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Soft Robots: Implementation, Modeling, and Methods of control

Shahad A.Al-Ibadi[1], Loai A.T.Al-Abeach[2],Mohammed A.Al-Ibadi[3]
[1, 2,3] Department of Computer Engineering, College of Engineering, University of Basrah

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ABSTRACT

Soft robotics is a branch of robotics focusing on technologies with physical features like those of live biological creatures. Additionally, they have many details that are hard, if not impossible, to realize with traditional robots composed of solid materials. This study concentrates on the current expansion of soft pneumatic actuators for modern soft robotics in recent years, emphasizing three areas: Implementation of soft robots, Modeling, and Methods of control systems. Therefore, numerous soft robotic designs and ways to make them suitable for medical, manufacturing, and agricultural applications have been presented. Moreover, functional and technological aspects have been given to review models similar to human hand functionality and motions. To realize the advanced soft robotic manipulation function, robotic hands must be equipped with tactile sensing, which is required to provide continuous data on the volume and direction of forces at all contact locations. The research examines achievements in material science, actuation, sensing techniques, manufacturing technologies, and how to model and control a soft robot's motion, which is scientifically challenging and, more importantly, practical.

Corresponding Author:

Shahad A. Al-Ibadi,
Department of Computer Engineering,
College of Engineering,
University of Basrah.
Email: engpg.shahad.lateef@uobasrah.edu.iq.

1. INTRODUCTION

Robotics is one of the engineering sciences specialized in converting abstract goals into physical actions by delivering power to actuators, controlling actuators, and directing objects toward the target. In robotics, the term soft usually refers to the mechanical compliance of a machine's components. The demand for soft robots has appeared lately because of research on the limits of service robots in navigating natural surroundings.

Currently, robots are becoming increasingly common, revolutionizing the way humans produce goods, perform surgeries, and transport products [1]. The recent development of robotics technology makes robots, called soft robots, like living organisms that don't have skeletons that help humans to work easily. Therefore, researchers developed soft robots that offer additional capabilities; using them in a wide range of applications could be possible compared to classic hard robots. Robots are categorized as soft and rigid based on their compatibility with manufactured materials. Soft robotics is widely studied in academia for its development and implementation in the industrial field [2]. In addition, the characteristics of soft robots have some advantages, such as low cost, lightweight, smoothness, and simple structure. They can also show unprecedented adaptability, sensitivity, and agility [1]. Due to the biological inspiration in soft robotics, the most influential aspect acquired is a bodily movement that can be described with infinite degrees of freedom, leading to adaptation and interaction with non-specific environments [3].

On the other hand, soft robots offer an advantage over rigid robots because they provide less resistance to compressive pressures, allowing them to adapt to impediments. As a result, they can safely transport soft and fragile cargo. They can squeeze through apertures that are narrower than their nominal size by using substantial strain deformation. Soft robotics may securely interact with live creatures and fragile items because of their compliant nature. They can respond to primary actuation inputs to conduct complicated movements, adapt to arbitrary geometries, perform multi-gate propulsion, morph into various forms, and resist massive deformation or impact without harm [4]. Soft robots can be used in many fields, such as medical, industrial, and agricultural. In the biomedical field, as seen in Figures 1 (A) and (B), they can be used for surgery, diagnostics, medication administration, wearable and assistive gadgets, prostheses, artificial organs, tissue-mimicking dynamic simulators for training, and biomechanical research are all examples of biomedical uses [5]. The advantage of soft robot service in this field is the ability to design components to distribute pressure equally over wider contact regions. As a result, soft robots as assistive gadgets are safe to engage with and interface with humans [6] [7].

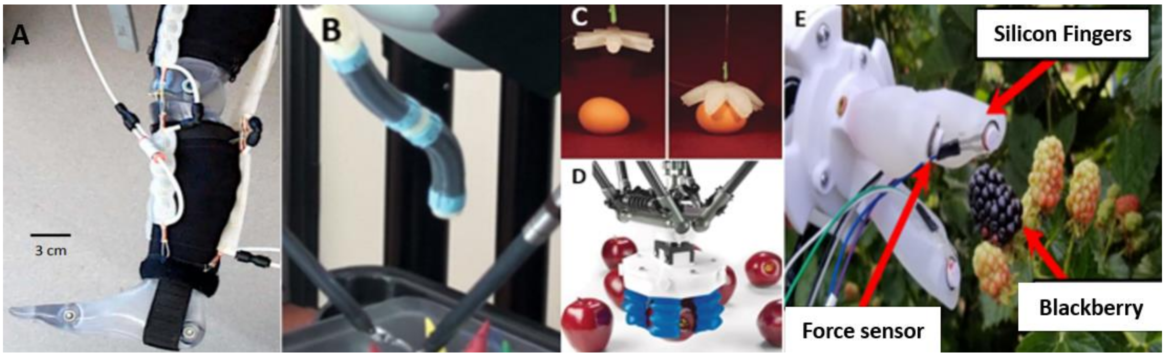

Figure 1. (A) prostheses [8]; (B) soft robots for surgery [7]; (C) Soft Robotic for food picking and placing [9]; (D) Soft robotics in the agricultural field [10] and (E) Soft Robotic for Harvesting Berry [11]

Up to now, many researchers have made soft components successfully that have developed soft robotics for several industrial applications, as shown in Figures 1 (C) and (D), taking into account the sizes and weights of the things without giving up the most important characteristics that distinguish soft actuators. Also, a soft robotic gripper has been proposed as a unique tendon-driven with active contact force feedback control that gently uses the gripper's passive compliance to harvest blackberries, as shown in Figure 1(E) [12]. Soft robotics produces a lightweight robot with highly adaptable utilize materials' compliance flexibility, which are flexible robot manipulators that enable secure interactions with surroundings and other objects. Therefore, the development of soft manipulators depends heavily on the material selection and fabrication techniques utilized in the construction.

Flexible manipulators consume less power, use fewer actuators, are simpler to transport and maneuver, cost less overall, and have a higher payload-to-robot weight ratio than rigid robots; these robots can be used for a variety of tasks, including simple pick-and-place operations for industrial robots, microsurgery, maintaining nuclear facilities, and space robotics [13]. A wide range of literature on flexible robotic manipulators deals with various aspects of these mechanical systems' dynamic analysis and control [14]–[16]. The system's dynamics are non-linear and complex because it is flexible [17]. Some issues with flexible manipulators are the problems brought on by a lack of sensors, vibration brought on by the system's flexibility, inaccurate location estimation, and the challenge of obtaining a correct model for the system. Furthermore, tests have shown that modifications in the flexible manipulator's payload have a considerable impact on the dynamic behavior of the manipulator, adding to the complexity of the problem [13]. Accurate models and effective controllers must be created if the benefits of lightness are to be preserved. The soft robot uses pneumatics or hydraulics to move their bodies. In addition, many researchers have added electroactive polymers to use in its movement [3].

The pneumatic actuators are the most dominant because they can realize high actuation strength, similar to a natural muscle. Further, they are highly versatile, allowing them to attain varied actuation modes [18]. In addition, soft robotics can be made of various materials, such as silicon rubber, to improve flexibility and variable stiffness [19]. Due to advances in additive manufacturing technology, soft robots may be designed, molded, and manufactured relatively easily through a wide range of materials. As a result, the materials chosen for soft robots and their production procedures have specific distinct characteristics, which have been addressed in this article [20].

In 1950, the PAMs were developed and known as the name McKibben Artificial Muscles, and it has been used in artificial limbs [21]. Additionally, Darwin G. Caldwell was the first person that calls these types of muscles "Pneumatic Muscle Actuators (PMA)" [22]. McKibben muscles (PMA) can be constructed by using a rubber cylinder surrounded by a braided shell that is responsible for the shape of the muscle to be a contractor or extensor like Walker's [17], [18]. The designed PMA was closed on both sides using two plates; one was used to insert air pressure, and the second was closed entirely. Due to soft robots' near-infinite degrees of freedom, they offer difficulties with accurate modeling and controls. As a result, developing accurate mathematical or numerical models of these robots is critical for analyzing and optimizing their design [19]. Therefore, the reason for deriving the mathematical model is to describe relationships between (pulling force, length of the actuator, air pressure, diameter, and material properties); these relationships are most important when using (PMA) actuators to control the overall function. However, the most common mathematical models are the Geometrical Model of PMA, the Phenomenological Biomimetic/Biomechanical Model, the Mathematical model of the curved PMA, and the Empirical Model of PMA) [20]. The behavior of such actuators improves strong non-linear force-length characteristics, which makes such actuators challenging to control [18]. To deal with the non-linearity of the soft actuators, they have been handled in many different methods such as the Proportional-Integral-Derivative (PID) [23], [24], Fuzzy [25], Neural-fuzzy [26], Model Predictive Controller (MPC) [27], etc.

Additionally, many assumptions must be made throughout the dynamic modeling process because some of the system's physical properties are unavailable because of uncertainties, which is typical for a real system. One of the future control strategies for dealing with a complicated, highly nonlinear system with uncertainty can be created using an intelligent control approach. These include fuzzy logic control, neural network control, and hybrid proportional-derivative [28], and the search is still proceeding to discover a more accurate and adaptive controller.

Integration in soft robotics is done by developing secure grasping with safety interaction; an essential part is "The soft gripper," which is joined with soft robots to interact with the environment for catching, handling, or processing as "The pick and place strategy" to be used in industrial applications and almost all the task depends upon it. Hence, researchers have dedicated considerable work to developing variable stiffness grippers, which are critical for achieving dexterous and safe actions. Consequently, recent research performed variable stiffness functionality to show how to improve the quality of adaptive grasping [29] and contains some critical categories in soft robotics like modeling, materials and construction, control systems, and sensors.

Soft-robotic systems have different kinematics and dynamics than traditional robotic systems because they lack a rigid structure. Thus, kinematic, dynamic, and new static models for the soft-robotic system have been established [3]. Designers use piecewise constant curvature (PCC) to simulate the kinematics of soft robotics [30]. The properties of the actuation system and the geometry of the robot's body are investigated and integrated into approaches to link the actuation and configuration spaces [23]. Two examples of forward kinematics-based strategies include applying the Bernoulli-Euler beam theory to forecast deformation and a link between joint variables and curvature arc parameters of high and medium-pressure robots.[31]. Existing inverse-kinematics solutions do not consider the end effector's position because of the limited computation; avoiding autonomous barriers and moving in a constrained area might be problematic [32]. Task-space planning algorithms that allow detailed tasks like moves in tight spaces and grabbing or putting things are challenging to implement without considering the whole robot body, including the end effector [33].

Soft robotics is such a complicated area that a field review is required to offer novices a quick introduction to the field. Due to the volume of new research being produced, keeping up with current events is challenging. This project aims to provide a solid foundation for others to use as a springboard for their independent research in soft robotics. Experienced researchers can quickly utilize this article to identify relevant research for their tasks. This study indexes the research as tables. Each table details each aspect of the soft robots integration in terms of construction, modeling, interaction with the external environment by founding sensors, and the control system and ability to adapt a strategy to external disturbances. As a result, this study is the first goal of the ongoing thesis, which is to develop a soft robot end-effector.

On the other hand, one of the outcomes of the thesis was the study of the properties of pneumatic muscle actuators to create a mathematical model for the functioning of these actuators [74]. When powered by pneumatic muscle actuators, this end effector produces physically supple end effects allowing secure contact with people. An adaptive controller was used to control the behavior of this soft robot end effector.

2. CONSTRUCTION OF SOFT ROBOTS

Recently, soft robotics advancement of technology has been increased through improved soft robotics design and construction. Silicone rubber has been used as the initial material of soft robotics construction [34]; it shapes into molds to fabricate soft robotic actuators. Many researchers used different materials in construction, such as 3D printed actuators, and they proposed a method of using multiple small actuators stronger than an oversized induvial actuator [35]. Soft robotic fingers have been employed depending on two materials Shape Memory Polymer (SMP) and conductive elastomer Thermoplastic Polyurethane (TPU), to control the variable stiffness and position feedback [36].

The researcher used TPU for conductive, which was acquired from piezoresistive materials and SMP filament as a base; piezoresistive material has high sensitivity, flexibility, stretchability, and formability. Soft grippers have been developed into two types of monolithic Ninja Flex material that have been used to make a soft gripper [2]. Low-Melting Point Alloy (LMPA) has been used as a stiffening layer that achieves the stiffing performance and motion of the design [30] and performs their design's stiffing performance and movement.

In Figure 2 (A) below, silicone rubber material of "soft pneumatic actuators (SPAs)" [34] has been designed to demonstrate the change in the curvature (bending SPA) or angular displacement (rotary SPA), and some 3D printing samples materials are shown in Figure 2 (B) and (C). Table 1. below illustrates a comparison between all the used materials in constructing soft robots and lists the features and advantages of each type.

Future soft bioinspired robots will be able to adapt and develop, be made of recyclable, biodegradable, or biohybrid materials, and use renewable energy sources without disrupting the energy balance of natural ecosystems.

Table 1. Comparison between all Soft Robotics Materials

Materials	Features	Advantage	Construction	References
Silicon Rubber	Stretchable, flexible, and soft	High bending torque	Soft variable stiffness actuators	[23];[31]
Conductive TPU elastomer	Safety protection and professional waterproof	Control variable stiffness and position feedback	Soft variable stiffness Gripper finger	[12]
Shape Memory Polymer (SMP)	It can change shape and returns to its original shape permanent shape.	Recovery temperature can be adjusted	Soft variable stiffness gripper finger	[36]
NinjaFlex	Abrasion and chemical resistance	Flexible, high DOF, and strong	Soft variable stiffness gripper	[2]
Low-Melting Point Alloy (LMPA)	Lightweight	Achieve controllability and variable stiffness	Soft gripper finger	[30]
Food Grade Silicon	Flexible, resistant, and safety	Provide greater stiffness, and withstand a maximum pressure of about 17 Kpa	Four Finger Soft Gripper	[38]
Shape Memory Alloy (SMA)	Large life cycle, low noise, and low driving voltage	Transform the coiling and heating	The wire inside the gripper fingers	[40]
Paraffin	Hard at room temperature degree, begins softly when the temperature degree reaches 37	Have the ability to conform to the object's shape and return to its original shape.	Three-finger variable stiffness grippers	[37]
Nylon	Cheap, economical, efficient, and flexible artificial muscle	Provide contraction overheating	Variable stiffness actuators	[41]
Nickle wire and iron wire	Sensitivity to temperature measurement	Heating and sensing media for artificial muscle	Variable stiffness actuators	[41]
Silicon Rubber with nylon mesh (PMA)	Cheap, and ability to change shape, and returns to its original shape	• Champer, flexible, and manipulation role. • Nylon mesh: bidirectional motion to ensure extract or contact	Variable stiffness continuum actuators	[34];[42];[43]
Polyethylene dielectric elastomer actuator (DEA)	Economical, high bending	• Low co-efficient of friction. • Good fatigue and wear resistance	Gripper binding	[44]
Fiber-reinforced	• Melting points below 300 Deg. C. • Enhances the ability to withstand freezing and thawing	• Changes its shape from solid to liquid • Have a greater range of motion and are more durable	Soft Pneumatic Actuators	[45] [39];[40]

Figure 2. (A) The silicone rubber material of “soft pneumatic actuators (SPAs)” [37], (B) and (C) Samples of 3D printing of SMP and conductive TPU elastomer [38]

3. SOFT ROBOT SENSORS

A sensor is a device that receives different types of inputs, such as physical, chemical, or biological inputs, and converts them into an electrical signal. It is used as a measurement device to give feedback signals to the control system and monitor its performance. In addition, much research has focused on creating low-cost, manufactured sensors that can be combined into flexible applications like the properties of soft robotics, stretching, and deformation without compromising their ability, as shown in Figure 3 [34]. Sensors are categorized into many categories based on their uses, input signal, switching mechanism, and properties of sensor materials, such as cost, quality, and range [33]. Most reviews have appeared around the sensing by touching process, where the resistive sensing technique is still a better choice [38]. In addition, there are other sensing techniques, such as piezoelectric, capacitive, optical, and organic field-effect transistors (OFETs). The resistive sensing technique has been classified into five methods: Stain gauge, piezoelectric, Conductive Polymers and Fabrics, conductive Elastomer Composites, and Conductive Fluids [46]. A strain gauge sensor has been used as an elastic that was incredibly sophisticated for curved surfaces [47]. Arrays of 32 nickel-chromium (NiCr) have been created in a polyimide layer to produce strain gauges with a total area of 55 mm x 65 mm. Authors attained a more extensive sensitivity range by putting thick polyimide layers (80 μm) to the strain gauge instead of previously published NiCr strain gauges on polyimide [38]. The sensor chip molded has been made into a fingertip-shaped polyurethane hemisphere. Both pushing (vertical) and sliding (horizontal) are measured with excellent precision by the authors [42]. Tactile array sensors, including 3x3 sensing elements, have been fabricated and detected stress distribution applied at the tactile sensor surface [43]. Artificial hollowed fibers have been combined with traditional cotton yarn to create a rectangular-shaped tactile sensor, similar to cloth. The sensor can detect a contact force by monitoring changes in capacitance at all junction locations of the artificial hollow fibers [48]. Two types of tactile sensors have been described using optical fiber sensors. The first sensor used a fiber Bragg grating (FBG) sensor. A spectral component at the Bragg wavelength is reflected by a Bragg grating etched in an optical fiber. A shift in the reflected wavelength can detect external force in this sensor. The second tactile sensor uses microlending optical fiber (MBOF) sensors. The micro-bending of the optical fiber causes light transmission loss from the optical fiber. This sensor may also sense external force via light loss [49]. A flexible sensor's capacitance varies in response to normal force (due to the armature approach). Between the grid-like aluminum electrodes, they utilize a flexible polyimide sheet as a support and an elastic dielectric layer. Even though the paper does not discuss sensor performance under bending, following a preliminary calibration step, this sensor might be utilized for bending analysis [50]. Pritchard et al. proposed a capacitive sensor array that can be made directly on thin polyimide sheets with thicknesses as low as 25 micrometers. Each capacitive sensor comprises two circular evaporated gold plates with a perylene dielectric layer inside. The sensors have a linear reaction to applied pressure, with output between 0.02 and 0.04 pico Farad for an applied pressure of 700 kPa when arrays of 5 sensors with 500 μm diameter and 1 mm pitch are used [38]. Table 2. Below is a comparison between some sensing techniques and sensor types used in constructing soft robots and each type's materials, advantages, and functions.

Figure 3. (A) Optical fiber sensors [38]; (B) A piece of canvas with silicon skin sewn [38]; (C) pressure sensor (D) A liquid metal embedded elastomer curvature sensor [51]; (E) Force flex sensor; and (F) potentiometer sensor

Table 2. Comparison between some sensing techniques and sensor types, with a list of the materials, advantages, and functions of each type

Sensing technique	Sensor type	Material	Characteristics	Function	References
Strain gauge	Force sensor	Chips of aluminum or stainless steel	High sensitivity and small size	Get a good approximation of the robotic finger’s stiffness	[52]
Piezoresistive	Force sensor	Germanium and silicon	Soft material and high resolution	Increased efficiency in grasping	[43]
Capacitive	Force sensor	Copper, indium tin oxide	Independent of temperature and well fabrication technique	Possible usage in a large area	[41];[54]
Conductive polymer	Force sensor	Polymer	Stretchable, sensitive, and 3D sensing	Detect force weight.	[55]
Strain gauge	Pressure sensor	Silicon, thin-film, and bonded metal foil	Lower current/power consumption	Detect air pressure flow and convert it to data	[56];[52]
Conductive elastomer	Pressure sensor	Elastomer	Stretchable and flexible	Good candidates for applying on a curve	[58]
Conductive fluid	Pressure sensor	Gold or nickel-copper, carbon	Embedded and sensitivity	Electrical component protection	[59]
Optical	Pressure sensor	Plastic optical fiber	Stretchable and high speed	Used for high-speed transformation signals	[48];[49]
Strain gauge	Linear potentiometers	Graphite, resistance wire, and aceramic/metal	Very good insensitivity and high accuracy	Measure displacement in contrast with for 4ce	[60]
Piezoresistive	Position sensor	Carbon, resistance wire, or piezoresistive material	The main advantage is the simplicity to utilize	Used for complex tasks and used to index measurement	[61]
Optical	IR sensor	BK7 and sapphire	Low power	Motion detection	[62];
Strain gauge	Nickel and iron wires	Nickel and iron	Heating and sensing	Heating the single artificial muscle fiber	[64]
Strain gauge	EGaIn sensor	An elastic rubber matrix containing liquid metal channels	The sensor could withstand 300 percent strain without fail	It uses applied strains to determine the joint angle.	[65]

The future direction of recent developments in the medical and industrial robot field leads to assumptions, especially about the future sensors. Distributed sensing will enable the more autonomous or intelligent use of soft grippers by allowing the sensors of the soft robots to not only sense contact or closeness to an object but also to gather a wide variety of information about the object and act on it. The sensors must be either flexible, soft, or tiny concerning the gripper's size so that their integration does not affect its overall compliance.

4. MODELING OF SOFT ROBOTS

In the first few years of the soft robotics era, many researchers published articles regarding PMA's mathematical modeling. Such a model aims to correlate the pneumatic actuator's length and pressure to the force it exerts throughout its axis [29]. Pulling power, actuator length, air pressure, diameter, and material properties all play a role in the dynamical behavior of the PMA, which is why mathematical models are used to characterize the relations between these factors. During the stages of actuation of PMA, it is not easy to measure these parameters due to PMA's characteristics of the used materials. Therefore, models have been suggested to describe PMA behavior. The relationship between displacement, the influencing force on the PMA, and air pressure applied inside the muscle have been calculated. The Chou and Hannaford and Tondu and Lopez models have been widely used [21] [66]. The model proposed by Chou and Hannaford is a simple geometric model for the static performance of a PMA, assuming the PMA form is cylindrical.

Table 3. Common types of modeling of the PMA with advantages and disadvantages

PMAs model type	Advantage	Disadvantages	References
Geometrical Model of PMA	The simplest approaches for static PMA performance	Due to the contraction of the muscle has got a conic shape; therefore, it is not achieved a cylindrical shape	[21];[66]
Experimental modeling	Express the stiffness and hysteresis of the muscle	Depending on physical parameters and variables	[74]
Empirical Model of PMA	Exhibit similar behavior of PMAs	Doesn't demonstrate hysteresis of the muscle	[29];[71]
Mathematical of the curved PMA model (Beam model and Membrane model)	Govern the mobility of the curved PMAs	Complicated approaches for PMA performance	[72]
Bouc-Wen model	Correctly presented for nonlinear hysteric behavior of PMA, and It can fit the load-displacement curve well	Force deprivation can only be modeled if displacement is the input function	[73]
Constant curvature model	A useful tool for describing the kinematics and dynamics of soft robots	Many issues limit their range of applicability in their three-dimensional formulation, such as discontinuities and singularities, which primarily affect the robot's straight configuration	[23];[75]
The Cosserat rod model	A robust continuum-based approach for simulating rod behavior under a wide variety of external stimuli and situations	It is limited to modeling slender	[76]
Piecewise constant curvature (PCC)	Define the shape of soft actuators and the variables of deformation	It is limited accuracy in adaptive control	[77]

Another geometrical model uses a comparable geometric explanation of the muscle, assuming the mesh material's inextensibility and angle changes during the changing of PMA length due to actuation pressure [67], [68]. Furthermore, When the contractor is under pressure, the PMA is distributed in a circular direction, resulting in a forced decrease in the longitudinal direction. Phenomenology has described the model carefully by describing the dynamics of PMAs using a model containing three elements [69]. The PMA changes length (contracted) due to the change of the pressure inside the muscle; the maximum of the contracted length is called unstretched length [70]. In addition, the PMA changes its shape or tends to increase its length due to the pulling force exerted on the muscle. The process presents spring expansion; therefore, the mathematical formula of the spring is applied. A pressurized PMA is modeled as a long, slender element loaded in a single plane whose behavior is governed by elasticity and buckling in the beam model [71]. The beam model assumes that the sleeve can only bear extensional stresses. To develop a moment-curvature connection for the pressurized beam, the beam model calculates the extent of the wrinkled part of the beam and adds the extensional stress findings over the tensioned, unwrinkled component of the beam. The membrane model uses a variation notion to relate the applied bending moment, the force applied at the ends of the curved PMA, and the curved angle of the pressurized curved PMA [72]. The Bouc-Wen hysteresis model is proposed and experimentally confirmed for extending PMAs; unlike prior models that were only capable of contracting PMAs, this model is capable of both contraction and extension PMAs. The model employs three parameters (Pressure, Displacement, and Force) to simulate hysteric activity. As a result, the entire model is simplified, simulations are faster, and direct control via pressure input is possible [73]. Contractor and Extensor muscle actuators are two types of McKibben's muscles that were experimentally evaluated for their mechanical behavior and performance. This mathematical model study compares and empirically tests the characteristics of the two types [74]. Finding techniques and adaptive models that are computationally practical and accurate to experimental values is one of the most significant challenges facing soft robotics in the future. Different common types of modeling of the soft actuators are demonstrated in Table 3.

5. CONTROL TECHNIQUES USED WITH SOFT ROBOTIC SYSTEMS

Controlling soft robotics is still an exciting task objective. Articulated soft robots' dynamics are nonlinear, resulting in hysteresis, bandwidth reduction, and delay. As a result, having a precise and dependable dynamic model is a complex challenge that can significantly impact the efficacy of model-based control strategies. Control systems have been improved for pneumatic systems that actuate soft robots [78]. Therefore, open or closed-loop controllers are proposed to control pneumatic actuators [69]. The open or closed-loop controllers are preferable depending on applying the complete process of controlling soft robotics. There have been a lot of studies that indicate the benefits and drawbacks of both open and closed-loop control systems. However, the most contentious aspect was whether or not the loops were linked with a feedback mechanism [79]. The closed-loop control system has employed sensors to supply a responsive signal that describes the actuators' actuation condition and their relation with the surrounding environment. When the environment or objective is differing or uncertain, closed-loop control becomes a necessity, just like a freed permit robot over an unknown area or an end-effector that will pick up objects of various volumes and forms. For example, the closed-loop controller is divided into two levels; the first is feedback, which regulates the state of deformation of individual actuators, as shown in Figure 4 (A) [81]. One of the most often used closed-loop control systems is the Finite Element Method (FEM), as demonstrated in Figure (4 B). Soft actuators allow continuous material deformation in all directions, whereas FEM is predicated on describing the robot as separated components. FEM is commonly used to describe all actuator systems; the implementation approach and simulation settings are varied. Improving the precision of FEM models requires including the pertinent physics of the system in the equations controlling the conduct of each node [82],[83].

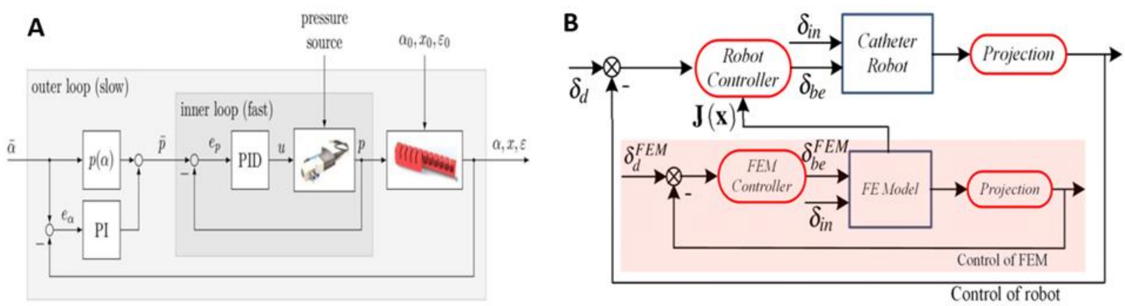

Figure 4. (A) Position control of closed-loop control system [81] and (B) Decoupled closed-loop bending control framework for catheter robot through contact [82]

In the subject of soft robotics, the term "autonomous" is used to describe systems that can run without the usage of an external power source or control system, also known as onboard control [84]. To separate from the idea of autonomous control systems, in which the controller possesses its own "brain" that works to adjust, foresee, and model. In this regard, independent control may be viewed as an improvement over the control techniques previously mentioned—both the open-loop and closed-loop control systems converted to autonomous control systems [85]. In soft robotics, nonlinear model-based control approaches are widespread. Nevertheless, the extremely complex and nonlinear models required for a soft robotic system make this technique difficult, and it looks to have reached its limit in the presence of soft robots. As a result, various methods that appear more beneficial in this situation have been used, such as control algorithms based on learning, the bang-bang control of the model-free method, control algorithms inspired by neuroscience, or morphological computation [87]. These techniques broaden the scope of the famous model-based method. Recently, several researchers have focused on soft robot dynamic modeling and control, building on existing methods based on second-order dynamics, or statics, and “model predictive control” (MPC), which uses fundamental combined parameters. In addition, researchers can get intermediate steady-states by using classic feed-forward control that is not easily reachable when that begins voltage profile above the pull-in threshold and then declines [78]. Certain study instances of electro-ribbon actuators are promising in soft robotics but difficult to control because of pull-in unsteadiness. There is a relatively small contraction range for feedforward control: Suphapol Diteesawat et al. have handled minor contractions below the pull-in voltage threshold and complete contractions [89]. An alternative perspective demonstrates how we might acquire helpful information from soft-arm compliant behavior. Using a controller and static model, Chen et al. used the state change model property to reduce sensor reliance, better understand the environment, and enhance high-level control tactics [90]. The dynamic model has been used as a model of approximation to create closed-loop task-space dynamic controllers for soft robots and is a powerful tool for simplifying feedback of sensory processes and planning while having little implications on controller accuracy [91].

Furthermore, a unique model has been provided with continuous joint soft robot dynamic model formulation that is more accurate than earlier models while remaining tractable for quick MPC. This model is based on the “Piecewise Constant Curvature” (PCC) assumption and a new kinematic representation that enables computationally efficient state prediction [77]. A generalized numerical technique has been presented based simply on geometrical inputs tailored to the desired actuator. It is used to quickly estimate its force-contraction profile for any set of variable geometrical parameters [92]. Another option to reconsider the fundamental method in robot control is to move from model-based to model-free techniques. Nonlinear PID controller and neural network have been merged to get better control performance of PAM [93]. However, controlling soft robots is discussed by noting that most typical robotic control methods, for example, high-gain robust control, feedback linearization, backstepping, and active impedance control, effectively combat or even entirely cancel the system's physical dynamics, replacing them with the desired model. This negates the objective of requiring bodily conformity in the first place [94]. Other works go into the sensing significance and its role in control. A sensor has been integrated into the fiber-reinforced actuator inertial measurement unit (IMU) and pressure sensing) to correlate it with PCC modeling and control loop closures on pressure and chamber lengths [95]. Sensing is also addressed, with locations for length sensors on a soft-linked robot joint and configuration estimation recommended, all while reducing errors [96].

This group of control methods sheds light on various modern robotic modeling and control methods. It demonstrates how the field's lively and productive scientific community approaches significant scientific problems, identifies unsolved scientific challenges, and offers intriguing research and growth potential. To demonstrate different kinds of control techniques used for soft robotics to be a springboard for researchers, see Table 4 below.

Table 4. Types of control methods, strength, and limitations of different types which are used in controlling the soft robotics systems

Control technique	Strength	Limitation	Design	References
Proportional Integral Derivative (PID) – Close Loop	Better controller where the details of the process cannot be modeled. Therefore, lead to a responsible solution when turned into most situations	Stable, optimal, and not dependent	Soft Gripper	[23]
Active Disturbance Rejection Control (ADRC)	The ADRC's settings are adjusted using fuzzy adaptive theory	The control algorithm can control the soft arm's stiffness and position	A novel soft arm	[25]
Model Predictive Controller (MPC) controller-autonomous control system.	Operate successfully with the actual actuator's modest restrictions.	A complex algorithm needs a longer time compared to the other controller.	Soft robot	[27]

Control technique	Strength	Limitation	Design	References
A strategy combining a dynamic spiral algorithm (SDA) and a bacterial foraging algorithm (BFA)	It achieves a faster convergence speed and a more accurate solution, and it tracks the desired system response very well	A slow convergence rate is the primary deficiency of BFA. On the contrary, SDA has a faster convergence rate	Flexible robot manipulator	[28]
Control of the Gait Pattern Generator-close-loop	Using this gait pattern generator, the robot can master arbitrary obstacle courses	The joint space of the robot was reduced from nine to two dimensions	Soft robot	[81]
Control Architecture	The control is concerned with dynamic inversion and trajectory-tracking issues	It allows the system to be controlled with a smaller number of variables	Soft robot	[89]
Model Reference Predictive Adaptive control (MRPAC) close loop control	Using the close loop control methods to demonstrate a model reference predictively	appear resistant to model uncertainty	Electro-Ribbon Actuators	[78]
First-Order Dynamic Control	For nonredundant scenarios, making path planning easier. Additionally, the simplicity reduces the sensory requirements for closed-loop dynamic control	We'll employ machine learning technologies to validate our modeling assumptions and construct our controller.	soft manipulator	[92]
Nonlinear PID Control and neural network	It was an online control with a simple structure, better dynamic features, and robustness.	It is appropriate for a kind of plant like the PAM manipulator.	Pneumatic Artificial Muscle	[94]
Fuzzy Active Disturbance Rejection Control (FADRC)	Controlling efficiency, position, and stiffness with adaptability	The FADRC was found to be superior to the PID in terms of response and tracking error to the intended value	Soft robot	[93]
Low-Level Control	Appropriate for estimating the state variables of the actuators	In the verification of the restructuring model, a mean inaccuracy of error of 4.1 mm with a standard deviation of 0.9 mm results from the camera data for a sinusoidal signal	Soft pneumatic actuators	[96]
Model-Based Reinforcement Learning - Closed Loop	Higher variability in the trajectories and reaching time	It does not impart any insights into the relationship between manipulator design and dynamics	Soft robotic manipulators	[99]
An echo state Gaussian process-based nonlinear model predictive control (ESGP-NMPC)	Realize high-precision PMA control as well as a certain level of load robustness.	Used to describe and measure nonlinear systems	Pneumatic Muscle Actuators	[100]
Neural network fuzzy sliding mode control	achieves fast, accurate, and consistent performance tracking sinusoidal reference trajectories up to 1 Hz in frequency	Careful and consistent execution tracking sinusoidal signal trajectories up to 1 Hz	Pneumatic Muscle Actuators	[101]

Control technique	Strength	Limitation	Design	References
Real-Time FEM Model Control Open Loop	Stability is not essential and is less expensive than a closed-loop system. It May be used if the output cannot be measured	Changes in the system cause errors	Inflatable soft jumper, soft robot	[100]
Switch Control Open loop.	The set point was reached in less time without excessive overshoot.	A common difficulty is a sensitivity to modeling the error	Soft wall-climbing robots	[103]
Model-Based Dynamic Control (MBDC) Closed Loop.	Have the ability to get the most out of the system, higher resilience, the capacity to offer physical insight into system performance, improved cost efficiency, and a shorter time-to-market.	The process is used as a comprehensive approach to standard embedded and systems development, which is a significant disadvantage	Pneumatic muscle	[100]
Radial Basis Function Network (RBFN)	The one-link trajectory and two-link robotic manipulators are predefined, Nonlinearity, Complexity with afixed structure	Complex system	Soft robot	[101]
Modified input shaping (MIS) with PD feedback law	Robustness and multimode vibration suppression	The length of an MIS shaper is shorter than that of a corresponding TIS shaper while both shapers have the same ability of vibration suppression	single-link flexible manipulator	[102]
Data-based PID control	Ability to produce better control accuracy	The updated tuning variable must enhance to adapt to the variation of the objective function during the tuning process	Flexible joint robot	[107]
Sliding Mode Control (SMC) based on a cascaded PID control	Fast trajectory tracking, good vibration attenuation properties, and good dynamic performance employing the combined SMC based on a cascaded PID with Multiple Positive Position Feedback (MPPF) vibration control.	Complex Control System	Flexible-link robots	[108]

Future soft robots with built-in artificial intelligence can develop into autonomous adaptive systems. However, adaptive control is required to compensate for the model's inadequate system approximation. Describe an adaptive control approach that works with model predictive control to enhance control performance. After receiving modified dynamic parameters from the adaptive controller, the optimizer then produces inputs for the system that consider all of this information.

6. CONCLUSION

In this article, we presented the study of the soft robot actuator characteristics and control methods. Keeping up with the latest developments is difficult because so many new studies are being done on soft robots. This investigation aims to offer a strong foundation that others can use as a starting point for their independent investigations into the complicated field of soft robotics. This article can help seasoned researchers quickly find a pertinent study for their tasks. Through the review, researchers can get easy solutions to challenging or time-consuming to choose materials without requiring experience in materials science and mechanical engineering to assist them.

Consequently, the ongoing thesis, which created a soft robot end-effector, has this study as its first objective. The study of the characteristics of pneumatic muscle actuators (PMA), on the other hand, was one of the results of the thesis and helped to develop a mathematical model for how these actuators work. Materials that can be catalyzed pneumatically, hydraulically, and electrically responsive to pressure differentials and chemicals have been viewed. Consequently, developing soft muscle-like actuation technology is one of the biggest obstacles in creating completely soft-bodied robots that can move, deform and adjust body stiffness. Therefore, soft technologies help develop robots capable of significant interaction with human users in their environment. As a result, soft technologies aid in developing robots capable of meaningful contact with human users in their surroundings. The robot adapts its shape and function to unknown or uncertain geometric objects and serves as the foundation for unique control and planning algorithms for soft robotics. We demonstrated how gentle actuator techniques, algorithms, detectors, and models affect the implementation path of a soft robot system with beneficial constructing control techniques in that field.

Future directions of recent developments in the flexibility of soft robotics in the medical and industrial robot field lead to assumptions about the future outlook of soft robotics, especially the future sensors and control approaches. Soft robot technologies can be used not only as end effectors but also as a way to actuate the entire body as the field of soft robotics develops. The active materials, processing methods, gripper architectures, distributed sensors, control methods, and local information processing must be improved to address critical challenges in soft robots. In addition, it will become possible to use a wide range of applications for soft robotics in manufacturing, haptics, drug delivery, or even object manipulation in space. Distributed sensing will enable the more autonomous or intelligent use of soft grippers by allowing the sensors of the soft robots to not only sense contact or closeness to an object but also to gather a wide variety of information about the object and act on it. The sensors must be either flexible or soft; however, if they are rigid (such as Micro-Electro-Mechanical System (MEMS), silicon-based inertial measurement units (IMUs), or thermal sensors), they must be so small concerning the gripper's size that their integration does not affect the gripper's overall compliance or, at the very least, does not affect the compliance of critical contact points. Control accuracy is becoming increasingly crucial as plants become more complex to obtain acceptable control performance. Therefore, controlling the shape and motion of soft robots are problems that must be addressed rigorously. The hysteresis and disturbance of the soft robotic must be considered. Appropriate model order reduction and efficient solution strategies may result in rapid but accurate dynamic models that are helpful for control. Inverse dynamics models will be important in creating trustworthy soft robot feedforward control systems. Future soft robots with provided artificial intelligence can be progressed into self-contained navigation (surveillance of difficult-to-reach areas, rescue missions in disaster zones, etc.) and manipulating systems that benefit industry, medicine, and the military. These control techniques aim to inject damping to reduce residual vibrations and to put the free end into a desired position or trajectory.

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BIOGRAPHY OF AUTHORS

Shahad A. Al-Ibadi she received the B.Sc. degrees in computer engineering from Iraq University Collage, Iraq, in 2009. Currently, she is M.Sc. student in computer engineering department, College of Engineering, University of Basrah, Basrah, Iraq. Her research interests include soft robots’ implementation, evaluation and control. She can be contacted at email: engpg.shahad.lateef@uobasrah.edu.iq.

Loai A. T. Al-Abeach has a Ph.D. in Electronics Engineering from the University of Salford, Manchester, England. The focus of his research is on the development and use of adaptable compliant actuators, e.g. pneumatic artificial muscles, and granular jamming manipulators in the soft robot end effectors. He has worked on variable stiffness continuum arms and adaptive control systems as well. In addition, he is a faculty staff member in the Computer Engineering Department- College of Engineering- University of Basrah. Reviewer for many international and local peer-reviewed journals. He can be contacted at email loai.talib@uobasrah.edu.iq.

Mohammed A. Al-Ibadi holds a Ph.D. in Computer Engineering from University of Basrah, Iraq. He is currently Head of the Computer Engineering Department at the College of Engineering, University of Basrah. His interest area of work is Parallel and Distributed Systems, FPGA-based systems, and ASIC. He has many projects implemented in the field of the internet of things and computer vision systems. In addition, he is a member of IEEE and a reviewer for many local and international journals and conferences. He can contact at email: mohammed.joudah@uobasrah.edu.iq.