Sensors & Actuators: A. Physical 372 (2024) 115364

Contents lists available at ScienceDirect

Sensors and Actuators: A. Physical

journal homepage: www.journals.elsevier.com/sensors-and-actuators-a-physical

A review on soft pneumatic actuators with integrated or embedded soft sensors

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ARTICLE INFO

Keywords:
SPA
Soft sensors
Embedded sensors
McKibben actuator
Pneu-Nets
Material jamming

ABSTRACT

Soft robotics has attained significant attention in recent years due to their infinite degree of freedom, adaptability, and safer interaction with humans and objects in various applications, such as robotics, biomedical devices, search and rescue operations, and wearable technology. However, the soft pneumatic actuator (SPA) is one of the most commonly and frequently utilized actuators in soft robotics due to its higher output at lower energy consumption. Further, an important development was the embedding/integration of soft and flexible sensors within the SPAs. This review article provides a comprehensive review of the frequently utilized SPA designs (McKibben, Pneu-Nets, and material jamming-based actuators), soft sensors (strain, pressure, temperature, tactile, flex, optical, and magnetic sensors), and SPAs with integrated or embedded soft sensors. Further, various emerging trends and breakthroughs in the SPA-sensors integration along with the limitations and challenges are discussed. Finally, it is found that there is an enormous amount of potential for revolutionizing the robotic and associated industries through the integration or embedding of soft sensors into SPAs. Even though there has been a lot of progress, there are still various challenges that need to be resolved and are provided in the future work section.

1. Introduction

The research, development, and application of robots made of flexible and malleable materials are the primary focus of the field of robotics known as "soft robotics." The distinctive qualities and capacities of biological organisms, such as their capacity to adapt to diverse locations, safely interact with humans, and carry out tasks that are difficult for conventional rigid robots, are the inspiration for soft robotics [1]. Soft robots use compliant and flexible materials, such as elastomers, fabrics, or inflatable structures, in contrast to conventional rigid robots, which typically use hard frames and joints. These materials give soft robots the flexibility and durability to move through complicated and dynamic situations by allowing them to deform, change shape, and exhibit changing stiffness. In order to create flexible and adaptable robotic systems, soft robotics places a strong emphasis on the integration of soft actuators, soft sensors, and soft materials [2]. Soft robots can create motion and exert forces due to soft actuators like pneumatic or electroactive polymer-based actuators. Soft robots can understand their environment and react to it due to soft sensors like pressure sensors and flexible strain sensors [3]. The conformity, flexibility, and safety of soft robots during interactions are enhanced by the use of soft materials in their construction. Flexibility and adaptation, safe human-robot interaction, robustness and resilience, manipulation and grasping, and bio-inspiration to mimic the abilities and behaviors exhibited by biological beings are the main objectives of soft robotics. Numerous industries, including healthcare, research, agriculture, manufacturing, and others employ soft robotics [4,5]. The field keeps developing as new studies focused on enhancing the actuation, sensing, control, and integration of soft robotic systems.

Actuators, as is well known, are essential for turning energy into important mechanical movement or physical action, allowing for the control and operation of different systems and devices in a variety of applications. Soft actuators come in many different varieties, each with special characteristics and actuation mechanisms that are employed in soft robotics [6,7]. Shape memory alloys (SMAs) [8,9], which retain a temporary state and return to their original shape upon heating or cooling, fluidic actuators (pneumatic or hydraulic) [10,11] that use compressed gas, air, or liquid to actuate the soft robots, electroactive

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https://doi.org/10.1016/j.sna.2024.115364
Received 23 January 2024; Received in revised form 22 March 2024; Accepted 7 April 2024
Available online 9 April 2024

polymer actuators (EAPs) [12,13], which use a material that changes size or shape in response to electrical stimulation, and soft electroactive hydrogels [14,15] that respond to electrical stimuli by swelling or contracting Just a few examples of soft actuators used in soft robotics are provided here. Researchers are coming up with new actuator designs to expand the capabilities of soft robotic systems because each type has its own benefits and limitations.

In comparison to certain other soft actuators, soft pneumatic actuators (SPAs) are comparatively simple to design and manufacture. They frequently comprise elastomeric materials and are actuated by pneumatic pressure alone. They are less expensive to build and maintain than actuators that rely on complicated materials or intricate control systems, in particular. They can bend and take on the contour of their surroundings because they are comprised of flexible materials [16,17]. In comparison to stiffer or high-force actuators, this compliance provides delicate and safe interactions, lowering the danger of harm or injury. SPAs are incredibly scalable and simple to include in many robot designs. To meet the requirements of a particular application, they can be modified in terms of size, shape, and actuation properties [18,19]. Additionally, SPAs may be modular, enabling the assembly of several actuators to create multi-DOF (Degree of Freedom) systems. They are capable of producing strong forces while being lightweight because they have a high force-to-weight ratio. When manipulating and grabbing objects, SPAs can distribute forces more uniformly, lowering the possibility of damaging fragile items. Due to its reliance on compressed air or gases for actuation, SPAs can be energy-efficient [20–22]. They are useful for applications where energy efficiency is a priority since energy consumption may be optimized by adjusting the pressure and timing of actuation [23]. It is crucial to remember that the selection of an actuator is based on the particular needs of the application. Some of the frequently utilized SPAs designs are McKibben SPAs, Pneu-Nets SPAs, and Material-Jamming based SPAs (shown in Fig. 1).

Firstly, the McKibben SPA commonly referred to as the McKibben or pneumatic artificial muscle, was developed by *J.E. McKibben*. It is among the oldest and most popular soft actuators [24–26]. A flexible elastomeric tube surrounded by braided strands or fibers serves as the basis for the McKibben actuator. The fibers are often made of nylon or Kevlar, whereas the tube is typically constructed of latex or silicone. A pressurized air supply is attached to one end of the actuator, which is sealed on both ends. Due to the tensile pressures produced by the expanding tube, the braided fibers or cords contract when air is pumped into the actuator. The contraction shortens the actuator and produces a pulling force. The actuator normally moves in a linear fashion, and the amount of force and displacement can be altered by changing the air pressure [27,28]. Secondly, Pneu-Nets is a kind of SPA that provides complex and varied motion by utilizing a network of interconnected air chambers. This actuator design allows a high degree of control over the form and behavior of the actuator by selecting particular chambers within the network to selectively inflate or deflate [29–31]. By separately altering the pressure in each chamber, various motions can be produced, such as bending, twisting, and expansion. The Pneu-Net's chambers are connected by routes or channels, which allow air to flow freely between them. The interconnectedness of the Pneu-Net structure allows for complex and synchronized action among the multiple chambers [32,33]. The chambers are typically built out of flexible materials like silicone or elastomers that can expand and compress under pressure. Some of the potential applications for Pneu-Nets include soft robotics, prosthetics, and biomedical devices [34,35]. Thirdly, the SPAs that utilizes the idea of material jamming to achieve shape change and mechanical functionality are known as material jamming-based SPAs. When exposed to external pressure, these actuators rely on the ability of granular materials to switch between a fluid-like state and a rigid-like one [36,37]. Jamming is the technique of tightly arranging granular components, such as tiny particles or grains, to create a solid-like structure. The granular substance behaves like a fluid and can flow when it is free or unobstructed [38,39]. However, by adjusting the pressure or vacuum within the actuator, the granular material can go through a transition between the jammed and unjammed states, changing the actuator's structure and causing deformation. These soft actuators are naturally flexible and compliant. They can readily be

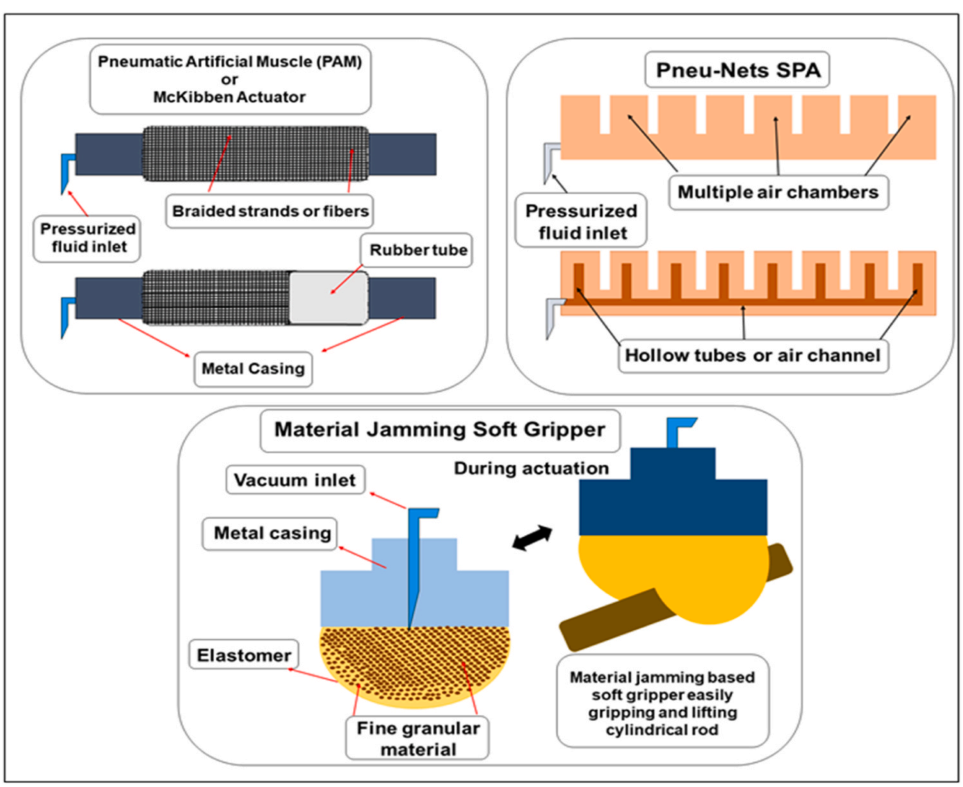

Fig. 1. The frequently utilized designs of SPAs.

maneuvered and can conform to a variety of unusual shapes when they are not jammed. It is safe to deal with soft and fragile objects because of this compliance. The actuator can keep a particular form or apply forces because of the rigidity it has acquired in the jammed condition. These actuators have been used in a variety of industries, such as soft robotics, prosthetics, and wearable technology [40,41]. Even though SPAs have many benefits, other soft actuators with specific actuation requirements, such as electroactive polymers (EAPs) or shape memory alloys (SMAs), may be more appropriate in some circumstances.

Soft sensors are frequently needed for SPAs—inflatable and flexible structures utilized for generating motion in soft robots—for a variety of purposes, including feedback control, actuation monitoring, safety, manipulation, defect detection, and energy efficiency [42–44]. They make it possible for soft robotic systems to behave adaptively and intelligently, improve performance, increase safety, and allow for precise control. Soft sensors are computer models or algorithms that estimate or anticipate the physical or chemical attributes of a system using indirect measurements or information from other readily available sensors [45,46]. Soft sensors are often referred to as virtual sensors or inferential sensors because they rely on data analysis techniques rather than physical sensors to infer the needed information. In manufacturing, control systems, and other industrial processes where it may be difficult, expensive, or impossible to measure a property directly, soft sensors are widely utilized. Soft sensors have a number of benefits, including affordability, adaptability, and the capacity to deliver vital data predictions in real-time. In addition to enhancing performance and process management, they can enable predictive maintenance [47–49].

The advancement of soft sensors has received significant attention in recent research and development. Stretchable and wearable sensors are two important developments in the field of soft sensors. Significant progress has been made in developing soft sensors that can adapt to the contours of the human body or other curved surfaces. Materials that are elastic and flexible i.e., conductive polymers, carbon nanotubes, and graphene, are used to create stretchable and wearable sensors [50,51]. These sensors can be included in items of clothing, gloves, or bandages to provide motion detection, gesture recognition, and continuous monitoring of physiological signals [52–54]. Flexible and transparent sensors are now being developed, which is extremely desirable for use in touchscreens [55], transparent displays [56,57], or wearable technology [58,59]. Soft sensors have self-healing components and structures to increase their robustness and lifetime. These sensors have the ability to self-heal cuts and cracks brought on by wear or outside factors [60–62]. A growing number of physical or chemical characteristics can now be measured simultaneously by soft sensors. These multimodal sensors combine various sensing components or substances to measure many quantities, including pressure, temperature, strain, and chemical composition. Robotics, healthcare, and environmental monitoring are just a few of the many applications where multimodal sensing makes it possible to collect data that is more thorough and accurate. The energy harvesting sensors transform mechanical or environmental energy into electrical energy using piezoelectric materials, triboelectric phenomena, or other methods [63–65]. These sensors can run independently without external power sources or regular battery changes thanks to energy harvesting. To improve their capabilities, soft sensors are being combined with cutting-edge data processing algorithms and methods. Real-time decision-making is made possible by the analysis of sensor data using machine learning, artificial intelligence, and signal processing techniques. Advanced sensing applications like predictive maintenance, anomaly detection, or context-aware systems are made possible by this integration. The characteristics and operations of biological sensors, such as touch receptors, strain sensors, or chemical sensors found in living things, are mimicked by bioinspired sensors [66–68]. They provide enhanced sensitivity, selectivity, and adaptability, creating new opportunities for applications in robotics, environmental monitoring, and healthcare. More adaptable, flexible, and conformable sensing systems are needed, which is driving improvements in soft sensor technology. These advancements led to the development of advanced applications in the fields of robotics, healthcare, the Internet of Things (IoT), and human-machine interfaces [69–71].

The ability, safety, and conformance provided by the soft robotic bodies while interacting with the soft human tissues make them suitable for different medical applications, such as assistive exercises, therapeutic, and surgeries [72,73]. Soft robotic exoskeletons support patients to rehabilitate and improve their physical movement and soft robotic grippers enable the safer handling of soft and fragile objects. By offering more functional and natural replacements for missing limbs or body parts, soft robotics has the capacity to revolutionize prosthetics and assistive technology [74,75]. The comfort, flexibility, and adaptability of soft robotic prostheses are superior to those of conventional rigid prosthetics. They can more precisely resemble the functions and motions of biological limbs, enhancing the quality of living for amputees. Soft robots are appropriate for places that are dangerous to people or challenging to reach. They are able to move through tight spaces, difficult terrain, and disaster-affected regions. Soft robots can be utilized in rescue search and operations, hazardous environment investigation, and infrastructure inspection for things like pipelines, tunnels, and nuclear power plants [76–78]. Soft robots are created with the intention of collaborating and interacting with people in a secure and comfortable way. They can be utilized in social robotics projects like robot companions for the elderly or people with disabilities. Soft robots with sensors and feedback systems are able to change their behavior in response to human stimuli, promoting interesting, and gentle interactions. Soft underwater robots are capable of navigating challenging marine conditions, carrying out inspection duties, acquiring samples, and keeping track of marine ecosystems [79–81]. Soft robotic suits can help with physical rehabilitation, can increase human strength and endurance, or can support employees performing physically demanding jobs.

Beyond soft robotics, soft sensors, and soft actuators are essential parts of many applications. Soft sensors can be applied to environmental sensing, wearable technology, human-machine interactions, and healthcare monitoring. Applications for soft actuators include shape-changing structures, active textiles, vibration control, and haptic feedback systems. As technology develops, we can anticipate seeing soft robotics play a bigger part in a variety of fields, solving complicated problems, and enhancing people's lives. The increasing demand of SPAs with integrated or embedded soft sensors in robotics and related area is the main motivation behind this study. With the advancement of technology, the increasing demand of compliant and adaptable robotic system that can safely interact with humans is increasing. To deal with these challenges, the SPAs with integrated or embedded sensors are the best optimal solution. Therefore, the main objective of this study is to provide a comprehensive review of design and functionality of frequently utilized SPAs and soft sensors. Further, review of SPAs with integrated or embedded soft sensors, associated challenges, and possible solutions has been provided which will facilitate the development of more intelligent, adaptable, and safer robotic systems for diverse applications. Thus, the remaining study is arranged in the following sections. Firstly, a comprehensive review of different types of soft and flexible sensors has been presented in 2. 3 describes the literature review of some important research related to the SPA integrated or embedded with soft sensors. Then, various emerging trends and breakthroughs in this field are presented in 4. Further, the challenges and limitations related to SPA-sensor integration are presented in the 5. Finally, 5 presents the ideas for future work, whereas the review is concluded in 6.

2. Soft sensors

Soft sensors are integrated or embedded into SPAs or soft pneumatic robotics to empower soft robots to acknowledge and sense their surroundings. The soft sensors are capable of sensing temperature, pressure, force, touch, strain, magnetic field, humidity level, chemicals, and a variety of gases. Some of the frequently utilized soft sensors as well as soft sensors that could be utilized in soft robotics and related fields are briefly reviewed and presented here.

2.1. Strain sensor

Generally, soft sensors can change their shape with respect to humidity, stress, and temperature. Since, the precisely growing significance of soft robotics, these sorts of sensors permit robots to pick up on and respond to their circumstance in greater detail and advance [82,83]. In the early 2000 s the initially developed soft sensors i.e., strain sensors, were initially used within healthcare institutions for monitoring whether tissues are softly deviated during operation [84]. This kind of sensor behaves like conductive material when carbon fragments and metal-like particles are introduced into them. Also, these are often made up of rubbery material like an elastomer. This material is capable of identifying variations in resistivity whenever they deform [85,86]. Over time the advancement of strain sensors into new material, sensing techniques, and fabrication methods are crucial factors to the researcher for enhancement of sensor efficiency and flexibility.

Soft strain sensors are being used in a variety of innovative products, including smart fabrics, wearable technology, robots, and prosthetics [87–89]. The development of novel materials and fabrication techniques has been one of the major developments in the field of soft strain sensors. Early soft strain sensors had limited sensitivity and range of motion because they were mostly made of elastomers. Nanoparticles, conducting polymers, and hydrogels are a few of the novel materials that scientists have developed that have enhanced mechanical characteristics, conductivity, and sensitivity [82,90]. The development of inventive sensing systems is another area of progress. Earlier soft strain sensors faced problems in deformation detection due to the fluctuations in resistance, which were caused by humidity and temperature-like environmental parameters. Recently, novel sensing technologies have been introduced with better or increased accuracy, dependability, and sensitivity, such as piezo-resistive, piezo-capacitive, and piezoelectric sensing [91,92]. These sensors are becoming increasingly complex due to the advancement in the field of manufacturing techniques. Researchers are using additive manufacturing techniques to fabricate these sensors with complex shapes and geometries, which are useful for a particular application [93,94]. Further, improvements in wireless communication technology and data processing led to the development of soft sensors that can transmit data in real time, which will improve the accuracy and responsiveness of the control system of the soft robots [95,96]. These sensors could be used in soft robots and other related fields, such as soft gripper that makes use of soft actuators and sensors to grasp and lift soft and fragile objects. To monitor changes in the body including breathing, pulse rate, and muscle activity, these sensors can also be used in smart textile and wearable technology. Medical devices, such as prosthetics can also make use of soft strain sensors to provide the user with feedback on the positioning as well as the movement of the synthetic limb. As a result, proprioception, or the sense of an individual's position and motion in space can be enhanced by these soft strain sensors.

2.2. Pressure sensor

Generally, to measure the pressure of a fluid or gas, pressure sensors are utilized. In soft robotics, soft pressure sensors can be employed to monitor the pressure within, which is essential for controlling the motion and for the operation of soft robotic parts. The mechanical deformation of a metallic element was utilized in early pressure sensors to detect pressure changes [97–99]. Piezoelectric materials were utilized in the early 1960 s to develop pressure sensors, which are very dependable and much more accurate than the previous ones. However, due to the absence of flexibility, they are not applicable to various surfaces [100,101]. Further, soft pressure sensors were developed in the early 2000 s as soft robotic technology evolved. These adaptable, lightweight sensors were made of elastic materials like elastomers, allowing them to adapt or conform to any surface [102–104]. From simple resistance-based sensing to more complicated ones like piezo-resistive, piezo-capacitive, and piezoelectric sensing, the detection mechanisms for soft pressure sensors have improved [105,106]. The output signal with greater accuracy and pressure sensitivity is provided by these sensing mechanisms. Various modern manufacturing techniques enable the fabrication of soft pressure sensors with improved resolution and sensitivity. With the use of techniques like microfabrication, 3D printing, and screen printing, sensors of all shapes and sizes have been developed. The combination of electronics and soft pressure sensors led to real time feedback and control [107,108]. Further, with the interoperability of these sensors with wireless networks and microcontrollers, it is possible to monitor pressure change remotely. These soft sensors allow us to measure the exerted pressure, pressure distribution, or contact pressure between the two bodies. Therefore, these sensors are extensively used in various fields such as healthcare, robotics, and wearable technology [109–111].

2.3. Temperature sensor

The soft temperature sensors are used in the soft robotic bodies to monitor the variation in the temperature of various parts, in order to maintain the integrity of the robotic body. Temperature sensing is an important factor in various fields, including biomedical engineering and industrial surveillance by incorporating soft materials. The earliest temperature sensors were based upon the expansion of material as a function of temperature change and comprised bimetallic strip thermometers [112–114]. RTDs and thermocouples which are known for their accuracy and reliability took over as temperature sensors in the 1960s [115,116]. In the 1990s researchers made progress, in developing temperature sensors based on materials and polymers. These sensors are versatile and easy to integrate into materials. They have slightly lower accuracy and sensitivity compared to traditional sensors [117,118]. Over time there have been advancements in their designs and fabrication techniques. Researchers have explored a range of materials like polymers, nanomaterials, and elastomers for making these sensors [119–121]. However current research focuses on developing materials that offer improved responsiveness and functionality across a temperature range. The sensing technique has also evolved from resistance-based sensing to thermoelectric and thermo-resistive sensing methods with temperature sensitivity [122,123]. Moreover, advancements in fabrication technology have enabled the development of temperature sensors with sensitivity and resolution. Techniques such as screen printing, microfabrication, and 3D printing allow for the creation of sensors, in shapes and sizes. These flexible sensors can be combined with electronics to remotely monitor and control temperature changes while providing real time feedback.

2.4. Tactile sensor

Tactile sensors are used to measure the pressure level exerted by the soft robotic structures, such as soft grippers on the objects around them. These soft sensors are used to mimic the sense of touch in bio-living things [124,125]. Recently, these sensors have developed significantly and fabricated devices that can sense or detect texture, temperature, and pressure [126,127]. Thus, they could be used in a variety of objects or devices, such as prosthetics and soft robotics. Researchers started developing these sensors in the early 1990s when the previous sensors had a very low response range and sensitivity was low [128]. Until the middle of the 2000s, there were no significant advancements in soft tactile sensors. In 2003, a team of researchers from MIT fabricated a polymer-based soft and flexible tactile sensor that can detect pressure and force [129,130]. This sensor had a resolution of 0.1 N and was designed to resemble a human fingertip. Further, in 2008, a team of researchers from Stanford University fabricated a soft touch sensor using a flexible substrate incorporating conducting wires. This tactile sensor can differentiate shear force from pressure by changing the resistance in wires under twisting and bending movement [131].

Considerable advancements have been seen in soft tactile sensors, since their fabrication. The most important development is the fabrication of a soft tactile sensor that is capable of detecting multiple parameters simultaneously. For instance, researchers from the *University of California, Berkeley* fabricated a sensor that was able to sense vibration, temperature, and pressure at the same time. This sensor was fabricated using the polymer and has the capacity to change its electrical resistance in response to changing temperature, pressure, and vibrations [130,132]. Further, another advancement in this field was the fabrication of sensors that can sense surface texture. In 2016, a group of researchers from the University of California, Los Angeles developed a soft tactile sensor that could detect the texture of the object. The surface pattern of a polymer used to make the sensor resembles the tip of a human finger [133]. The sensor was able to determine an object's texture by detecting the deformation of the polymer. Soft touch sensor fabrication techniques have considerably advanced over the past several years as well. As an illustration, sensors with complex shapes and precise measurements have been produced using 3D printing. In 2019, a group of researchers from Carnegie Mellon University developed a 3D-printed soft touch sensor that could assess the stiffness of an object [134,135]. Therefore, due to the unique properties of soft tactile sensors, they are contributing to the advancement of biomechanics research, assistive technologies, and the fabrication of humanoid and soft robots.

2.5. Flex sensor

In soft robotics, flex sensors can be used to monitor how flexible robot components bend in response to pressure changes or other environmental factors. Flex sensors have existed since the early 20th century. Harold B. Law created the first flex sensor in 1928. The wire that made up Law's flex sensor was coiled around a cylinder [136]. The wire would stretch as the cylinder was bent, altering the wire's resistance. The degree of bending might be calculated using this change in resistance. Flex sensors first appeared in the aerospace and medical industries in the 1950s. More sensitive and precise flex sensors were produced in the 1970s as a result of advances in thin film technology [137].

The development of soft robotics has raised the demand for soft flex sensors. Flexible materials, such as silicone, rubber, or conductive polymers, are used to create soft flex sensors. These sensors are used to monitor how soft robotic structures flex, stretch, or twist [127,128]. Soft flex sensors have made a number of breakthroughs in development. The usage of conductive elastomers is one of the most important developments. The materials with electrical and elastic qualities are known as conductive elastomers. Soft flex sensors made of these materials have high sensitivity and accuracy [138,139]. 3D printing technology is another important development. Complex soft flex sensors with sophisticated shapes and features can be produced quickly and affordably using 3D printing. Soft flex sensors that may be tailored to work with particular applications have also been made possible because of 3D printing technology [140]. Nanoscale soft flex sensors have also been created as a result of recent developments in nanotechnology. These sensors have great sensitivity and can detect extremely minute changes in bending or deformation since they are constructed of nanoscale materials like carbon nanotubes or graphene [139,140]. Soft robotics uses soft flex sensors in a variety of ways. They can be utilized in soft exoskeletons to track wearer movements and device deformation, wearable robotics to measure joint angles and movements, and soft grippers to identify the size and shape of items.

2.6. Optical sensor

Optical sensors employ light to measure a substance's or environment's characteristics. These sensors can be used in soft robotics to measure the displacement or deformation of soft robotic components or to find things in the surrounding area [141]. Soft optical sensors have been there ever since researchers first began developing fiber optic sensors in the 1970s. These are developed using elastomers, such as silicone rubber and Ecoflex, and are used to monitor the changing pressure, strain, and temperature [142]. Various additive manufacturing techniques, such as 3D printing, screen printing, and photolithography, are used to print these sensors having complicated structures with high accuracy and resolution [140,143]. The development of novel and innovative materials, such as Polydimethylsiloxane (PDMS), elastomers, and silicone rubber, has significantly contributed to the improvement of soft optical sensors. Soft optical sensors, having high sensitivity, resolution, and great optical properties, are developed using these materials. Recent advancements in these sensors have made it possible to fabricate soft optical sensors that can detect multiple parameters such as temperature, strain, and pressure [144]. Further, technological advancement led to the development of wireless soft optical sensors that can be remotely monitored and controlled using wireless communication technologies such as Bluetooth, Wi-Fi, and Zigbee. These sensors can be incorporated into the soft grippers to measure the contact pressure and grip force [145,146]. Further, to analyze the force and pressure applied by the devices, these soft sensors can be employed in orthotics and prosthetics. Moreover, wearable devices could use these sensors to monitor strain, pressure, and temperature of the body.

2.7. Magnetic sensor

The qualities of an object or environment are evaluated by magnetic sensors using magnetic fields. Among the many different types of sensors, the magnetic sensor is one of the most well-liked and commonly used ones [147]. Magnetic sensors, which are based on the detection of magnetic fields, are used to measure closeness, position, and movement. The development of magnetic sensors began in the late 19th century, with the discovery of magnetoresistance in 1857 by German physicist Friedrich Kohlrausch [148,149]. The first magnetic compass was created later, in 1879, by William Thomson, popularly known as Lord Kelvin, and was used for navigation. Modern magnetic sensing technology was made possible by the invention of magnetometers and magneto-resistive sensors around the turn of the 20th century. University of California, Berkeley researchers created the first soft magnetic sensor in the late 1990s [150,151].

Significant developments have been made in this area since the invention of the first soft magnetic sensor. The development of gigantic magnetoresistance (GMR) sensors by Peter Grünberg and Albert Fert in the late 1980 s, for which they received the 2007 Nobel Prize in Physics, was one of the most important developments [152,153]. Nowadays, a variety of products, including computer hard drives, automotive sensors, and medical equipment, use GMR sensors extensively. Recently, the field of soft robotics has paid a lot of attention to the development of soft magnetic sensors [154]. These sensors could be used by the soft robotic structures to provide information about the orientation and position. For example, the manipulation of objects using soft magnetic sensors in soft robotic grippers [155]. These sensors could also be used by haptic feedback systems to identify and analyze the magnetic fields generated by magnets and supply tactile input signals to the user. Moreover, another advancement is the application of magnetic field tomography, which is a non-invasive technique for analyzing the inner magnetic fields of soft materials. By mapping the magnetic field distribution of soft magnetic sensors, crucial information regarding their performance and design can be revealed. Soft magnetic sensors are used widely in many areas, including robotics, healthcare, and the automobile sector [156,157]. Soft magnetic sensors have applications in medical imaging and diagnostics. Strong magnetic fields and radio waves are employed in the widely used medical imaging technology known as magnetic resonance imaging (MRI) to provide precise images of the inside organs and tissues of the body [158,159]. Soft magnetic sensors are employed in the automotive industry for a variety of tasks, including determining the location and speed of the wheels, spotting metallic items inside the engine, and measuring the earth's magnetic field for navigation.

Various soft sensors have been successfully integrated or embedded into SPAs to improve their functionality in various types of applications. For example, strain sensors are based on resistive and capacitive type materials which are embedded in SPAs to measure the developed strain and deformation during actuation. These sensors are subjected to durability, calibration, accuracy, and reliability challenges, especially in deformable environments. Pressure sensors are embedded into SPAs to measure the change in internal pressure for the precise control and feedback of the system. These sensors face problems related to calibration, drift, robust connection, and proper alignment within the flexible SPAs. Soft temperature sensors embedded into SPAs are utilized in applications where thermal monitoring is essential, for example medical devices or temperature varying environments. These sensors have accuracy related problems, whereas calibration and compensation for thermal effects are the fields of ongoing research. Tactile sensors are integrated into SPAs to measure touch feedback and contact force (as in soft robotic grippers) but they face difficulty in maintaining balance between sensitivity and softness. However, integration of multiple tactile sensors and decoding tactile information is an area of ongoing research. Flex sensors are embedded to measure the bending and flexing of SPAs but maintaining the sensor integrity during repeated bending and ensuring precise reading is highly challenging. Further, soft optical sensors (such as fiber optic sensors and photodetectors) are integrated to measure non-contact parameters such as change in shape and displacement developed by SPAs but ensuring the robustness of optical components in dynamic and deformable structures is highly challenging. Moreover, calibration and interference problems in varying light conditions requires further research. Finally, soft magnetic sensors are integrated or embedded for detecting magnetic fields or positions of soft robotic structures. They are subjected to mitigating interference from external magnetic fields and maintaining accuracy during deformation is an area of ongoing research. The following section presents the integration or embedding of fewer above-mentioned soft sensors with SPAs.

3. SPA with in-built sensor

A type of flexible SPA that contains a sensing element inside its structure to monitor physical parameters or properties during actuation is known as a SPA with an embedded or integrated soft sensor [160]. With this setup, the actuator may keep track of its own deformation, strain, pressure, or other physical parameters while it is in use, providing real time input on its condition. Self-sensing allows the actuator to react to changes in its surroundings or operational settings, improving safety and effectiveness, particularly in scenarios involving human-robot contact [161]. Some of the fabrication techniques, such as screen printing, inkjet printing, or aerosol jet printing can be used to print or deposit soft sensors directly onto the surface of the SPA (shown in Fig. 2).

On the soft material of the actuator, strain or pressure sensors can be directly fabricated using conductive inks or substances like carbon nanotubes. However, during the fabrication process of the SPA, soft sensing elements can be included or embedded within the structure. This can involve placing conductive fibers, films, or elastomers at strategic locations to act as strain or pressure sensors [92–96,162]. Optical fibers or photonic sensors can be embedded within the actuator to measure deformation or strain based on changes in light propagation. Fiber Bragg Gratings (FBGs) are commonly used in this approach [142–144,163]. Soft sensors based on magnetic field changes can be integrated by placing magnetic particles within the actuator's material. The deformation or strain in the SPAs can be measured by detecting changes in the magnetic field [155–157]. The SPA can be covered with a soft sensing skin made of conductive materials or sensors which is conformable and stretchable, enabling measurements over the entire actuator's surface. SPA can also be equipped with wireless sensors, such as flexible strain gauges or pressure sensors that communicate their measurements to an external receiver [145,146]. The choice of integration technique depends on factors such as the sensing modality required (e.g., strain, pressure, deformation), the actuator's material properties, the desired sensing resolution, and the intended application. It often involves a trade-off between sensing accuracy, complexity, and the impact on the actuator's performance. Researchers in the field of soft robotics continue to explore and develop innovative techniques to integrate soft sensors effectively with SPAs for enhanced functionality and adaptability. Some of the important papers related to the integration of soft sensors with the SPA are summarized in Table 1.

The author reported a novel PAM actuator for sensing contraction [164]. In this PAM, the elastomer is reinforced with Kevlar fiber and

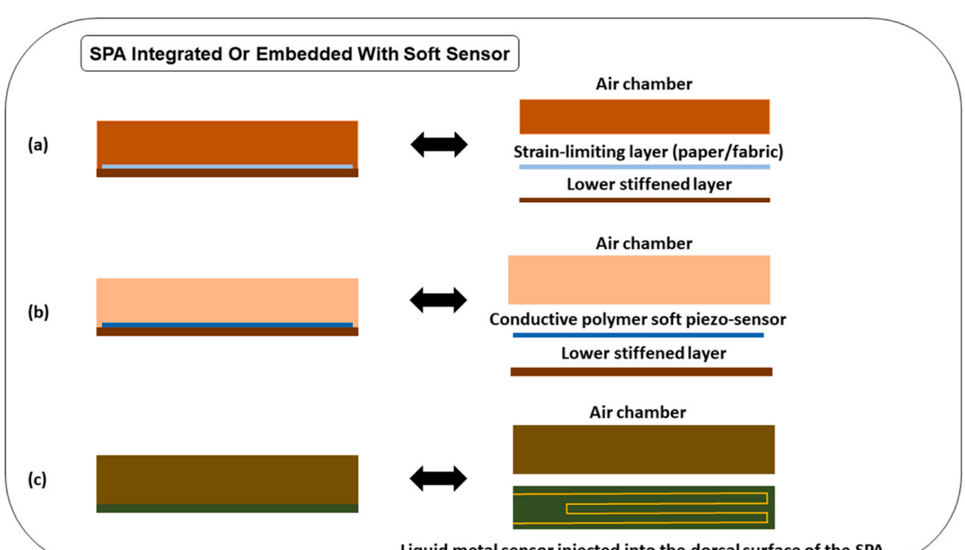

Fig. 2. Generalized designs for SPA with embedded or integrated soft sensors.

Table 1
Summarized literature review of SPA with integrated or embedded soft sensors.

S. No.	Author	Year	Actuator Design	Outcomes	Application/Purpose
1	Park et al. [164]	2013	PAM with helical microchannel for liquid metal	PAM actuation, sensing capability, and geometrical change of the muscle	A new fabrication technique to embed Kevlar threads and microchannel in the elastomeric tube
2	Lu et al. [165]	2020	A conductive liquid metal (EGaIn) sensor integrated with the SPA	Strain and pressure	SPA with the integrated sensor is used to detect the softness, size, and profile of different objects
3	Sonar et al. [166]	2016	SPA skin integrated with lead zirconate titanate (PZT)-based piezoelectric sensor	Mechanical characteristics, sensitivity, resolution of soft contact sensing, and accuracy of control on vibrotactile feedback	SPA skin prototype that allows bidirectional tactile information transfer to facilitate a simpler and more responsive wearable interface
4	Vural et al. [167]	2023	Soft haptic electromagnetic actuator, consisting of stretchable conductor, pressure sensitive conductive foam, and soft magnetic composites.	Actuation and sensing performance of the haptic device	This haptic device could be used in the future to develop multi-functional electronic skin for human-machine interface
5	Huaroto et al. [168]	2019	A haptic device made up of elastomer that can generate two motions over the skin such as traction and pression	Maximum vertical and tangential deformation	This haptic device provides its application in mechano-tactile feedback for wearable devices.
6	Yu et al. [169]	2022	Self-sensing actuator (SenAct)	The resolution, fast response, robustness, and output force	Based on the SenAct, a haptic feedback glove, performing accurate operations, has been developed
7	Takizawa et al. [170]	2018	SPA with built-in strain gauge	Grasping force	To measure the grasping force without using the force sensor
8	Wang et al. [171]	2020	The lower limb exoskeleton consists of links and soft hinges (actuated by bidirectional curl PAM)	Inflating pressure and bending angle of the soft hinges	A well-controlled exoskeleton for the lower limb in the range of motion of a gait cycle
9	Liu et al. [172]	2021	A spiral sensor made up of conductive fiber and a central elastic base pillar integrated with a gripper	Electrical performance of the proposed spiral sensor	The developed spiral sensor integrated into the outer surface of the gripper to determine the diameter of the unknown grasping object
10	Pinto et al. [173]	2017	CNT-based sensor connected using silver nanowires at the bottom of the SPA	Local strain	To measure the localized strain at the bottom of the SPA using a CNT-based sensor connected with silver nanowires
11	Xiao et al. [174]	2023	(SISPA) Self-sensing intelligent SPA (integration of SPA with silicone rubber/ NdFeB composite sensor)	Bending deformation and generated voltage	Using SISPA, a bionic hand has been developed that generates different output signals
12	Gariya et al. [175]	2023	Conductive polymer nanocomposite sensing membrane integrated with SPA	Bending angle and sensor reading in electric volts	The SPA-P is used for the finger rehabilitation exercise of the index finger
13	Xiao et al. [176]	2023	(SPTA) Self-sensing pneumatic torsional actuator based on electromagnetic induction effect and magnetically responsive material	Improved torsion angle and output torque. Feedback signal is in the form of voltage and current. Relation between torsion angle and change in magnetic flux is linear.	The SPTA will improve the accuracy and intelligence of the soft robots.
14	Yang et al. [177]	2023	Tactile self-sensing two finer soft gripper with online learning self-tuning nonlinearity impedance controller.	The tactile self-sensing two-finger soft gripper utilizes a liquid lens-based optical tactile sensing unit, which provides quick response, stability, high sensitivity, resolution, linearity, and cost-effectiveness.	Robust performance of controller in nonlinear contact allows the nondestructive grasping of biological samples and industrial products.

provided with a helical microchannel for liquid metal sensors. During actuation, the helical microchannel can sense the changing shape of the artificial muscle. This sensing property increases the controllability of the PAM. However, conductive liquid metal, such as Eutectic Gallium Indium (EGaIn) has both strain and pressure-sensing capabilities [165]. The developed EGaIn-based strain sensor has a higher sensitivity up to 28.6–30.8. This improvement in sensitivity is because of the embedded fibers and low hysteresis. Further, the EGaIn sensor is integrated at the bottom surface of the SPA and successfully detects the size, softness, and profile of objects. In order to facilitate a more straightforward and responsive wearable interface, the author offers a skin prototype based on a SPA that supports bidirectional tactile information transfer in vibrotactile feedback [166]. Findings from experiments demonstrate that by closing the control loop, this ultra-thin SPA and the distinctive integration technique of the discrete piezoelectric sensors based on lead zirconate titanate (PZT) are able to accomplish high-resolution soft touch sensing as well as precise control of vibrotactile feedback. The functionality of new electronic skin technologies may be increased by soft vibrotactile devices. However, those devices frequently lack the overall performance, sensing-actuation feedback and control, and mechanical compliance required for smooth integration on the skin. Thus, the author reported a soft haptic electromagnetic actuator made of soft magnetic composites, pressure-sensitive conductive foams, and inherently stretchable conductors [167]. The aforementioned parts are put together with a soft magnet to create soft vibrotactile devices that offer high-performance actuation and amplitude sensing.

Haptic devices are high in demand due to their applications in the biomedical field, teleoperation, and video games. These devices are often created using stiff materials, motors, and mechanisms to give users tactile input relevant to a specific job by applying pressure, tangential force, or vibrations to the skin as stimuli. A soft pneumatic haptic device that uses an inflatable hyperelastic membrane as its base and can deliver traction and pressure over the skin with just one energy input [168]. The use of this technology in mechano-tactile feedback for wearable devices is now possible because of its two mechanically programmed movements, lightweight design, low-cost hardware, and gentle skin-to-device contact. However, the majority of commercially available haptic feedback systems today are rigid, simple, and not powerful enough to fully immerse users in virtual and remote settings. Thus, the author reported the design, construction, and operation of a low-cost, lightweight self-sensing actuator (SenAct) that accurately reproduces the tactile sensation through force and vibration feedback [169]. SenAct exhibits strong performance, including quick reaction (10 ms), great resilience (>10,000 cycles), and a large output force (up to 1.55 N) with a high adjustable resolution (up to 0.02 N) based on real-time closed-loop control. A soft actuator-based forceps grasper that can measure grasping force without a force sensor has been reported [170]. The grasper is made up of a tiny cylinder and a slider-crank system that is integrated into the tip of the forceps. The cylinder is fitted with a silicone-based pneumatic soft actuator. By blowing air into the soft actuator, the grasper is activated. The newly created soft actuator has a built-in strain gauge to track actuator movement, thus calculating the grabbing force by adding the strain gauge and internal pressure data. Further, an exoskeleton for the lower limb has been proposed by the authors [171]. Three soft hinges are used to drive the hip, knee, and ankle joints, and four rigid links are used to align the exoskeleton with the waist, thigh, crus, and foot. The rigid links are fabricated using 3D printing while the soft hinges are fabricated using a unique bidirectional curl PAM. Multiple sensors are built into each of the modules, including two pressure sensors for monitoring inflation pressures, two flex sensors, and an inertia measuring unit for estimating the bending angles of the soft hinges through data fusion.

The authors [172] suggested a flexible strain sensor based on the theory of resistance sensing to estimate the curvature information of the soft pneumatic gripper. A central elastic foundation pillar and a spiral conductive fiber make up the majority of the proposed sensor. A specialized platform is created to perform extrusion in order to create the conductive fiber, which is fabricated by using a mixture of multi-walled carbon nanotubes (MWCNTs) and the stretchable elastomer DragonSkin-30. The prototype was attached to the outside of a soft pneumatic gripper, and calibration and grasp-release tests revealed that it accurately reflected the diameters of the unidentified objects with an inaccuracy of 3.99%. Also, a novel silver nanowire-connected CNT-based sensor array for detecting localized strain along the SPA bottom surface has been reported [173] to measure the bending of the SPA. Further, by combining a sensor layer made of silicone rubber/-NdFeB composite twined with a varnished wire, a self-sensing intelligent soft pneumatic actuator (SISPA) is produced [174]. The sensor layer's bending deformation produces the induced voltage. As the mass percentage of magnetic powders, varnished wire turns, thicknesses, and widths of the composite increase, so do the induced voltage levels, according to experimental results. In the end, a SISPA is used to create an intelligent bionic hand that produces various signals in response to various gestures. Moreover, a SPA embedded with a piezoelectric membrane (SPA-P) has also been reported by the authors [175]. It consists of a flexible conducting polymer nanocomposite (CPNC) membrane that is sealed inside the silicone rubber body of the SPA. Utilizing the solvent casting process, the CPNC is made up of a dielectric polyvinylidene fluoride matrix, conducting carbon nanofibers for charge transmission, and ionic liquid for additional ions and flexibility. When actuated by pneumatic pressure, the experimental research of SPA-P revealed a sizable voltage change, which can be used to control SPA by supplying feedback voltage equivalent to the deformation during bending. The proposed SPA-P has also been evaluated for use in the rehabilitation of human fingers. Recently, author [176] develops a self-sensing pneumatic torsional actuator (SPTA) having magnetically responsive materials and works on electromagnetic induction effect. The SPTA in comparison to pure rubber SPA shows maximum torsion of 66.35^0 and improves output torque by 23.19%. Additionally, the feedback signal is generated in the form of voltage and current, which can be further increased by increasing number of turns of wires and magnetic powder material. Moreover, authors [177] utilized an online learning self-tuning nonlinearity impedance controller to enhance the grasping capabilities of soft grippers. For handling soft and fragile objects, a liquid lens-based optical tactile sensing unit is used in the tactile self-sensing two-finger soft gripper, which offers quick response, stability, high sensitivity, resolution, linearity, and cost-effectiveness. The proposed force controller utilizes adaptive laws and the Hammerstein nonlinear model, which exhibits efficient online parameter adjustments. The outcomes from simulations and experiments validate the strong performance of the controller in nonlinear contact, which demonstrates its potential in real-time applications such as the sorting of industrial products and nondestructive grasping of biological samples. Finally, it can be concluded that the developed SPAs with integrated or embedded soft sensors are useful for the automatic control of the system based on the feedback signal generated by the sensor. Additionally, they are also used for different applications such as measuring the bending curvature of the SPA and detecting touch, grasp, size, and level of softness of the objects. Further, the accuracy and intelligence of the integrated SPA-sensor system can be improved by utilizing force controller.

4. Trends and breakthroughs

4.1. Emerging trends

Over the past two decades, there has been an increasing trend in research related to SPAs and their integration with soft sensors. This increase in interest reflects the escalating demand for compliant and versatile robotic systems across various sectors, including robotics, healthcare, prosthetics, and human-machine interaction. To analyze this trend, a research publication trend was extracted from the Web of Science (WOS) database using the search topic - "Soft pneumatic actuators" AND "Soft pneumatic actuators with embedded or integrated soft sensors." A total of 165 research publications indexed in WOS since 2009 were identified. Notably, the topic saw minimal attention in 2009, with only one related research published. However, with time, interest in the topic continuously increased, as shown by the rising number of publications over subsequent years (as shown in Fig. 3a). The maximum of research publications occurred in 2021, with a peak of 30 research articles published on the topic, highlighting its increasing significance and relevance in present research.

The most recent developments in the integration of soft sensors into SPAs, providing an overview of the innovative developments that are changing the field of soft robotics (shown in Fig. 3b). The concept of integrating multi-modal sensors within SPAs is becoming more and more popular as an emerging trend. The versatility of these actuators is increased by integrating sensors that can measure temperature, humidity, pressure, strain, and even tactile feedback [178–180]. This type of sensing increases the potential applications and makes it possible for SPAs to interact with their surroundings more effectively. Further, researchers are looking into bioinspired designs for sensor-integrated SPAs by taking inspiration from natural organisms. These designs seek to enhance the overall performance and responsiveness of soft robotic devices by mimicking the adaptability and flexibility of biological systems. The bioinspired SPAs with integrated soft sensors show high potential for application in soft exoskeletons, prosthetics, and rehabilitation [73,75,87,102]. Additionally, the development of SPAs with integrated sensors has been accelerated by developments in flexible electronics and soft materials. Innovative sensors with naturally flexible and stretchable materials allow for smooth integration with the soft and flexible nature of pneumatic actuators [58,86,120,172].

However, the integration of SPAs and embedded sensors with machine learning algorithms is a noteworthy trend. By utilizing this integration, SPAs can adjust to changing conditions, learn from interactions with their surroundings, and gradually improve their performance. Various applications such as soft robotic grasping and manipulation requiring adaptive and intelligent behavior could benefit from machine learning-driven SPAs with integrated sensors [181–183]. Additionally, the development of wearable and assistive devices has been accelerated by the integration of soft sensors into SPAs. Numerous applications for soft robotic devices with integrated sensors include soft prosthetics, wearable exoskeletons, and assistive devices for individuals with mobility impairments [28,53,87,169]. This trend shows that the improvement in human-robot interaction and further extending human capabilities are becoming increasingly important. Finally, to improve collaborative interactions between robots and humans, recent trends

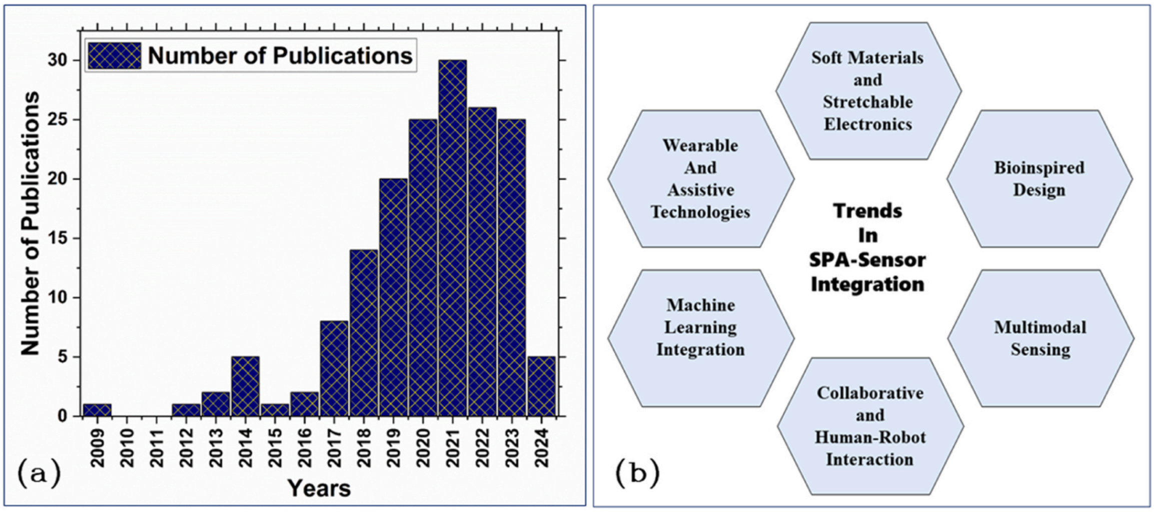

Fig. 3. (a) Publication year-wise and (b) various emerging trends in the field of SPA with integrated soft sensors.

emphasize the integration of soft sensors in SPAs. Applications such as medical robotics, human-robot collaboration, and interactive environments are made possible by soft robotic systems that are embedded or integrated with soft sensors that allow for safe and responsive interactions. In conclusion, these trends represent the dynamic development of SPAs with built-in sensors and demonstrate their potential to have game-changing effects in a variety of fields. The integration of sensors into SPAs is expected to be a crucial step in expanding the potential applications of soft robotics.

4.2. Breakthroughs

Recent developments in the integration of soft sensors into SPAs have led to a redefining of the capabilities and functionalities of soft robotic systems. The major developments in SPA-sensor integration are covered in this section, along with the innovative designs, advanced materials, and enhanced performance (shown in Fig. 4) that have revolutionized the technology.

4.2.1. Innovative designs

Initially, the SPA and sensor integration involves external mounting, embedded wires, embedded chambers, rigid support structures, and external sensor networks. This type of integration causes several losses, such as mechanical integrity, sensing accuracy, sensor protection, maintenance, repair, fabrication complexity, and limited scalability. Therefore, the development of modular designs that enable smooth

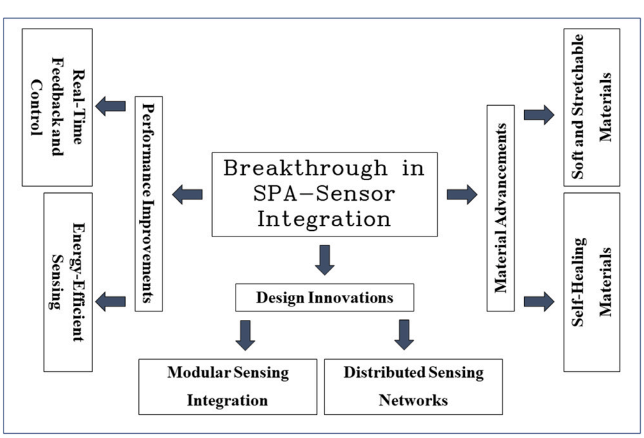

Fig. 4. Recent breakthrough in the integration of soft sensor and SPA.

sensor integration into SPAs is one of the significant advancements. Researchers have looked into modular sensor units, which are readily integrated or fastened to various soft actuator sections [171,175,178]. This design modularity improves flexibility and sensing capabilities can be tailored to fulfill the requirements of individual applications. Further, the implementation of a distributed sensing network is one of the breakthroughs in SPA-sensor integration. The distributed networks integrate sensors all over the actuator's surface, as opposed to depending on a single and centralized sensor [175,179,184]. This innovation improves spatial awareness, which makes it possible to provide feedback that is more accurate and localized, especially for applications that require precise control and manipulation.

4.2.2. Advanced materials

The successful integration of sensors with stretchable surfaces has been largely attributed to advancements in soft and stretchable materials [58,86]. The technological advancements in material science have resulted in the development of elastomers and polymers with customized mechanical characteristics, ensuring their compatibility with the flexible characteristics of soft actuators [12,89,175]. This innovation enhances the robustness and efficiency of integrated systems. Additionally, the use of self-healing materials in SPA-sensor integration is another important innovation [17,62,142]. This novel method expands the lifespan of soft robotic systems by enabling the actuator to gradually heal from small damages. These materials enhance the overall robustness and operational lifespan of the robotic system.

4.2.3. Improved performance

Innovations or breakthroughs in real-time feedback and control systems have improved SPAs with integrated sensors substantially [87,145,169]. The control system and advanced algorithm allow these systems to dynamically adjust to changing environments. This innovation is especially useful for applications like soft robotic grasping and manipulation which require precise and responsive control. Additionally, a significant advancement in SPA-sensor integration is the development of energy-efficient sensing mechanisms [20,185]. Therefore, to reduce energy consumption, researchers have looked into low-power sensor technologies and enhanced sensing techniques. These findings are essential for increasing the operational life and use of battery-powered soft robotic systems in environments with limited resources.

Collectively, these breakthroughs or innovations represent a revolutionary phase in the integration of soft sensors and pneumatic actuators. An entirely novel approach in soft robotics is emerging as a result of convergences in design, material science, and performance enhancements. The integration of SPA and soft sensor provides more complex and versatile functionalities for a broad range of applications. Further advancements in this field are going to influence soft robotic systems as long as researchers keep exploring new ideas and addressing unresolved problems.

5. Challenges and limitations

5.1. Challenges

The integration of soft sensors with SPAs increases their areas of application but several challenges are required to be addressed, which are provided in this section (shown in Fig. 5).

5.1.1. Material compatibility

To achieve compatibility between the materials utilized for SPAs and soft sensors poses a significant challenge. SPAs rely on elastomers with specific mechanical properties to enable flexibility and deformation, while soft sensors often require materials with high stretchability [12,148]. The mechanical mismatch between these materials presents difficulties in integrating them without compromising the overall performance of the integrated system. This challenge directly impacts sensor accuracy, as any mismatch in mechanical properties can lead to inaccurate sensing or unreliable data. Currently, compromises are often made by selecting materials that partially meet the requirements of both sensors and actuators, but this approach may result in reduced sensitivity, durability, or overall performance [78,160]. Moreover, ensuring the long-term durability of soft sensors, particularly those intended for deformable applications, increases complexity. It necessitates the use of materials capable of withstanding repeated cycles of deformation without degradation [62,142]. However, developing robust and fatigue-resistant materials that simultaneously satisfy the needs of both sensors and actuators remains an ongoing challenge in the field.

5.1.2. Sensing accuracy

The presence of nonlinearity in soft sensors integrated with SPAs reflects a variety of challenges, ranging from intricate calibration processes to managing dynamic response complexities [44,59]. The accuracy, reliability, and adaptability of these sensors are significantly impacted by inherent nonlinear behaviors, particularly in deformable materials. Addressing nonlinearity requires a comprehensive approach that encompasses advanced calibration techniques, adaptive control strategies, and a deeper understanding of material nonlinearities [45,50,70]. To fully unlock the potential of soft robotics and enable more precise and dynamic applications across various environments, research efforts must prioritize overcoming nonlinearity in SPA-integrated soft sensors. However, soft sensors within SPAs are susceptible to external forces, temperature fluctuations, and humidity changes, which can compromise their accuracy and reliability [46,105]. Thus, ongoing research is dedicated to developing materials and sensor designs that offer resistance to environmental factors while preserving flexibility and softness. This endeavor aims to ensure that soft sensors maintain accurate feedback even in the presence of environmental interference.

5.1.3. Robustness

In the complex area of complicated robotic structures, ensuring the robust integration of soft sensors with SPAs can be challenging. Design considerations must be carefully completed to ensure that soft sensors maintain optimal functionality during the deformations and movements of the soft actuators [12,48,52]. Thus, the development of resilient integration strategies and connection methods capable of withstanding the mechanical stresses encountered during actuation becomes essential. Moreover, it is crucial to safeguard the fundamental functions of SPAs during the integration of soft sensors. Additional components, wiring, or sensing layers have the potential to alter the mechanical properties of the actuator, potentially reducing its effectiveness and responsiveness [59,73,110]. Therefore, balancing the integration of sensors while preserving the functionality of the SPA demands thorough analysis of the dynamics of the entire system, presenting a formidable challenge in achieving seamless integration without compromising overall performance.

To achieve the full potential of soft sensors integrated with SPAs, these challenges must be addressed. To address these challenges and make soft robotic systems widely used in a variety of applications, research is still being done on novel materials, enhanced sensor designs, and advanced control techniques. Moreover, it is expected that the integration of soft sensors with SPAs will bring in a new era of flexible and adaptable soft robotics as these challenges are resolved.

5.2. Limitations

Despite the promising advancements of SPAs with embedded soft sensors, there are still some inherent limitations which adversely affect the experimental implementation and performance of these integrated systems. These associated limitations are provided in this section (shown in Fig. 6).

5.2.1. Experimental constraints

An anticipated rise in costs related to the soft sensor integration into SPAs is one of the main limitations [48,148]. The development and utilization of soft sensors frequently require specialized materials and manufacturing techniques, which raises the overall cost of the system. This could be a major limitation, especially in situations where

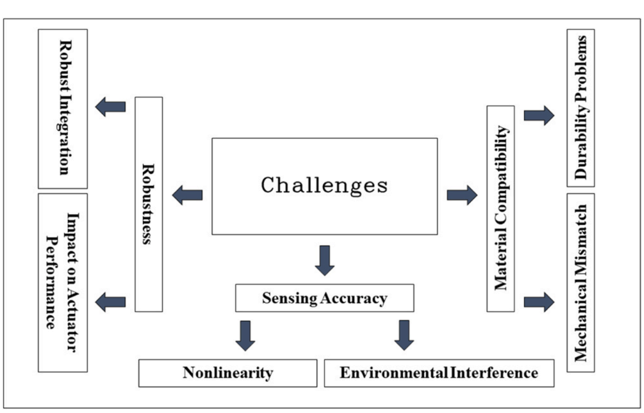

Fig. 5. Challenges experienced during the development of SPAs with integrated soft sensors.

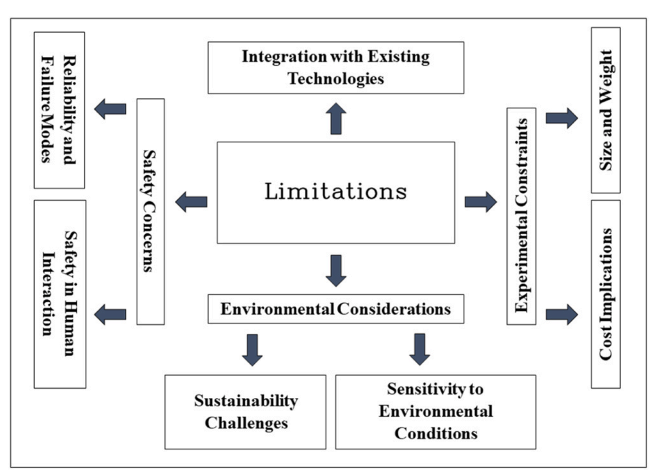

Fig. 6. Key limitations in the SPA integrated with soft sensors.

cost-effectiveness is a crucial factor [157,183]. Additionally, the increased size and weight of the SPA could be the result of soft sensor integration. This additional variable may make SPA-sensor integration less feasible in situations where lightweight and compact designs are essential. It is difficult to overcome weight and size constraints without sacrificing sensor functionality, therefore, careful design considerations are needed [148,157].

5.2.2. Environmental considerations

Soft sensors that have been integrated into SPAs may be sensitive to external factors, such as temperature, humidity, and other environmental factors [46,105,117]. This limitation may have an impact on the accuracy of sensor readings in practical applications, particularly in harsh or dynamic environments. Therefore, to reduce this limitation, it is essential to develop sensors with enhanced environmental resilience [186]. Moreover, the sustainability of the materials used in both SPAs and soft sensors may be a problem. As this field develops, it will be necessary to address how manufacturing processes, material disposal, and the entire life cycle of SPA-sensor integrated systems affect the environment [120,121]. However, it is still difficult to maintain a balance between sustainability and performance.

5.2.3. Safety concerns

Safety concerns become critical in applications where SPAs are used in close proximity to humans. The integration of sensors involves the addition of extra parts, such as stiff elements or electrical wiring, which could be dangerous [3,7]. Thus, it becomes difficult to protect individuals while preserving the soft and compliant nature of the system. That is the reason why researchers are more focused on the research and development of conductive polymer nanocomposite sensors [175,184]. Further, these integrated systems must be reliable as it becomes very difficult to identify and eliminate potential failure modes, such as sensor malfunctioning and actuator deformation. For addressing reliability issues, thorough testing procedures and strong fault-diagnosis designs are crucial.

5.2.4. Integration with existing technologies

Integrating with current technologies or conventional control systems may present difficulties for the integration of soft sensors with SPAs [12,44]. This is due to the different communication protocols, signal processing, or power requirements, which can lead to compatibility problems [50,53]. Therefore, for SPA-sensor integrated systems to be effectively adopted in a variety of applications, these integration limitations must be overcome.

In conclusion, to overcome these limitations, a comprehensive strategy that takes into consideration the economic, environmental, and safety consequences of SPA-sensor integration in addition to its technical aspects is required. Additionally, to clear the path for the wider acceptance and useful application of SPAs with integrated soft sensors, ongoing research efforts are concentrated on finding solutions that can reduce these limitations.

6. Future direction

The investigation and development of SPAs with embedded or integrated soft sensors have opened the way for revolutionary developments in the field of soft robotics. Further research could concentrate on the smooth integration of various sensing modalities in SPAs. An even more comprehensive understanding of the surrounding environment can be obtained by integrating temperature, pressure, strain, and even biosensing capabilities. Moreover, soft robotic systems can be made more versatile and adaptive by looking into ways to combine data from different sensors. Furthermore, one more promising direction is the development of self-sensing actuators, which can detect pressure changes and deformation on their own without the assistance of external sensors. Investigating materials with intrinsic sensing capabilities and developing actuators with real-time feedback capabilities could simplify system design and boost efficiency.

In the future, SPAs and biological systems might be integrated more thoroughly, which would result in the development of biohybrid soft robots. Further, soft sensors that mimic biological sensing mechanisms, like touch and proprioception, can improve the biomimicry of soft robotic systems and provide new opportunities for biomechanics research, medical applications, and human-robot interaction. Additionally, improvements in neuromorphic control algorithms may make it possible for SPAs to simulate more complex and natural movements. By integrating soft sensors that are capable of providing sensory data similar to biological feedback, neuromorphic control algorithms could be developed more easily. This will result in more intelligent and adaptive soft robotic systems. Moreover, SPA-sensor integration might undergo a revolution if smart materials with integrated sensing capabilities are investigated. It may be possible to use certain materials as both actuators and sensors because they naturally alter their properties in response to external factors like pressure, temperature, or light. This dual functionality can simplify designs and improve the overall efficiency of the system. Additionally, the use of biocompatible materials for sensors and actuators in wearable and medical applications is a promising direction for future work. The field of soft robotics in healthcare will advance significantly if soft sensors that can function and integrate effectively with biological tissues are developed.

As soft robotic systems find more and more applications in human environments, future studies could focus on improving safety when humans and robots collaborate with one another. One crucial step towards the widespread use of soft robots in everyday environments is the integration of soft sensors that can recognize and react to human presence and touch, enabling safe and gentle interactions. However, it is anticipated that SPAs and soft sensors will be more widely integrated into wearable technology, providing support and enhancement for a variety of operations. For example, soft exoskeletons with built-in sensors for better mobility, improved user experience, and better adaptability to specific user needs are possible future developments. Furthermore, one promising approach is to process and interpret data from integrated soft sensors using machine learning algorithms. Soft robotic systems can perform better overall and gain more autonomy by learning and adapting to complex and dynamic environments through the development of data-driven models. Finally, future research could explore sensor-based predictive modeling approaches to predict environmental changes and improve SPA responses. This could be helpful in applications like assistive devices or soft robotic prosthetics where proactive and predictive control is essential. Conclusively, there are various exciting opportunities for SPA-sensor integration in the future. These include the development of biohybrid systems, improved sensing capabilities, and new materials and control techniques. These future directions are anticipated to be driven by a collaborative effort of researchers from interdisciplinary fields, opening up new possibilities for soft robotic systems in a variety of applications.

7. Conclusion

This review article has demonstrated that the researchers are successful in integrating SPAs with soft sensors by overcoming challenges or difficulties regarding the material compatibility, sensing accuracy, and robust integrations. Various examples, from soft robotic grippers to assistive and wearable exoskeleton has shown the versatility and significant impact of SPA and soft sensor integration. Despite this successful integration, there are several inherent limitation, such as nonlinearity, cost, size and weight, which are need to be resolved. The review has presented the breakthroughs in soft sensors (strain, pressure, tactile, magnetic, and optical sensors), which contributed to enhance the adaptability and performance of SPAs. These breakthroughs provide the foundation for the development of sophisticated soft robotic systems with enhanced sensing capabilities. Moreover, the successful integration of SPAs with soft sensors opens up new opportunities for soft robots to interact more intelligently with their surrounding environment and subsequently improving their dexterity, responsiveness, and adaptability. This will conclude the significant impact of SPA-sensor integrated system into the human-robot collaboration. Further development of soft robots that can interact effectively and safely with humans are suitable for applications in rehabilitation, healthcare, and assistive technologies.

Future directions that are highlighted by this review article include the integration of smart materials, multimodal sensing, and biohybrid soft robotics. These fields offer encouraging possibilities for researchers to enhance the functionalities and capabilities of SPA-sensor integrated systems. Furthermore, integrating predictive modeling and machine learning with soft sensors offers a data-driven approach to soft robotics. Additional research into these strategies could be performed in the future, allowing soft robotic systems to adapt, learn, and optimize their performance based on real-time sensor data. In defining the future of robotics, the conclusion emphasizes the revolutionary potential of SPA-sensor integration. It recognizes that the effective integration of soft sensors improves the field of human-robot interaction and robotics applications in addition to soft robotics technology. Finally, continuous research and interdisciplinary collaboration is required to resolve the remaining challenges and limitations to expand the area of soft robotics.

Ethics approval and consent to participate

Not applicable.

Funding

This research received no external funding.

Consent for publication

We consent to publish the paper in this journal.

CRediT authorship contribution statement

Narendra Gariya: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sanjeev Kumar:** Writing – review & editing, Visualization, Supervision. **Hemant Nautiyal:** Supervision, Visualization, Writing – review & editing. **Amir Shaikh:** Supervision, Visualization, Writing – review & editing. **Brijesh Prasad:** Supervision, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

Acknowledgments

Not applicable

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