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Recent Developments of Actuation Mechanisms for Continuum Robots: A Review

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Abstract: Traditional rigid robots face significant challenges in congested and tight environments, including bulky size, maneuverability, and safety limitations. Thus, soft continuum robots, inspired by the incredible capabilities of biological appendages such as octopus arms, starfish, and worms, have shown promising performance in complex environments due to their compliance, adaptability, and safety. Different actuation techniques are implemented in soft continuum robots to achieve a smoothly bending backbone, including cable-driven actuators, pneumatic actuators, and hydraulic actuation systems. However, designing and developing efficient actuation mechanisms, motion planning approaches, and control algorithms are challenging due to the high degree of redundancy and non-linearity of soft continuum robots. This article profoundly reviews the merits and drawbacks of soft robots' actuation systems concerning their applications to provide the readers with a brief review reference to explore the recent development of soft robots' actuation mechanisms technology. Moreover, the authors have surveyed the recent review studies in controller design of continuum robots as a guidance for future applications.

Keywords: Actuation mechanisms, flexible robot, soft structure, twisted cable polymer.

1. INTRODUCTION

Nowadays, robots play a significant role in human life more than ever due to the spread of epidemics such as COVID-19 [1], which restricts person-to-person contact. As a result of the catastrophic side effects of the COVID-19, which was described as a once-in-a-century global pandemic [2], a high number of people around the world were infected as well as millions of deaths happened according to the World Health Organization (WHO) [3]. From a technical point of view, world governments have relied on robots to overcome the difficulties caused by COVID-19 in reducing infection rate by rapidly identifying symptoms, improving biomedical applications and continuity of the traditional industrial processes to maintain the economy [4]. So, robotics designers are in a constant quest to design and develop robot structures inspired by surrounding organisms to navigate, detect, sense, grasp, and to adapt challenges brought by the COVID-19 pandemic [5].

The structure of the traditional robotic manipulators consists of a series of rigid links connected by revolute, prismatic or spherical joints inspiring by human arms. The robot links were made of high stiffness material such as Steel or Aluminum, which can be manufactured with electrical-mechanical machinery such as Computerized Numerical Control (CNC) machines [6]. Traditional rigid robots can efficiently achieve positioning tasks in medical applications with fast dynamics and feedback controllers. In [7], a robotic arm was developed to collect oropharyngeal swab (OP swab) samples to decrease COVID-19 infection of healthcare workers from patients while enhancing OP swab efficiency. A low-cost miniature robot was designed for collecting COVID-19 Nasopharyngeal (NP) samples [8]. The robot consists of two Degrees of Freedom (DOF) gripper with the capability of force sensing attached to a 6-DOF manipulator for adjusting the global position and orientation of the robot's tip. The designed robotic platform was fully controlled via teleoperation through a passive Phantom interface. In [9], serial robotic manipulator was developed to perform endoscopic surgery with an advanced 3-Dimensional (3-D) vision sys-

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tem. Recently, Learning from Demonstration (LfD) has proven a great success, and high efficiency as a motion planning approach, especially in medical robotics [10]. LfD aims to transfer movement skills through collecting of human demonstrations kinesthetically [11] or via teleoperation [12,13] to the robotic manipulator. The fuzzy approximated based task space control strategy of the 7-DOF serial robotic manipulator for teleoperated surgical operation with active Remote Center of Motion (RCM) constraint motion was developed in [14]. The experimental results showed that the fuzzy approximation controller enhanced the overall performance regarding the surgery's accuracy and safety. In [15], a novel motion planning technique of serial manipulator (KUKA) for Minimally Invasive Surgery (MIS) was introduced. The learning methodology was integrated using the LfD approach and decoupled controller with RCM constraints. The recurrent neural network (RNN) control scheme based on RCM constraints of the redundant serial manipulator for surgical operations was developed [16]. The surgical operation skills were implemented based on LfD approach. The simulation results showed that the developed RNN controller successfully achieved trajectory following while the tracking error converged to zero.

However, rigid robots have proven their success in medical applications, but they have faced multiple difficulties such as heavy weight and bulky size, which limited their maneuverability and adaptability, especially in highly congested environments. In addition, rigid robots require advanced protection techniques and stable control algorithms to safely achieve human-robot interaction operation successfully. Motivated by the limitations of rigid robots, many researchers were inspired by the incredible capabilities of biological appendages such as tongues, elephant trunks and snakes to design continuum robots that were made of soft materials like rubber or polymer silicon. The soft robotic arms were manufactured using 3-D molding process or by 3-D printer. The stiffness of soft robots is within the soft biological materials $10^4 - 10^9$ (like skin or muscle tissue), which helps in absorbing energy due to collision more than rigid robots, making them qualified to work in human-robot-interaction applications [17]. Additionally, due to the intrinsic and/or extensible characteristics, soft robots can bend, elongate, and gentle adapt their shape perfectly while maneuvering in many applications such as soft hand for rehabilitation [18], Soft Swimming Robot for inspection process [19], and MIS [20].

Pneumatic driven soft robot for COVID-19 OP swab test was designed in [21]. The soft robotic system consisted of two main parts: a collecting segment with Yoshimura origami structure which allowed effective throat sample collection, and a soft driving actuator for elongating and twisting purposes. The experimental results showed that the proposed design improved the throat samples collection test. The Rigid-flexible coupling (RFC) robot for the COVID-19 OP-swab sampling test was developed [22]. The whole system composed of an electrically-driven 6-DOF rigid manipulator and a pneumatic-driven 3-DOF soft robot for sample collection. The RFC robot was controlled based on pseudo inverse kinematic control with joint and velocity constrains via teleoperated Phantom interface movements. The experimental tests showed the effectiveness of the proposed design motion with the application of the developed kinematic control algorithm.

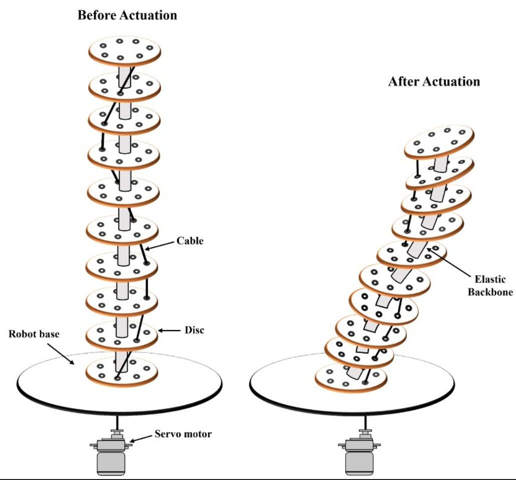
Comprehensive review papers of soft robots focus on applications [5,23,24], actuation mechanisms [6,25-27], and control strategies [28,29]. However, there is no in-depth analysis of the advantages and disadvantages of actuation mechanisms of soft continuum robots. Furthermore, they lack focus on the recent actuation technologies that may become superior in medical applications over traditional actuation systems because of their unique features. This paper summarizes the merits and drawbacks of soft robots' actuation systems, starting from cable-driven actuation, pneumatic actuation, hydraulic actuation, Magnetic actuation, and SMA actuation. Also, an investigation of the modern actuation techniques in soft continuum manipulators, including Piezoelectric actuation, dielectric polymers actuators, and Hygroscopic actuators, is carried out. Additionally, this paper surveys combining multiple actuation techniques within the same robot structure to improve efficiency and reliability in medical applications. Moreover, it provides the readers with fast review references, including the current and under-development actuation systems concerning their applications, and summarizes the recent review studies of different control strategies in the soft robotic field.

2. ACTUATION MECHANISMS

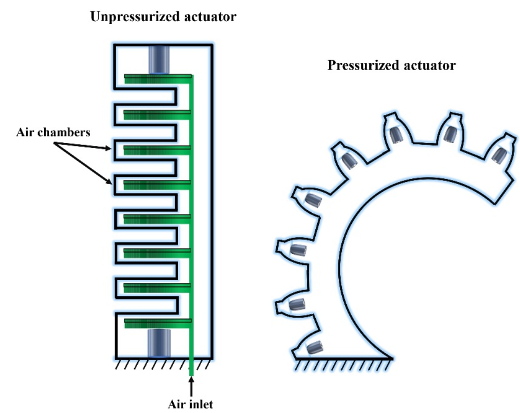
With the insistent need for flexibility end efficient maneuverability, soft continuum manipulators were designed to be used in many applications, including congested and dynamic environments, while handling particular objects. The main construction of soft robots depends on an elastic backbone controlled by actuation systems such as cable-driven, pneumatic, hydraulic, Shape Memory Alloy (SMA),... etc. Continuum robot actuation strategies are divided into; extrinsic actuation, where the actuators are away from the robot body while the movement is transferred through mechanical parts, and intrinsic actuation, in which the actuator is implemented within the robot structure. A combination of intrinsic and extrinsic actuation systems could also be available. Table 1 presents the working principle of most of the actuation mechanisms of continuum robots. It is worth noting that the actuation system could be adjusted or modified depending on the application requirements.

Table 1. Working principles of the actuation systems of continuum robots.

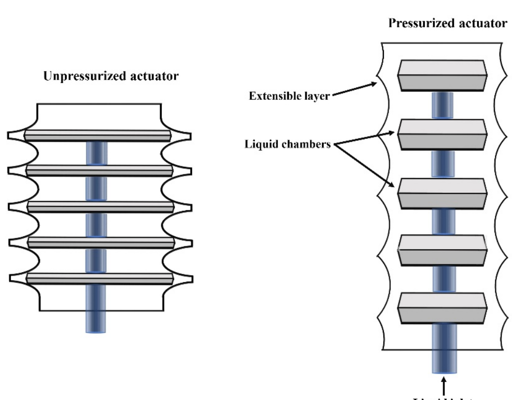
Cable-driven actuation



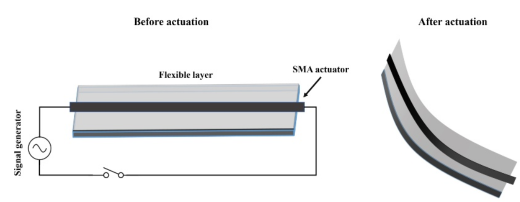
Pneumatic actuation



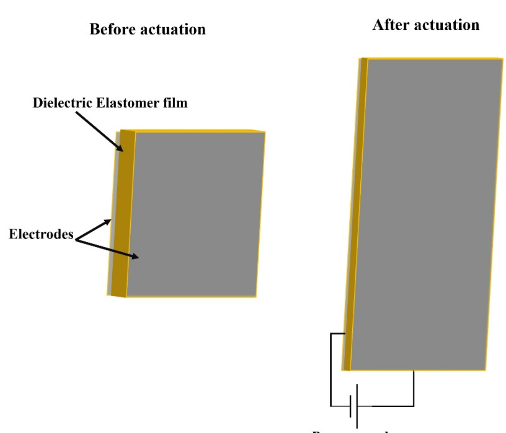
Hydraulic actuation



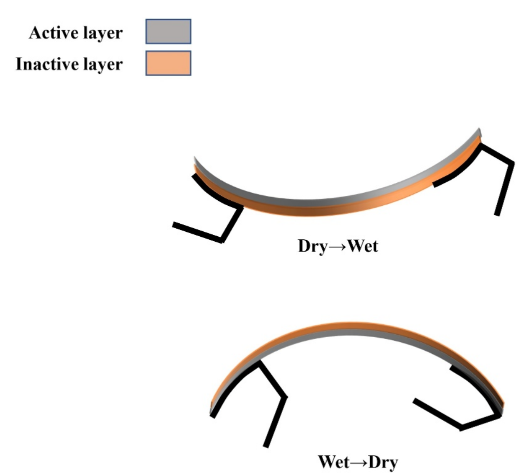
SMA actuation



Electrically Polymer actuation



Hygroscopic actuation



2.1. Extrinsic actuation mechanisms

2.1.1 Cable-driven actuation system

Design simplicity and scalability features of the cable-driven actuation mechanism qualify it for use in multiple applications such as inspection [30], medical instruments [31] and exploration [32]. The simplified design of cable-driven after and before actuation is shown in Table 1. It consists of a base, elastic backbone, circular guidance discs with equally interval holes and cables. Each cable is connected through the holes to the actuator from one end, and the other is attached to the most distal disc. The cable length changes when the actuator rotates while the flexible robot bends according to the specified task.

In [33], a combination of two under-actuated fingers and a single section continuum robot was designed for fixing and turning on the drill machine. The two underactuated fingers were used to fix the drill body while the continuum robot turned on drill power. Each finger consists of three phalanges that were actuated using only one tendon, while the continuum robot was articulated with three tendons. The electrically driven motors can pull the cables to reach the desired shape. The general 3-D kinematic model with an exact geometrically approach of a single section continuum manipulator based on a Cosserat beam was presented in [34]. The simulation of a single section continuum robot with four cables for improving insight of the movement during motion and a two-section flexible arm was carried out. The novel 2-DOF flexible gripper was designed in [35]. The gripper consists of two trunks; each includes many rigid parts like teeth attached to an elastic belt. Each trunk was controlled by pulling a steel wire through the tooth hole and fixed to the wire pulley. The two trunks are identical, so timing belts were used to drive the wire pulley and belt pulley to get symmetric motion. Multiple griper prototypes were presented to enhance flexibility and adaptability in pick and place applications. However, it is not easy to use those designs to pick soft objects safely. In [36], a low cost gripper, soft cable-driven continuum robot was developed. The soft gripper composed of three sections with variable compliance at the beginning of grasping to adapt its shape to the object and ensure a stable grasp. The experimental results showed that the soft gripper design was able to grasp and hold cylindrical objects of different cross-sectional shapes.

A novel multi-section extensible cable-driven continuum robot design was implemented in [37]. Counter to the constant curvature design that has fixed section lengths which limits its maneuverability, the extensible robot contains a variable section length in combination with the bending advantage through cable actuation. The flexible manipulator consists of three sections and a telescoping backbone made of Ni-Ti SMA to control the section lengths during the specified task. Guidance discs were equipped with permanent magnets, and the magnetic repulsion forces kept the discs distributed along the backbone equidistantly over each section during extension operation. In [38], a novel single section soft continuum robot was designed. The backbone consists of several segments, each segment consists of two layers, and each layer contains three springs, 120° apart radially distributed. The robot design provides a linear output motion using compliant planar springs and improves the linear bending in applications that require high bending due to the serially connected segments. The simulation results of the proposed design showed superiority to increase the bending configuration workspace over cable-driven with a pneumatic or helical spring backbone. In [39], the dexterity of a one segment cable-driven continuum robot was improved by using a non-straight tendon routing technique. The authors investigated different helical tendon routing configurations of one segment and two segments. The simulation results showed that the reachable workspace volume increased compared to straight tendon-driven routing. Also, the dexterity of the robot improved to avoid obstacles. The hybrid soft continuum manipulator composite of tendon-driven actuation and concentric tube to get an independent translation, bending, and complete shrinkage to 0 mm was developed in [40]. The soft robot contains two sections with different design structures. According to these designs, the workspace boundary of the proposed variable curvature hybrid soft manipulator was enhanced, and the path tracking error decreased compared to the traditional constant curvature design. A new flexible continuum arm was designed in [41]. The robot was used as a passive interface for mapping precisely the human hand motion to the growing robot and mapping the hand motion precisely while solving the roll-over problem compared to other mapping techniques. The interface was made from flexible Ningaflex rubber material. The interface was successfully developed to simulate the motion of an active cable-driven two-section continuum robot with the similar interface structure in [42,43]. Development of 6-DOF cable-driven flexible robot for controlling the supporting platform neck pose was presented in [44]. The pose estimation model was developed based on a nonlinear least-square optimization (NLS) and Extended Kalman Filter (EKF) with IMU sensor measurements without depending on the deformation model.

The design, experimental validation, and Finite element analysis (FEA) of soft continuum robot for skull base and inside hip surgeries capable of C and S-shaped bend ware presented in [45]. The robot backbone consisted of two sections with 27 compliant joints and was made of Ni-Ti super-elastic material. The FEA method was proposed to optimize the joint distribution parameters depending on treatment space requirements. The simulation results of the proposed FEA optimizing technique showed enhancement of the boundary exploration with unevenly distributed compliant joints distribution. A single section constant curvature flexible manipulator was developed in [46]. The backbone wad is made of Polyether Ether Ketone (PEEK) elastic material, and the robot tip was controlled via four tendon-driven actuation. Force feedback control was applied to prevent tissue damage based on Fiber Bragg Grating (FBG) force sensors. The simulation results proved that the developed model-based FBG sensors estimate the applied tip forces correctly with low errors compared to other force-sensing models such as rigid link and Cosserat. In [47], a soft organ retractor manipulator was developed. Counter to previously rigid retractor designs, the retractor here was designed on the buckling principle from super-elastic Ni-Ti material with composite material to ensure superior safety operation and increase the friction slightly to improve supporting the organ supporting during surgical operations. The movement of the soft retractor was accomplished based on a push-pull telescopic rod controlled through a cable-driven wrist joint. The wrist joint increased payload capability, strengthened the structure and enhanced the range of movement. The retractor was tucked to be easily inserted through the cannula by pulling the rod. Then the surgeon can easily push the rod to expand the retractor again when reaching the exact organ position. The design of a novel multi-section extensible continuum robot was presented in [48]. The soft manipulator consisted of three soft tubes with different diameters and stiffness, four nylon ropes passing through guidance discs, two for stretching, and two for retraction. Applying a combination of pull-push sequences of the ropes, the robot's sections' bending structure happened. The experimental results showed that the improvement of the payload capability was achieved. In [49], a single section 2-DOF continuum robot was developed. The actuation was based on four nylon wires passing through a rigid guidance disc to the robot's tip, while the other end was connected to two DC motors. The wires were divided into two antagonistic tendon pairs; each pair was attached to the DC motor via a dual spool to control 1-DOF. The developed design successfully improved the resistance against loads. The 2-DOF cable-driven soft surgical robot for Pediatric Neurosurgery was designed in [50]. The robot used a cable-driven bending of two flexure joints that were micro-machining from Ni-Ti elastic material to allow bending procedure in the opposite direction to get an S-shape. Novel design of tendon-driven continuum robot combined with cam-fitted Nitinol rod for high scale bending and an accurate motion was implemented in [51]. The main components of the robotic tool were a soft Ni-Ti super-elastic backbone, and the cables passed through multiple guidance spacers. Rotating the cam introduced a distance geometric constraint between the cam and elastic backbone which was shifted due to the generated internal forces. The robot with a single fitted cam allows the soft robotic manipulator to move straight or circularly. At the same time, two cams with the same stiffness can provide arbitrary movements. Two cooperative tendon-driven flexible catheters for positioning tasks in surgical operations were developed in [52]. The two catheters are fixed at parallel connection points, constraining the DOFs to have a relative axis rotation. The simulation results showed the effectiveness of the joint load manipulations in the congested environment. In [53], three flexible section cable-driven continuum robot for laparoscopic surgery was developed. Each section contains 12 spherical joints made of Aluminum, represented the robot backbone. Each segment was controlled independently with four cables. The experimental results prove the effectiveness of the proposed design with acceptable payload capabilities. The design of a multi-section surgical manipulator with a spring backbone was proposed in [54]. The soft manipulator was controlled through a tendon-driven actuation mechanism. The simulation results proved the dexterity of the robot in a wide workspace. However, the robot shape should be optimized for working in small congested environments.

However, the tendon-driven actuation system was used extensively in medical applications due to its flexibility, low cost, good torque, speed, and motion accuracy; it suffers from energy loss and lack precision in control due to the friction between the cables and the guidance disks.

2.2. Intricsic actuation mechanism

2.2.1 Pneumatic actuation system

Pneumatic actuation was developed to overcome the tendon-driven actuation limitations, especially for tasks that require extensive payload capability. On the other hand, the design and fabrication of pneumatic-driven soft robots are easy and inexpensive, and they need simple control for providing complex movements. The pneumatic actuation system is divided into tethered actuation in which the air pressure is supplied through tubes and untethered actuation in which the whole air powering components are implemented within the robot structure.

The quadrupedal multi-gait soft robot was designed in [55]. The robot had four legs attached to the central body, four actuators, and a valving system to control the supplied air at low pressure. The robot efficiently performed the crawling task by applying a cycle of pressurization and depressurization sequences. The demerit of the proposed design was that the pneumatic actuation power was supplied through external tubes, which may limit the motion in the practical field. In [56], an untethered pneumatically powered soft robot consisted of main soft backbone with four legs. Each leg was driven based on a pneumatic net. Two mini air compressors with six two-way valves were used to control the supplied air at constant pressure. However, the experimental results showed that the robot could carry a heavy payload; the system suffered from slow motion with high tracking error. A novel design of a single section constant curvature continuum manipulator with a pneumatically driven backbone surrounded by a series of Pneumatic Artificial Muscles (SPAMs) was presented in [57]. The SPAMs were used to add force to the backbone while bending to achieve a constant curvature shape. Unlike a tended-driven soft robot that sometimes contains rigid components such as guidance discs, the proposed design was made from soft components for safe interaction with a human. In [58], the pneumatic-actuated differential drive soft robot was developed. The robot consisted of two parallel columns of soft airbags, frontal and rear foot, which were made of high frictional material and used as anchors during motion, a middle layer made of paper material to minimize baseboard expanding, and a three-axis compass for obtaining the robot's azimuth angle. The experimental data showed that the locomotion speed was low, and the robot deflected to the left after nine cycles of linear motion. In [59], a soft pneumatic-driven robot inspired by the inchworm motion technique for soil penetration was developed. The robot consisted of three pneumatic actuated sections, head, tail, radially expanded, and another segment in between for body elongation. Also, the robot body was covered by Kirigami skin which popped up while the pneumatic actuator expanded radially. The locomotion technique started with fixing the tail, extending the middle section, fixing the head, and releasing the tail. Finally, the middle section was released and repeated the sequence for different movements. The experimental results showed that the proposed design performs in a cohesive soil environment with large forward displacement. A soft manipulator for soil penetration and exploration was designed in [60]. The manipulator consisted of five sections; each section represented a cylindrical pneumatic chamber made of elastic silicons. The robot's sections were fitted to a single braided sleeve to get a continuous motion. The motion working principle depended on the peristaltic wave, which consisted of elongation and shortening sequences. However, the results introduced the acceptable efficiency of robot locomotion in the planer and cohesive environment based on peristaltic wave sequences; the locomotion technique can not be generalized for different environments.

Although the pneumatic-driven actuation delivers many advantages in design, price and payload capability, some designs which depend on tethered actuation may face difficulties in many practical environments. At the same time, the untethered mechanisms suffer from low actuation speed because of the extra components inserted within the robot's body during locomotion. In addition, pneumatically actuated continuum robots suffer from inaccurate control due to complex dynamical modelling resulting from the viscoelastic material.

2.2.2 Hydraulic actuation system

Hydraulic actuation techniques were developed to improve the soft robot efficiency with high torque and heavy payload capabilities. The hydraulic actuation technique provides a fast response with accurate position control than pneumatic actuation [61]. In [62], the Electro-Rheological (ER) valve design for actuating Wormbot-inspired soft robot was presented. The ER is an intelligent fluid transformed to a phase state by applying an appropriate electric field. The robot consisted of multiple soft rubber segments; the actuator position was at the end of each section like the guidance discs in a tendon-driven soft robot structure. Each actuator comprises two ER valves for controlling forward and backward movements. Due to the small size of the ER valves, they could be used in robotic applications. The designed experimental prototype showed that the robot motion based on ER mechanism is technically feasible. The design of three section continuum manipulator based on McKibben water hydraulic artificial muscle (WHAM) was introduced in [63]. Each section consisted of a soft gripper for Swallowing and Disgorging purposes. When the WHAMs of 3-sections were pressurized, the soft griper diameter decreased for grasping an object. The robot can bend by applying pressurized and depressurized sequences of the vertical and horizontal WHAMs. The experimental data showed that the proposed design could grasp an object with a 120 mm diameter and swallow an object with a total length of 500 mm. The robot design is complex and needs high efficient control algorithm to perform manipulation.

Continuum hydraulically driven micro-robot for endovascular surgical operation was presented in [64]. The micro-robot consisted of two parallel cylindrical platforms which were connected to each other by three three hydraulic actuated bellows. while, two spacer disks were used to prevent buckling during bending process. Varying the hydraulic pressure lead to micro-robot bending structure. The differential model-based orientation control which linearizing the reference trajectory into small segments was applied. In [65], multisection hydraulic active catheter based on water pressure through micro valves for surgical purposes was introduced. Each section composed of bellow and micro valve with certain pressure range. For preventing danger of leakage during operation, Physiological saline was used as a driving fluid. Pressure pulse drive was applied to control the bending angle based on providing the pressure in pulses. The experimental results presented that the proposed control algorithm can be applied for multisection robot.

The main disadvantage of hydraulic actuation systems is that they are bulky and exhibit high non-linearity due to the actuators' nonlinear mechanical characteristics and complex geometrical structure.

2.2.3 Magnetic actuation system

Electromagnetic actuators improve the actuation efficiency and wireless control compared to the conventional actuation methods such as pneumatic and hydraulic used in soft robots. Compared to pneumatic, tendon-driven actuation systems, Continuum robots-based magnetic actuation can also be produced in small dimensions.

A soft worm-inspired robot with voice electromagnetic coil actuators was presented in [66]. The robot separated five elastomeric segments; each segment contained one coil, permanent neodymium magnet, and coil power circuit. The coil components could generate 1 Newton force to extend or contract the elastomeric segment. The robot segments were covered and connected to the elastomeric body. Also, the elastomeric body provides friction with the surface and protects the embedded electronic circuits. The test results showed that the designed worm-like robot was robust and easily extended or repaired. In [67], the design and fabrication of inchworm-inspired soft robots were developed. The robot was manufactured based on particle-polymer soft material with electromagnetic actuators in the front leg and back leg. The experiments showed mimicking inchworm crawling motion successfully.

A novel magnetic continuum manipulator for medical applications was presented in [68]. Most continuum manipulators that use magnetic actuation can deform in a C-shape, which is insufficient for a wide range of surgical operations and obstacle avoidance. The proposed design can bend in C, S and J-shapes. The robot consisted of a flexible rubber tube with variable stiffness and two opposite axially-magnetized magnets to simplify the design structure and provide sophisticated deformations. Mobile magnet-based systems controlled the generated magnetic field to enlarge the reachable workspace. However, the experimental results showed that the novel design of the magnetic-based catheter provided dexterity and a wide workspace; the mean robot tip position error was high. Also, the robot needs a sophisticated control algorithm to perform complex deformation. deformation.

2.2.4 SMA actuation system

SMA is a unique alloy that can change its shape when subjected to a specific thermo-mechanical procedure [69] as shown in Table 1. SMA was used in different applications such as aerospace [70] and medical [71]. The position control of SMA is simple and accurate as the applied electrical power is directly converted to mechanical movements.

In [72], a starfish-inspired sot robot was developed. The soft robot structure consisted of five legs made of soft rubber material. SMA actuator was fixed under each robot limb and was used as a driving actuator. The results showed that the robot navigated while avoiding obstacles, crawling, and standing on flat surfaces. In [73], an untethered soft robot with a U-shape SMA actuation mechanism was designed. The SMA actuator had low wight (3 gm) for high-speed applications and is enclosed between thermal-conductive elastomer material, which helped the SMA actuator to carry the driving circuit battery and outline frame. Two untethered sot robot prototypes were implemented; the first one was able to be used in rough and inclined terrains. While the second one is Caterpillar inspired, with the ability to carry a payload of 30 gm. However, the proposed designs were exposed to the risk of overheating at peak speed. Caterpillar-inspired flexible robot was developed in [74]. The soft robot was made of silicone sheet and actuated by series-connected six SMA actuator segments. When the electric current passed through the wire that covered the SMA actuator, the wire heated up, and the SMA actuator was activated. The results showed the successful movement of the robot for one cycle. The one gait movement requires around 3.5 seconds to complete, representing low motion speed in some practical applications.

In [75], a novel S-shape continuum robot with a single actuation structure was presented. The backbone was divided into two parts; the primary backbone consists of four Ni-Ti slices, while the secondary backbone consists of multiple Ni-Ti discs with steel cover. One slice was used for actuation function, and other slices improved the robot rigidity and shape deformation. The Ni-Ti slices pass-through square cutting slots inside the Ni-Ti discs.

SMA actuators overcome the limitations of tendon-driven, Pneumatic, Hydraulic, or dielectric elastomer actuators systems, such as complexity and bulky external hardware. However, the generated displacement from the SMA actuator is small while providing low speed and low torque. In addition, the SMA actuator needs an optimization technique of heating to enhance the actuator performance during tasks. Due to the non-linearity high hysteresis characteristics, SMA requires complex control approaches. Furthermore, the robot designs that use super-elastic Ni-Ti wires or Ni-Ti backbone have low rigidity.

2.2.5 Piezoelectric actuation system

Piezoelectric material is a smart material that provides mechanical strain while subjected to the influence of an electric field [76]. Designers used this feature for its simplicity, compact and simple control as an actuation mechanism for continuum robots.

Continuum robot with an optical fiber rod based on Piezoelectric actuation for micro-scanning applications was designed in [77]. Due to the highly nonlinear system behavior, a 3-D Port Hamiltonian modeling approach based on Cosserat rod dynamical equations was used to derive the dynamic model of the flexible continuum robot. Optical fiber rod and piezoelectric actuator parameters such as stiffness and damping were approximated based on system identification to get an accurate model. Interconnection Damping and Assignment (IDA) and Passivity Based static feedback Controller were applied for tip position control of the optical fiber continuum robot. Experimental results showed that the robot's end-effector tracked the reference trajectory with small errors. The disadvantages of the proposed modeling technique require high computational time due to the complex behavior for modeling and control.

However, piezoelectric actuators provide advantages such as quit, good performance, and compact size. It suffered from a complex dynamic model due to parameter identification, expensive, and high operating voltage.

2.2.6 Electrically polymers actuation system

Electrically Polymers are smart materials that change their shape when exposed to electricity as shown in Table

1. Electrically Polymers Actuator (EPA) has high flexibility with fracture toughness, highly mechanical damping properties, simple composition, low weight, and inexpensive [78]. Here, the most commonly EAP mechanisms that were used as soft robotic actuation systems, dielectric elastomer actuation (DEA), Ionic Polymer–Metal Composite Actuation (IPMCA), and Twisted Coil Polymer (TCP), are summarized as follows:

1) Dielectric elastomer actuator: The main working principle of DEA is like a compliant capacitor in which the elastomer film is sandwiched between two electrodes. The elastomer film expands by applying an electrical voltage between two electrodes while the film thickness decreases [79]. The DEA can return to the original shape when short-circuited.

A soft crawling robot, which was caterpillar inspired, was developed in [80]. The robot body was composed of eight DEA-driven segments. Activating one DEA lead to elongation, and the segment beneath can move up and forward. When DEA reaches full elongation, it discharges and comes in contact with the supporting surface while the second leg is activated to move up and forward. By completing this wave deformation, the robot can easily move forward. Tethered soft robot for climbing different surfaces such as paper, wood, and glass was presented in [81]. The robot combines DEA as a deformable body and electro adhesive copper pads as the robot's feet. The DEA was covered by a flexible frame and sandwiched between two electrodes made of carbon grease. The climbing process was achieved by applying a sinusoidal waveform on the DEA to extend and contract while energizing the feet by a square wave. Experiments showed that the designed robot could climb glass, paper, and wood surfaces while carrying a 10 gm payload. However, the climbing speed was low with a small payload capacity.

Multi-layer soft artificial skin, including DEAs and soft electro adhesives (EAs), was developed in [82]. The electro skin was flexible and stretchable and composed of three main parts, a middle layer of dielectric elastomer material, two electrodes enclosed DEA in between or on one side of the DEA and the encapsulating layer. The designed electro skin was successfully used to gripper the object by activating the EA pair and moving the same object by energizing the middle DEA layer.

The main disadvantages of DEA are current leakage and very high activating voltage, which may lead to electrical breakdown and electromechanical instability [83] while generating small forces [84].

2) Ionic polymer–metal composite actuator (IPMCA): IPMCA results from the doping process of polymers to produce cations and anions which can transfer freely inside the polymer backbone. The advantages of IMPCA are high flexibility, low operating voltage and high conductivity compared to DEA.

In [85,86], a soft artificial muscle that depends on IPMCA for imitating the swimming procedure of Manta ray fish was introduced. The robot consisted of two pectoral fins as a thrust in Manta ray to produce undulatory flapping movement. Each fin consisted of two edges leading edge with IMPCA and trailing edge contain a passive polydimethylsiloxane membrane. When the IMPCA was activated, the trailing edge fall to the leading edge with a phase delay and created an undulatory flapping motion. The test results showed that the developed design successfully generated a swimming robotic manta ray with high tip deflection and a 40° twisting angle. The limitations of IPMCA were low force [87], limited cycle life and rate, sensitivity to oxygen and operation restrictions in aqueous environments [88].

3) Twisted coil polymer actuator: Twisted Coil Polymer (TCP) generated mechanical power when the temperature increased due to the material thermal expansion like SMA actuators. TCP is made of twisted polymer rods; then, the twisted rods were coiled into a helix that is finally annealed to give the required shape. TCP had multiple features that qualify it to become a pioneer actuation mechanism for use in the medical field compared to commonly used actuation methods like tendons, pneumatic, hydraulic, or traditional DEA actuator. TCP is operated simply by resistive heating resulting from applying electrical voltage and can be embedded simply inside the soft material to increase flexibility. Also, it is low-cost with simple components compared to the bulky structure was needed in tendons or fluid actuation techniques. In addition, TCP could detect its shape deformation while changing the applied voltage, which provides self-feedback geometry sensing [89,90]. Moreover, the fabrication process of TCP allows it to expand or shrink while on the other side, SMA can only contract, which leads to an increase in the hosting thickness for adding prestretch actuation [91].

A robotic hand-based super-coiled polymer (SCP) actuation technique was proposed in [92]. The SCP actuator model was approximated by simply combining a parallel connection of spring, damper, and thermal constant. The robotic hand contains four fingers, and a thumb fabricated by using a 3D printer with ABS material. Each finger was actuated independently through the SCP actuator. Three controller algorithms were developed for performance improvement; open-loop compensator control, closed-loop force control, and position control. The test results showed that the SCP actuators produced a large force per weight with a short responding time of 30 ms. Silicone elastomer soft muscle depending on Twisted and Coiled Polymer (TCP) actuation was presented in [93]. In [94,95], a soft gripper with a TCP actuation strategy was developed. The gripper consisted of two soft fingers attached to a rigid base; a single TCP actuator actuated each finger. A general modeling approach was developed, which consisted of a physical-based model for predicting the motion of TCP with given physical parameters and a kinetostatic model for describing the coupling between the actuator and the soft body deformation. The experimental results verified the modeling results while comparing it to the modeling base system identification technique [96], which was limited to the parameters of specific TCP actuator.

The advantages of using TCP are low voltage for actuation compared to DEA actuators, low cost, and safe human-robot interaction. Optimization methodologies should be carried on for the silicon skin thickness, applied voltage, and displacement between TCP rods and the actuation time to improve the actuation efficiency. On the other hand, the cooling process of the TCP actuator requires a longer time as it is inserted inside the soft skin, so designing effective cooling techniques is a mandatory challenge to increase the actuator performance.

2.2.7 Hygroscopic actuator

On the other hand, Hygrobots are inspired by the characteristics of plant cells which are responsive to light, heat, or humidity as shown in Table 1. Hygroscopic characteristics also inspire micro-robots to perform different tasks in the military, industry, and medical applications [97].

In [98], the development of hygrobot continuum robot that actuated depending on the environmental humidity level, was introduced. The robot used a bilayer structure, active hygroscopic nanofibers layer, and inactive hygroscopic layer, which was made by the electrospinning process. Two simple geometry legs were attached to the end of the continuum actuator. The temporal change of humidity caused bending of the actuator structure. Increasing humidity lead to the actuator bending upwards, while decreasing humidity level generated downward bending. Although these robots have promising applications, they face many challenges such as low response and complexity of the dynamic response.

3. COMBINATION OF INTRINSIC AND EXTRINSIC ACTUATION SYSTEMS

Recently, the development of surgical robots has increased dramatically to perform delicate and difficult operations such as MIS and Neurosurgeries [31]. One of the most important surgical robots was *da Vinci* which the surgeon manipulated via teleoperation with the aid of hand motion controllers and a visualization environment

One of the most important surgical robots is *da Vinci* which is manipulated by the surgeon via teleoperation with the aid of hand motion controllers and visualization environment [99]. However, the developed surgical robots provided manipulation dexterity in confined incisions that were controlled directly by the surgeon. There are many significant disadvantages, including the high cost, bulky and rigid parts, and require semi-fully control. This was the motivation for researchers to design and develop continuum robots that combine both intrinsic and extrinsic actuation mechanisms to minimize the system drawbacks and improve the simplicity, adaptability, and robustness.

In [100], a 2-DOF continuum manipulator was developed for endoscopic surgeries. The robot's outer part was a spring that consisted of four steel tendons and four pneumatic cylinders. The backbone was made of super-elastic Ni-Ti to prevent spring compression. The results showed a good position tracking performance. The linear potentiometer computed the position of each cylinder.

Flexible constant curvature of two section catheter for medical purposes was developed in [101]. Each catheter section was driven using two tendons. Actuation force must be applied to the distal tendons that compress or stretch the proximal section depending on the load to bend the distal section. So, a tendon path coupling model for proximal section to distal section. On the other hand, the catheter is a composite of a super-elastic backbone made of Nickel-Titanium (NiTi) material and covered with steel plait for improving tendon constrains. A new design of non-extensible two-bending sections of tendon-driven continuum robotic arm neurosurgery was designed in [102]. The robotic arm composed of two bending sections, each with 1-DOF while controlled by antagonistic pair cables passed through PEEK guidance disks and SMA backbone. The Extended Forward Kinematic Mapping (EFKM) was developed to compute the cable-driven continuum robot's hysteresis action. The experimental results showed that the EFKM enhanced the robot's control accuracy with a small tip position error for neurosurgery application. A novel modular cable-driven continuum manipulator design for MIS was proposed in [103]. The manipulator consisted of an SMA backbone that offered deformation restoring force, three silicon wires connected the distal and proximal guidance discs, and a silicone shell. Experimental results were conducted to validate the proposed geometric kinematic and static models related to shape deformation and the driven force. Also, the workspace range was simulated in two-dimensional plane *XZ* for one section, two section, and three sections besides optimization of the section lengths for enhancing the kinematic performance. In [104], a 3-D polyamide continuum robot for MIS application was driven by springs made of SMA. The main parts of the robot were 2 DOF continuum end-effector with eight guidance discs with distributed 90° driving cables and two helical antagonistic SMA springs connected by routing cables through pulleys. Improvements of the SMA actuators' performance were accomplished by using Joule heating and forced air cooling technique. Model-based open loop control was applied for all experimental trials with a tracking system for detecting the manipulator tip position. Model Predictive Control (MPC) was implemented to overcome the tracking error due to kinematic inaccuracy.

The advantages and disadvantages of the used actuation systems in soft continuum manipulators summarized in Table 2. While the reported design parameters include the robot length, weight, and applied force, and the applications of each soft robot system are presented in Table 3. On the other hand, the weight, size, and control algorithm play a major role in implementing continuum manipulators, especially in medical applications. It can be predicted that continuum manipulators with TCP which represents type of DEA but with low actuation voltage, can become a pioneer in the medical field due to its multiple advantages, including compact size and small weight added to its control simplicity.

4. CONTROL ALGORITHMS FOR CONTINUUM ROBOTS

Due to the compliance behavior and decoupled nonlinearities of soft robots, designing an efficient control algorithm for those robots is challenging to enhance system performance and compensate for the model uncertainties, hysteresis, and interaction forces. Recently, many researchers have paid much attention to reviewing different control strategies of soft continuum robots.

A review of the control algorithms for hydraulically-driven soft robots was presented in [17]. Low-level control, which was divided to pressure control based on differences in actuator compliance, and volume control that supported safe interaction limits, was presented. Control methods of soft robots were introduced in [6], in which they were classified to open-loop and closed-loop model-based controllers. The in-depth survey of control strategies of continuum manipulators was discussed in [28]. The control strategies were divided to model-based static controllers, model-based dynamic controllers and model-free static controllers, and model-free dynamic controllers. In [115], multiple control strategies of one segment pneumatic-driven soft robot were developed. The controller algorithms were divided into kinematic control, Proportional-Derivative (PD) dynamic control, passivity-based control, and adaptive passivity-based control. Kinematic control represents the simplest control form which depends on the error difference of the robot's tip pose trajectory. It is unable to represent the dynamic behavior of the robot. At the same time, PD dynamic control is a model-based control algorithm that depends on dynamic cancellation. Passivity dynamic control added a term to PD-dynamic control to compensate for the model uncertainties. On the other hand, adaptive passivity-based control was developed to compensate for time-varying uncertainties such as stiffness and damping coefficient matrices. A review of the crawling locomotion modes, applications, and control of soft robots was presented in [27]. Most soft crawling robots used open-loop control, while some used model-based and few used feedback controllers and machine learning methods.

On the other hand, machine learning was used as a modeling approach for the system uncertainties and hysteresis or as a control algorithm for soft continuum robots. In [116], a review on different machine learning approaches in modeling and controlling soft robots. This study categorized the machine learning approaches into calibration and characterization methods of sensors and modeling and control of cable-driven actuators, pneumatic-driven actuators, SMA actuators, and EAP actuators.

A brief comparison between actuation mechanisms regarding the total weight, size, and simplicity of the control algorithm is proposed in Table 4.

5. DISCUSSION AND CONCLUSION

In general, designing actuation systems is one of the significant challenges facing soft continuum robots to achieve the desired functions properly. At the same time, the robots' soft material characteristics should not be affected by the mechanical design of the implemented actuation system. The actuation mechanisms of soft continuum robots are mainly divided into intrinsic and extrinsic, based on the implementation method of the actuator itself. The cable-driven actuator is characterized by the design simplicity and adaptability, which qualifies it to work in many applications. In biomedical applications, this actuation technology is preferred as it offers flexibility, reasonable force control, and motion accuracy while maintaining safety by pulling the wires out of the body at any time in the event of a problem inside the body. However, cable-driven actuation suffers from energy losses due to cable friction. Pneumatic and Hydraulic actuation systems are widely used in tasks that require high torque and extensive payload capability. These actuators have no problems performing complex actuation procedures and offering a fast response with accurate position control compared to other actuation methods. However, these actuators suffer from limitations such as bulky size, design complexity, and high nonlinearity, making them difficult to miniaturize. Magnetic actuation offers small dimensional size and wireless control; however, a sophisticated control algorithm is needed to provide complex movements.

The SMA actuators offer simple structure, low noise, accurate positioning, and smooth movements, which qualifies them to be used as a soft robot's actuation mechanism. However, its high non-linearity, hysteresis, low speed, and low torque are not preferred in quick response applications. On the other hand, Piezoelectric actuation has been recently implemented in soft robots due to its simple working principle of converting electrical energy to mechanical deformation. However, the Piezoelectric actuator has good performance, compact size, and low noise; it requires high operating voltage, is expensive, and has

Table 2. Advantages and disadvantages of continuum robot's actuation mechanisms.

Category/Group	Actuation type		Advantages	Disadvantages
Extrinsic actuation	Tendon/Cable [33-35,37-41,43-52,54,105-111]		• Design simplicity • Scalability features • Low cost • Performance can be improved using large motors • Cables provide high friction • Qualifies for use in multiple applications	• Low reachable workspace • High dynamical uncertainties • Low precision control • Bulky mechanism • Lack lifting heavy loads
Intrinsic actuation	Pneumatic [55-60]		• Extensive payload capability • Simple control for providing complex actuation • Easy and inexpensive fabrication	• Low actuation speed • Bulky external hardware • Complex dynamical modelling • Inaccurate control
	Hydraulic [62]		• High Torque • Heavy payload capabilities • Fast response • Precise position control	• Complex geometrical structure • Bulky • High non-linearity
	Magnetic [66-68]		• Simple design • Efficient actuation • Wireless control • Small dimension actuation	• Sophisticated control algorithm • Small actuation movements
	Shape memory alloy (SMA) [72-75,112]		• Simple design • Easy position control	• Small actuation displacement • Low speed • Low torque • Require heat optimization technique • Complex non-linearity • High hysteresis • Sophisticated control for complex movements • Low rigidity • Need prestretch actuation
	Piezoelectric [77]		• Design simplicity • Compact • Simple control	• Highly system non-linearity • Require high operating voltage • Complex system identification
	Electrically polymers	Dielectric elastomer actuator (DEA) [80-82,113]	• Smart material • High flexibility • Fracture toughness • High mechanical damping properties • Simple composition • Low weight	• Large activating potential energy • Current leakage • Electrical Breakdown • Electromagnetic instability • Generate small forces
		Ionic polymer-metal composite [85,86]	• Flexibility • Low operating voltage • High conductivity compared to DEA	• Low generating force • Limited cycle life and rate • Sensitive oxygen • Operation restrictions in aqueous environments
		Twisted coil polymer [92-95,114]	• Simple operation • Low cost • Low actuation voltage • Simple construction • Ability to detect shape deformation • Safe in human-robot interaction applications • Suitable in the medical field • Expand and shrink actuation technique	• Require optimization process for improving actuation efficiency • Longer cooling process due to the actuator construction
	Hygroscopic [98]		• Simple actuation • Used in multiple applications such as industry, military and medicalpurposes	• Low response • Complex control

Table 3. Applications of continuum manipulators with different actuation mechanisms.

Actuation type		Reference No.	Design parameters length, weight	Application	Applied force
Cable-driven		[33]	–	Soft gripper	–
		[34]	310mm		–
		[35]	250 mm 2610 gm		–
		[36]	50 mm		34.3 N
		[37]	Section 1, 100 mm Sections 2 and 3, 14 mm ∼ 70 mm	Search and inspection	4 N ∼ 7 N
		[38]	143 mm		–
		[39]	180 mm 3.58 gm		6.15 N
		[40]	15 mm ∼ 70 mm		$[-20 \quad 20]$ N
		[41]	18 cm		–
		[44]	10 cm		$[0 \quad 70]$ N
		[45]	35 mm	Minimally invasive surgery (MIS)	$[10 \quad 20 \quad 50 \quad 70 \quad 100]$ gm
		[46]	210 mm		$[0 \quad 100]$ N
		[47]	10.5 mm		0.85 kg
		[48]	280 mm		$[0 \quad 70]$ gm
		[49]	100 mm ∼ 200 mm		10 ∼ 50 gm
		[50]	20.5 mm		22 N
		[51]	100 mm		50 gm
		[52]	Supportive continuum robot, 6.1 cm Operative continuum robot, 6.8 cm		–
		[53]	116 mm		$[0 \quad 30 \quad 50 \quad 100 \quad 150]$ gm
		[54]	150 mm		–
Pneumatic		[55]	170 mm	Search and rescue	–
		[56]	650 mm		8 kg
		[57]	420 mm	Pick and place	50 gm
		[58]			
		[59]	65 mm	Soil exploration	–
		[60]	60 mm		–
Hydraulic		[62]	260 mm	Pick and place	–
		[63]	500 mm	Soft gripper	–
Magnetic		[66]	160 mm	Search and inspection	–
		[67]	40 mm		
		[68]	60 mm	Medical catheter	–
SMA		[72]	99.80 mm	Search and inspection	50 gm
		[75]	57.5 mm	MIS	
		[73]	–	Search and inspection	–
		[74]	88.6 mm 17.7 gm	Soft caterpillar	–
Piezoelectric		[77]	50 mm	Medical application (Micro-scanning tasks)	0.5 N
Electric polymer	Dielectric elastomer	[80]	250 mm	Search and inspection	–
		[81]	Foot diameter = 32 mm		10 gm
		[82]	100 mm	Medical app-lication (soft skin)	–
	Ionic polymer–metal composite	[85]	111 mm	Inspection and surveillance	–
		[86]	40 mm		1 – 1.5 gm
	Twisted coil polymer	[92]	100 mm	Medical application (artificial muscle)	50 gm
		[93]	140 mm		–
		[94]	95 mm		50 gm
		[95]	40 mm	Soft gripper	5, 10 gm
	Hygroscopic	[98]	15 mm	Search and inspection	–

Table 4. Comparison between different actuation mechanisms regarding weight, size and control algorithm.

Actuation type	Weight	Size	Control algorithm Simplicity
Cable driven [103,117,118]	High	Large	Simple
Pneumatic [119]	High	Large	Complex
Hydraulic [64,65]	High	Large	Complex
SMA [104]	Low	Compact	Complex
Electrically actuated polymer [120]	Low	Compact	Simple

a complex dynamic model due to its complex parameter identifications. the shape of Shape Memory Alloy is changed when subjected to a specific temperature.

Recently, researchers have developed Electrically Polymer Actuators (EPA), a smart material that modifies their shapes when exposed to electrical energy. EPA is listed as a well-established technology because it has a simple structure, simple operation, high flexibility, and is inexpensive, which qualifies it to be implemented in biomedical applications in the future. Based on the fabrication procedures, EAP is divided into dielectric elastomer actuation (DEA), Ionic Polymer–Metal Composite Actuation (IPMCA), and Twisted Coil Polymer (TCP). However, each EPA type has merits and drawbacks; the TCP provides superior advantages compared to DEA and IMPCA, including simple operation, inexpensive fabrication process, and self-feedback geometry sensing. Finally, the Hygroscopic actuation system is also made of smart material that changes its structure based on climate changes such as temperature, humidity, and light intensity. It can be used in a complex environment, such as in military applications. This actuation system requires many developments due to its weak response and complex control algorithm. Recently, researchers have combined multiple actuation techniques within the same soft continuum robot to minimize the system limitations and enhance flexibility and robustness.

Through the survey carried out in this paper, selecting a specific actuation system mainly depends on the trade-off process between merits, drawbacks, and application type. Also, most actuation mechanisms were implemented and tested only in the laboratory, not in the practical field. Therefore, many developments should be carried out to implement the actuation systems in practical applications. In addition to, the recently implemented actuation technologies, including SMA, Piezoelectric, EPA, and Hygroscopic, are in a growing stage, so they need concentrated development efforts to be used in the practical field.

6. FUTURE DIRECTIONS

Flexible robots represent a promising breakthrough in robotics, especially in medical applications, due to their unique compliance, adaptability, and safety. At the same time, most of the current research directions on soft continuum robots focus on using traditional actuation mechanisms such as cable-driven, pneumatic, hydraulic, and SMA actuators. We believe that the next period of soft robotic research should focus more on combining conventional actuation systems and electrically polymer actuators that present a simple design and safe actuation process.

Researchers recently paid much attention to designing and developing complex control algorithms to perform sophisticated motions while ensuring dexterity and safety. Therefore, it is necessary to search for more efficient and simple techniques to perform complex locomotion by utilizing soft material properties or morphological structures. The morphological specifications allow the robot to change its dynamic behavior based on the soft material characteristics to reduce the controller complexity and perform difficult movements [121-123].

CONFLICT OF INTEREST

The authors declare that there is no competing financial interest or personal relationship that could have appeared to influence the work reported in this paper.

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