hand in mind as illustrated in Fig. 30, It has three characteristics. The fruit is to be detached from the stalk using a single-joint rotation, sinusoidal contour, and finger-end grabbing in accordance with the linear motion of the constraint portion and the rotating gripper. The primary contributions include raising agricultural robots' degrees of automation and intelligence, decreasing the need for manual labor, and boosting production efficiency [49].

Fig.30. gripper modeled after the Human Hand [49].

VI. CONCLUSION

This paper highlights the value of soft actuators in creating robotic systems that are more environment-adaptive and flexible, particularly when handling intricate objects and structures with precision and sensitivity. It is evident from a review of technologies like artificial pneumatic muscles, magnetic actuators, shape memory alloys, and electroactive polymers that soft actuators are essential to the design of soft robots, particularly for industrial and research applications where natural movement and environment adaptation are required. In addition, the research on soft-armed robots highlights the materials, mechanics, and advantages of these technologies and shows how they might be used in advanced robotics. The findings suggest that soft actuators will keep enhancing robot performance due to the ongoing advancements in this field, creating new opportunities for future uses in industry, research, and medicine. Because of these technologies' great flexibility and enhanced efficiency, robot design is likely to undergo a revolution.

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