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Review

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Better interaction experience: human-machine interface for soft robotic systems

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Abstract

As an emerging robotics technology, soft robots have received extensive attention and research in recent years, and are gradually emerging in the field of robotics by virtue of their soft materials and unique drive methods. They are able to adapt to a variety of unstructured environments and interact with humans in a safer way, opening up a whole new direction for the development of robotics. As an important component of the human-machine interface (HMI), the performance of the sensor also determines the smoothness and accuracy of human-machine interaction. The emergence of new materials and the maturity of various technologies and algorithms also make the HMI of soft robot systems increasingly refined, bringing more possibilities to soft robots. The abstract introduces the development of HMI in recent years, and discusses the role played by HMI in soft robot system and mentions some optimization solutions.

Keywords: Soft robotics, human-machine interface, medical robotics, algorithmic control, sensors

1. INTRODUCTION

Robots can replace or assist humans in accomplishing complex, heavy and dangerous tasks, and have been widely used in equipment manufacturing, resource exploration, biomedicine and other fields. Traditional robots are generally composed of rigid materials such as metals, ceramics, and hard plastics, which have high strength and high modulus and are easy to realize precise control so as to perform specific tasks efficiently; however, these rigid-body robots also suffer from the disadvantages of poor suppleness, poor environmental adaptability, and noise, limiting their environmental adaptability and human body affinity, and their human-robot interaction-related applications have great limitations. At the same size, soft-bodied robots have lighter structures and more degrees of freedom than rigid robots. Due to these characteristics, soft-bodied robots are used in industries such as ocean exploration[1,2], food processing[3], and medicine[4-6].

As a class of robots that can actively interact with the environment and withstand "large" deformations by relying on their intrinsic or structural flexibility, soft robots are gradually demonstrating their unique advantages and application potential, which are made of soft materials, with a variety of drive modes and sensing technologies, and can be adapted to different working environments and tasks.

The human-computer interface, as an interface for information exchange between the system and the user, realizes the conversion between the internal form of information and the form acceptable to humans[7]. The user inputs information to the system through the human-machine interface (HMI) and receives feedback from the system to operate and control the system. The role of these interfaces is to simplify the complex operations of the robotic system and to realize an important role for the overall user experience aspect while improving productivity, usage and interaction safety. Regarding the framework of the paper, first, we present a comprehensive survey of recent advances in HMIs for soft robotic systems, focusing on a number of applications for wearable, wireless transmission, and so on. Second, we summarize the future challenges and work in this area, including the design of soft structures, coordination of multiple sensors, and integrated decision-making of information. Finally, the paper is concluded.

2. RESEARCH ON SOFT ROBOTS

As a new type of robot, soft robots have a flexible external structure that does not cause damage or pose danger when they collide with objects or people. This gives them an advantage in human-robot interaction and collaboration, allowing safer coexistence and cooperation with humans. Soft robots also often have enhanced tactile capabilities and can more closely resemble human tactile perception.

Due to the characteristics of flexible materials, soft robots can more accurately perceive and control the external environment, enabling more delicate and precise operations. This is one of their unique advantages. The design and optimization of the HMI of soft robots is crucial, as efficient information transfer and data feedback make them superior to traditional rigid robots in remote control and autonomous learning.

According to their drive mode, soft robots can be categorized into pneumatic drive[8-10], hydraulic drive[11-13], shape memory alloy (SMA) drive[14,15], electroactive polymer (EAP) drive[16], and magnetic drive[17-19]. Due to the diversity of drive modes, soft robots can adapt to various environments, allowing researchers to select specific characteristics and advantages to design soft robots that meet different requirements. According to their structural characteristics, they can be categorized into continuous type, modular type, and cavity type. Based on bionic principles, soft robots can be categorized into bionic mechanical fish[20,21], peristaltic type[22], and inchworm type[23]. In addition to the above categorizations, there are also soft robotic arms[24-26], flexible gripper claws[27,28], and more. Table 1 summarizes the advantages and disadvantages of different driving methods.

The wide range of applications of soft robots - whether in industry, badlands exploration, or medical treatment - presents unique needs and breakthrough points. Researchers design the HMI according to these specific requirements to enable more efficient human-robot interaction. Table 2 shows the main application areas of soft robots.

Table 1. Driving methods and advantages and disadvantages of soft robots

Driving methods	Advantages	Disadvantages
Pneumatic drive	Quick action Highly adaptable	Less power for the same volume Not easy to control the speed
Hydraulic drive	High positional accuracy High stability	High cost Greatly affected by temperature
SMA drive	With sensing function No mechanical drive required	High friction loss Low output power
EAP drive	High deformation capacity Low power consumption Rapid response	Lower output force Low response frequency
Magnetic drive	Good targeting Can be miniaturized Good biocompatibility	Poor accurate reconfiguration Stiffness limited by material particle concentration

SMA: Shape memory alloy; EAP: electroactive polymer.

Table 2. Application areas of soft robots and related research

Application area	Relevant work in the application area
Industrial automation	[29,30]
Environmental investigation	[31-34]
Medical treatment	[35-37]
Victim search and rescue	[38]
Daily services	[39,40]
Food production processing	[41,42]

2.1. Industrial automation

Traditional industrial robots have a series of problems such as complex operation and debugging, large size, lack of flexibility in production, *etc.*, and need to be isolated from human beings when working for safety reasons[43], which greatly limits the application of traditional robots in a series of industries such as the service industry and high-end manufacturing. Similarly, this also limits the interaction between humans and robots, greatly reducing the role of the HMI, which is not conducive to the realization of efficient automation in industry.

Flexible robot arms are characterized by flexibility and easy manipulation, but in the field of industrial automation, only having a soft nature is not enough to meet some heavy-duty industrial tasks, such as the production of steel and related products. Therefore, flexible arms need to have flexible components that realize complex movements such as bending, twisting, and stretching, and are able to realize the switching of the robot arm between flexibility and rigidity. Inspired by lockjaw, Xie *et al.* constructed a chain of extensible particles with a special geometry and enclosed it inside a flexible membrane as a reinforcement layer, a structure that realizes reinforcement through air removal[44]. The reinforcement works even at 90% extension and the stiffness can be increased by a factor of 15. However, there is still room for improvement in this type of robot, such as choosing a more flexible material for the reinforcement layer particles or refining the size of the particles.

While automation has helped improve product quality and productivity in many industrial sectors, manual work still plays a very important role in production, consignment and many other areas. In industrial production, it will be difficult to get a return on investment from automation due to the decreasing volume of individual products and the increasing number of individualized products. In logistics and consignment, automation in this area is difficult due to the different weights and sizes of parcels. Otten *et al.* introduced an exoskeleton robot for the upper limb[45]. It consists of a HMI including gloves equipped with haptic sensors to measure the grip force as a way to estimate the user's intention, together with force sensors coupled to the user's forearms to support the user and reduce the burden of industrial tasks. However, the authors also need to increase the contact surface of the sensors or choose more appropriate sensors, such as electromyography (EMG) sensors, to avoid the omission of some test objects and thus accurately predict the user's intention to operate.

2.2. Environmental investigation

In nature, from mollusks to reptiles, organisms show amazing diversity and adaptability, after a long time of evolution, biological body structure, body shape, *etc.* can be well adapted to the living environment. Bionic soft body robots for biological imitation can realize the special movement of some animals[46], so that it is more conducive to the survey in different geographic environments.

2.2.1. Tight terrain survey

In extremely confined spatial explorations, such as ruins, products or building crevices, where it is not easy to destroy the products or buildings, there is a need for small robots with multiple motion modes to explore[47]. Exploring unknown and complex environments using soft robots is important and challenging because it needs to be able to adapt to the environment and make behavioral decisions similar to those of humans, which requires a combination of power, sensors, and control for intelligent computing[48]. Taking the bionic earthworm robot as an example, earthworms have the characteristics of inhibiting muscle contraction and isovolumetric cavities, which can be adapted to the complex terrain environment[49], based on which Das *et al.* designed a soft modular robot similar to earthworms, and according to the experimental results, the maximum elongation of this earthworm robot under the pressure of 1 bar is 10.97 mm, and the maximum compression rate under the pressure of 0.5 bar is 11.13 mm[50]. At a depth of 40 mm, the robot was able to move at a speed of 0.26 mm/s, implying that the design can be explored into deeper and narrower areas. The crawling motion of the robot in different environments is shown in Figure 1.

2.2.2. Underwater robots

Underwater robots can reach depths and hazardous areas that are inaccessible to humans due to their flexibility and efficiency[51]. Therefore, they are able to explore and perform complex operational tasks in performing restricted underwater spaces, such as underwater cleaning, underwater rescue, underwater building mapping, and deep-sea cave exploration. Swimming involves complex interactions between deformable objects (e.g., fish undulating their bodies and flapping their fins) and water motion. Flapping motion is a fast and energy-efficient mode of locomotion for birds, insects, and marine animals, among others[52]. For example, fish[53,54] soft robots are designed to have faster movement speeds in water, facilitating better work in underwater environments. Zou *et al.* were inspired by the shape of a starfish to design and build a starfish-like soft robot with a unique design of five directional valves that allowed it to adjust its shape to fit through narrow gaps[55].

Despite significant advances in pliability, soft-bodied robots still face numerous challenges in performing underwater operations, collecting vital information, and feeding the collected information back to the operator. For example, the robot's vision control system must recognize targets in the environment with pinpoint accuracy. In conducting underwater rescue operations, it is important to be able to safely extract victims from the water without posing a threat to the victims or the surrounding environment. In addition, an effective interaction interface is essential to ensure seamless cooperation between underwater robots and

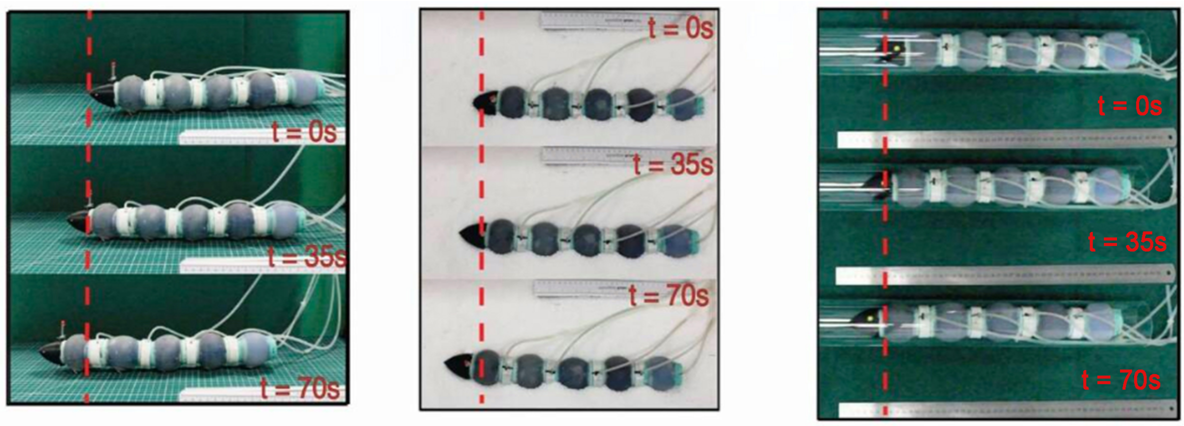

Figure 1. Crawling motion of earthworm-like robots in different environments[50].

human operators. However, in existing research, the technology on underwater robot-human interaction is still in its infancy and lacks in-depth research and development.

2.3. Medical field

Diverse treatment scenarios and needs exist in the medical field, such as rehabilitation training[56,57], patient care[58,59], and drug transportation[60-62]. Soft robots can adapt to different medical scenarios and needs by virtue of their flexibility and adaptability. For example, in rehabilitation training, soft-bodied robots can provide personalized training programs according to the specific conditions of patients to help them recover their functions faster. When performing medical operations, they can more flexibly adapt to different surgical environments and operational needs. In neurosurgery, ophthalmology and other fields that require highly detailed operations, soft robots can assist doctors to carry out more accurate and safe surgical operations.

2.3.1. In vivo surveys

Current research in the field of biology is still in a limited stage; the reason is that it is difficult to collect data from living bodies in real time. Although implantable micro-robots are currently available, in living organisms, robots are not only limited by the size or change of space, but also by different wetness, acidity and alkalinity, *etc*., which will affect the performance of the robot, and most importantly, the guarantee of its safety. Wu *et al.* designed a controllable peeling and loading mechanism of an adhesive pad, and utilized an applied magnetic field to regulate the adhesion and detachment of the adhesive pad to achieve the climbing on the surface of tissues, and experimentally demonstrated that the robot crawled up and down the three-dimensional surfaces with different geometric shapes, roughness and softness[63]. Experiments showed that the robot crawled up and down three-dimensional surfaces with different geometries, roughness and softness. Due to its unique foot pad design, the robot can carry objects with large mass or volume and small wireless electronic sensors for environmental monitoring. Figure 2 shows the robot crawling on the surface of the soft tissues of a pig.

Unlike the static observations of traditional medical imaging techniques, implantable electronic sensors are capable of continuously tracking key parameters of soft tissues during dynamic physiological activity[64,65], including interfacial adhesion properties, acid-base homeostasis status, viscoelastic mechanical response, and changes in the concentration of specific biomarkers. When a robot monitors data in the human body, it also engages in human-robot interaction, which, unlike other forms of human-robot interaction, is robot-

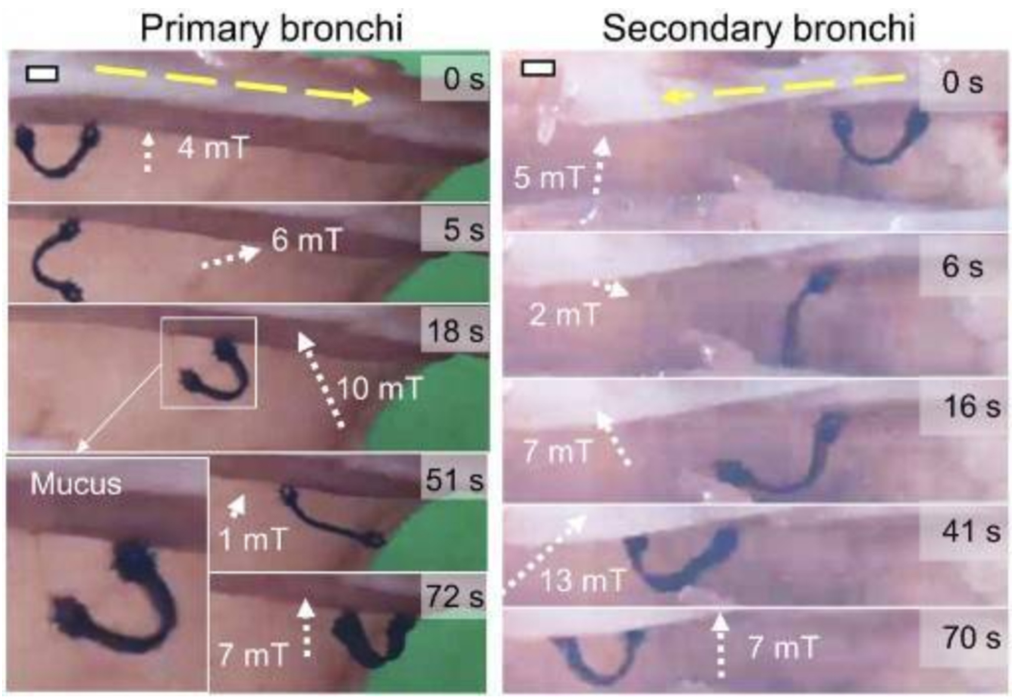

Figure 2. Vertical and inverted climbing on the surface of pig tissues[63].

driven and humans are in a passive position. This means that for a safe and good interaction, the robot needs to be precisely targeted and controllable. Wang *et al.* used a minimally invasive approach of *in situ* sensing of physiological properties of tissues using a wireless miniature soft robot to accurately recover tissue properties from the shape of the robot and the magnetic field by controlling the robot's interactions with the tissues using an external magnetic field, which was visualized by medical imaging[66]. The authors synthesized a variety of substrates for testing the robot's adhesion in their experiments, which ranged from 0.13 ± 0.02 to 0.82 ± 0.02 mN; however, the robot was slow to respond to pH, typically taking about 30 s to sense a change in pH. Rogatinsky *et al.* demonstrated a millimeter-scale soft robotic platform capable of guiding existing interventional devices to various targets in the right atrium through a 2 mm (i.e., 6 Fr) working channel running its entire length[67]. The authors deployed a stabilizing mechanism in the explanted portion of the porcine superior vena cava, and in experiments with a given displacement, the stabilizing mechanism withstood a radial force of 0.98 ± 0.02 N at 5 mm displacement and an axial force of 3.63 ± 0.11 N at 2 mm displacement, demonstrating that it is sufficiently stable to maintain continuous contact with a moving target, providing new ideas for robot-biological tissue interaction. Dong *et al.* embedded magnetized neodymium-iron-boron (NdFeB) particles into a network of adhesive stickers in order to form a programmable magnet for a soft robotic system, which was driven by an external magnetic field to apply a drug-loaded therapeutic film to the ulcer[68]. Figure 3 shows the process of transferring the therapeutic patch in the gastric environment by the robot.

2.3.2. Assisted rehabilitation

Soft robots have also shown good results in rehabilitation therapy. For patients with limb dysfunction, these robots can provide long-term, safe and economical rehabilitation therapy[69]. Their soft nature allows them to interact with patients without causing serious injuries, and at the same time, the soft robot can mimic natural movement to help patients recover motor function[70,71]. Maintaining an intense rehabilitation program can be challenging for many, especially for vulnerable populations with limited resources. The use

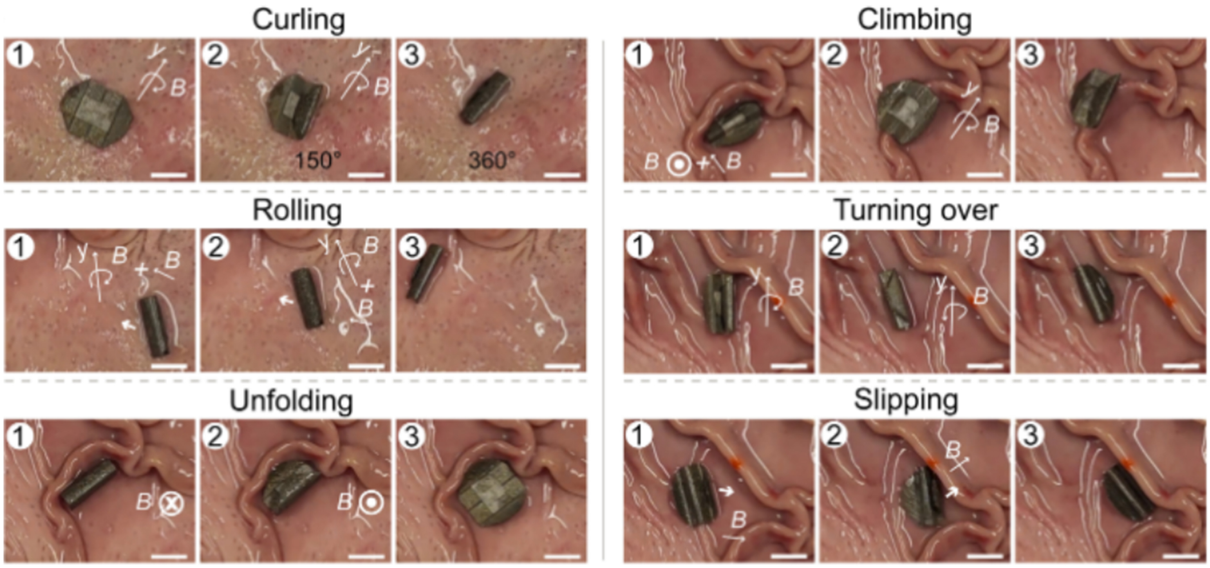

Figure 3. The therapy patch transfer by soft robot in stomach[68].

of robots for rehabilitation may lower the threshold for accessing rehabilitation treatment and promote a more sustainable rehabilitation process for patients in need. In addition, for patients with neurological deficits, therapeutic robots can be targeted and designed to achieve therapeutic or physiological assistance through precise tracking and targeted stimulation. As shown in Figure 4, Yang *et al.* proposed an implantable magnetic soft robotic bladder that applies mechanical compression to the bladder via magnetic actuation to assist urination[58]. Experimentally the authors implanted this magnetic soft robotic bladder in pigs with low bladder function and tested its assisted performance at 14 days postoperatively, obtaining 110 mL of urine voided in 20 s. However, despite the similarities in shape, volume and urodynamics between porcine and human bladders, the applicability of this technology to patients with low bladder function needs to be investigated further in terms of biocompatibility and stability.

Most patients prefer wearable assistive devices to implantable rehabilitation robots; on the one hand, they generally do not require surgery and are safer for patients. Sadeghi *et al.* designed an exoskeleton glove specifically for finger rehabilitation, which is actuated by a NiTi SMA, and the experimental data show that the minimum torque of the exoskeleton glove at each finger joint is 0.2 Nm, which is sufficient to counteract joint resistance and meet the rehabilitation torque requirements[72]. torque of 0.2 Nm, which is sufficient to counteract joint resistance and meet the rehabilitation torque requirements to be able to successfully move to the desired position during rehabilitation therapy. In healthcare, eye tracking technology has many applications. For people with severe cerebral palsy or those suffering from neurological disorders, muscular dystrophy, *etc.*, eye tracking enables devices to help them express their needs through eye movements. Basic deliberate eye movements such as sweeping, gazing, and blinking can be used for operations in HMI, where the HMI translates the user's eye movements into information and connects to other electronic devices, enabling operations such as simulating a computer mouse, typing using a virtual keyboard, or using a smartphone, helping the user to convey complex information in a relatively short period of time. Golparvar *et al.* proposed for the first time a wearable eye-tracking system based on graphene textiles, which, in combination with electrooculogram (EOG) recordings, enables complex operations to be accomplished through eye movements alone[73]. According to the experiments, the average typing speed of 6 characters was about 62 s or about 6 CPM when a random sequence of 6 letters was typed using the eye. The greatest excellence of this research is that the graphene preventive skin with

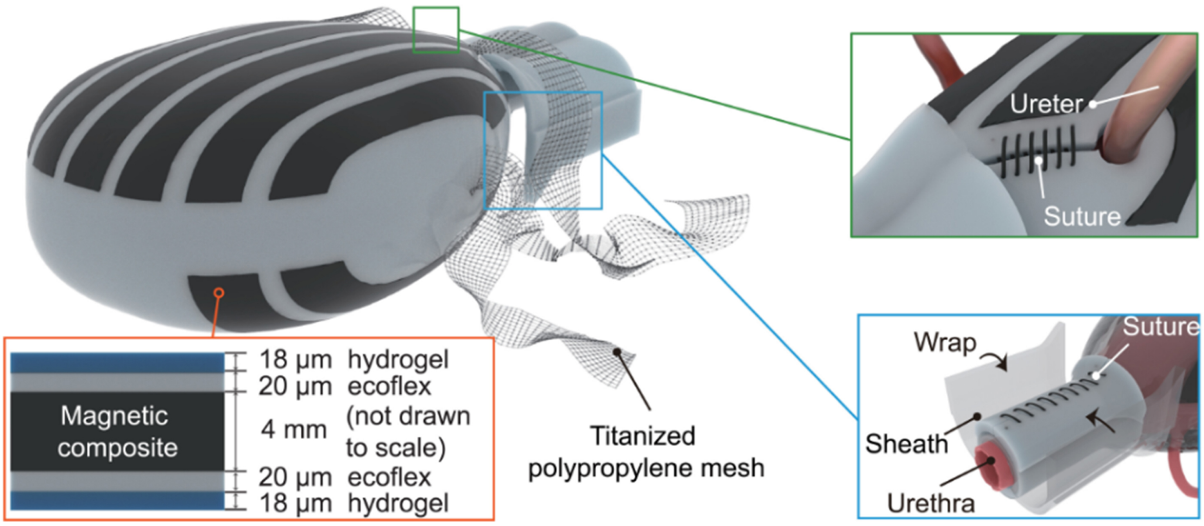

Figure 4. A titanized polypropylene mesh is used to bind the MRB with pelvic fascia[58]. MRB: Magnetic soft robotic bladder.

eye tracking system is very soft and lightweight and is very simple to use. Figure 5 shows a wearable device maneuvering a four-wheeled robot.

3. HUMAN-ROBOT INTERACTION WITH SOFT ROBOTS

3.1. Forms of HMI

As soft robots become increasingly diverse with the invention of new materials and the improvement of drive methods, the forms of HMIs must also evolve to expand application scenarios and enhance the functions of soft robots. The goal of all these interfaces is to simplify the operation of complex robotic systems. Table 3 shows the various forms of HMIs applied to soft robots.

Traditional HMI surfaces are bulky, rigid, and expensive, and mostly focus on robot control without giving sufficient feedback to the user, preventing applications from accomplishing complex tasks. Therefore, it is particularly important to develop an HMI capable of accurate sensing and feedback. HMI modalities can be categorized into several types[74]: (i) soft-touch sensors; (ii) biosensors; and (iii) multi-sensor data. To understand the development of soft-touch sensing technology, we focus on the following four types of sensors: piezoelectric sensors, piezoresistive sensors, capacitive sensors and acoustic sensors. With the development of strain sensors based on piezoresistive materials, they are often used for continuous strain data detection. Wajahat *et al.* fabricated flexible strain sensors using carbon nanotube (CNT)-polymer composites embedded in a smart glove to monitor continuous data of finger deformation and bending[75]. Under cyclic loading-unloading conditions with a strain range of 2.0%, the response rate of the strain sensor was about 400 ms. Xu *et al.* used a laser-engraved silver-plated fabric as the electrode of the sensor, and the linear operating range of this flexible sensor reached the level of 800 kPa, with a high sensitivity of 6.417 kPa^{-1} and a response time of only 4 ms, which indicates the sensor's excellence[76]. As shown in Figure 6, Huang *et al.* inspired by the origami structure, proposed an electrode structure in the form of a folded plate, where the capacitance is adjusted by adjusting the folding angle[77]. According to the experimental results, this stretchable capacitive sensor can be stretched up to 200% with a low hysteresis of 1.2% and a response time of < 22 ms, which offers the opportunity to accurately measure large and complex soft deformations in wearable devices, soft robotic sensations, and human-computer interfaces, which offer potential applications for the accurate measurement of large and complex soft deformations in wearable devices, soft robot sensations and HMIs.

Table 3. Major classifications of HMIs and related research

Forms of HMI	Relevant work in the application area
Physical control panels	When the user presses a button or toggles a switch, it changes the mechanics inside the control panel, generating different electrical signals for different operations
Touchscreens	Applying pressure by touch changes the internal resistance, causing a change in the electrical signal and realizing the delivery of commands
Gesture recognition systems	Optical devices such as cameras and infrared sensors are used to capture the user's gesture movements, motion trajectory, *etc.*, combined with deep learning and response
Voice commands	The microphone is utilized to capture voice information, which is processed to parse and recognize the operator's commands and sent to the execution module
Brain-computer interfaces	Communication and interaction between humans and machines by capturing signals from brain activity and translating them into commands that the robot can interpret and execute

HMIs: human-machine interfaces.

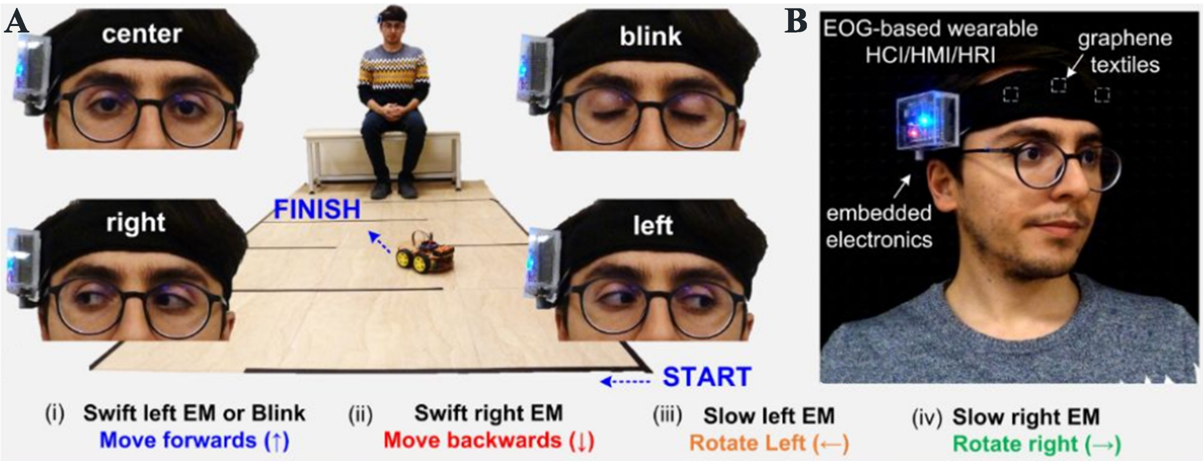

Figure 5. Overview of the technology demonstrator for the wearable graphene textile-based assistive device for HMI applications[73]. (A) Manipulating a four-wheeled robot through four eye movements; (B) Picture of the wearable eye tracker including smart headband with graphene textile electrodes and embedded electronics housed by an acrylic holder all mounted on the head. HMI: Human-machine interface.

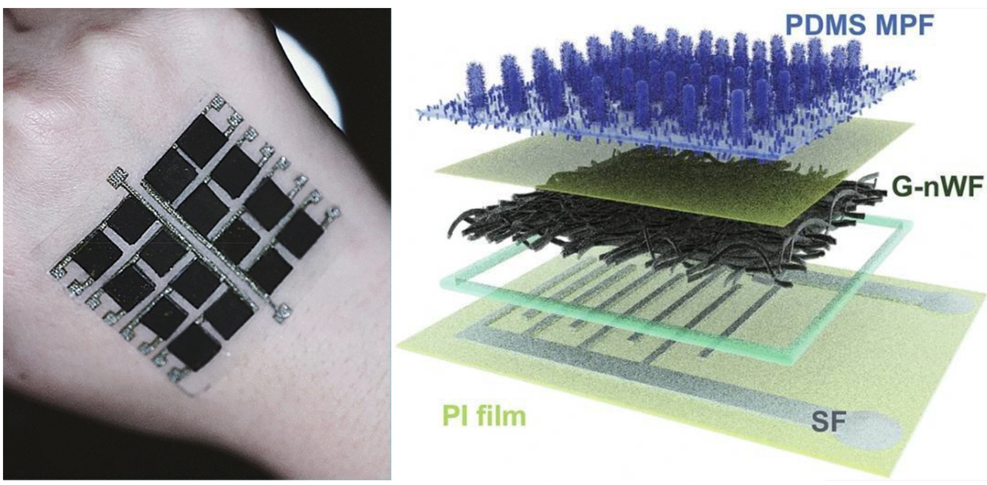

Figure 6. Sensor attached to the hand and its structure[76].

Bioelectrical signals from sources such as electroencephalogram (EEG)[78,79], EOG[80,81], and EMG[82,83] are often used in HMI to predict the user's intention by extracting and recognizing the characteristics of the bio-signals, and to control the movement of external actuators based on the signal content. In current research, biopotential sensors are mainly used in two main directions: wearable devices and wireless remote control. As shown in Figure 7, Liu *et al.* investigated skin-like sensor patches that convert human motion into electrical signals, which are processed and wirelessly transmitted to a target robot to perform operations by tightly fitting them to various skin surfaces of the human body[84]. The results show that the wireless transmission distance can be extended to any place covered by the Internet, the response time is from 30.2 to 47.8 ms, and the operating duration can last up to 240 min. However, there is a risk that the sensors of this skin patch can be dislodged due to sweating of the user's skin and collision, and the authors should compare the patch approach with the portable wearable model in terms of stability and accuracy. Qin *et al.* investigated a flexible dual-mode capacitive sensor (FDCS), which is noteworthy for its two interaction modes, non-contact and direct touch, and for its detection distance of up to 20 cm under wireless sensing, with a similarly excellent response time of around 90 ms[85]. Unfortunately, the authors centered on wireless sensing in the proximity case, with less description of pressure touch.

In order to realize wearable HMI, researchers have worked on linking traditional electronic devices to soft human skin. Due to the rigid and brittle nature of traditional strain sensors, they cannot stretch under large deformation conditions, which will hinder their use on soft surfaces or in situations of large deformations, especially in complex and large deformation systems, where the deformations are usually large, and this is a major trend in the development of flexible sensors. Lotti *et al.* for the first time, combined an HMI based on EMG-driven musculoskeletal modeling combined with a soft wearable arm exosuit to produce an online controllable upper limb exosuit, and showed that the tracking accuracy of the signal was 0.9 ± 0.04, which is much more accurate than 0.8 ± 0.06 when assisted by a gravity compensator, which provides a new paradigm for symbiotic interactions between human and exosuit devices[86]. Based on a musculoskeletal model of the shoulder, Liu *et al.* designed an HMI incorporating a soft bendable stretch sensor for capturing the user's shoulder muscle signals for virtual wheelchair driving[87]. The advantage of this sensor is its ability to excellently record shoulder movements and decode user behavior.

3.2. The influence of materials on the HMI

In recent years, soft-adaptive materials have received increasing attention due to their applications in tissue engineering, soft robotics, biosensing, and flexible displays, where their properties change their properties and performance in response to changing environmental conditions. To design these soft responsive materials, a variety of active materials have been utilized, including hydrogel[88,89], SMAs[90-92], and liquid crystal elastomer[93,94].

New materials are driving the field of soft robotics, where multifunctional composites can integrate multiple functions[95], such as sensing, imaging, and adaptive environments. The application of new materials, such as flexible screens and wearable materials, is gradually being used in human-computer interfaces, and these materials provide designers with more room for innovation, making interface design more diverse and personalized. On the one hand, the texture, color and glossiness of materials can affect the aesthetics and attractiveness of the interface. High-quality materials such as metal, glass and plastic can give devices a high-end, stylish appearance and bring visual appeal to users. On the other hand, choosing soft, skin-friendly materials can enhance user comfort when touching the screen or buttons. Everyday smartphones and tablets, for example, are often made of a glass and plastic composite, which ensures a sturdy screen while providing a smooth touch. Table 4 compares the performance of different soft materials.

Table 4. Types and performances of soft materials

Soft materials	Tensile strength	Elongation at break	Elastic modulus	Fatigue life
Silicon rubber	Normal	High	Low	High
Dielectric elastomers	High	High	Low	High
SMAs	High	Low	High	High
Hydrogel	Low	Very high	Low	Low

SMAs: Shape memory alloys.

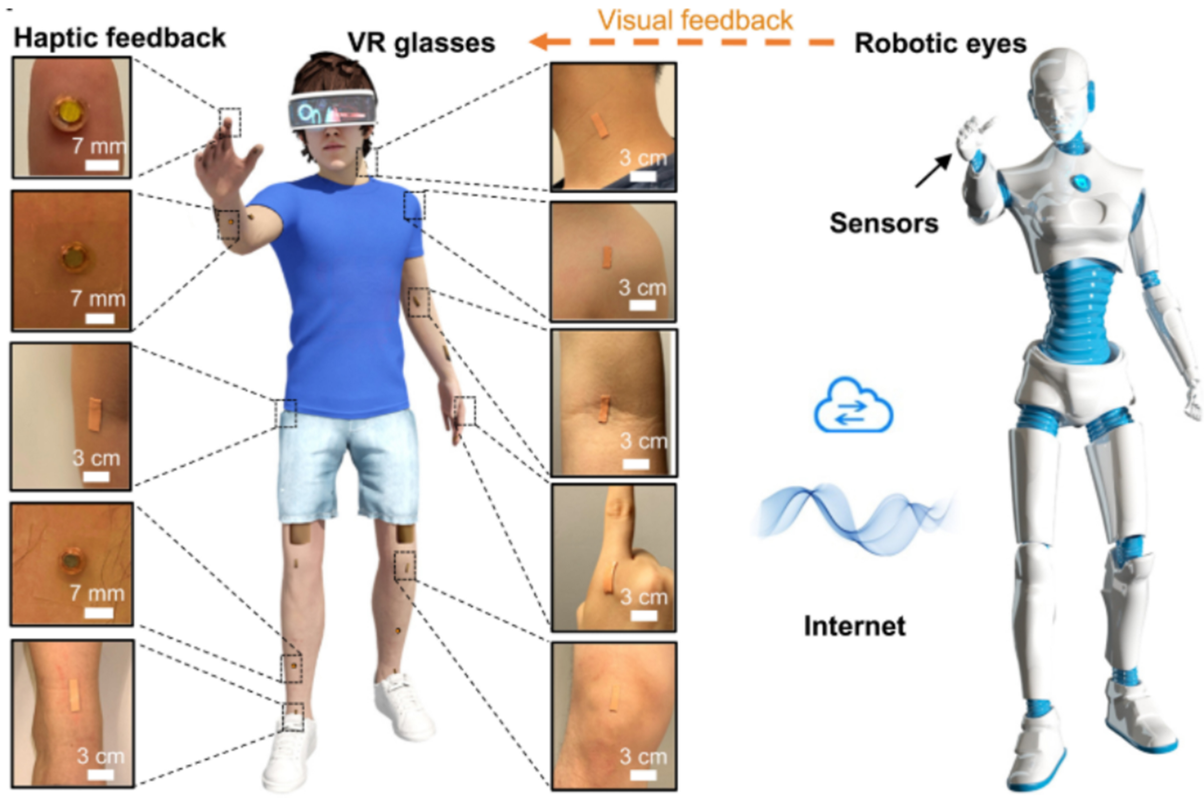

Figure 7. Sensor patches wirelessly manipulate robots with haptic and visual feedback over the Internet[84].

Here we briefly introduce magnetorheological elastomeric materials, a newly invented smart composite material whose modulus of elasticity can vary in response to changes in the strength of an applied magnetic field, which in turn allows for contraction and expansion as well as bending motions. The material exhibits precise adhesion control, stability, and repeatability through rapid stiffness changes controlled by an external magnetic field[96]. Smart materials such as shape memory polymers (SMP) and EAPs have the ability to sense and respond to external stimuli. These materials can generate corresponding deformation or movement according to the stimulation of electrical, thermal, magnetic, optical and other signals, thus endowing soft robots with a higher level of perception and adaptive capabilities. For example, by combining synthetic materials with biomaterials, new soft materials with biocompatibility and vitality can be developed, enabling soft robots to better integrate with the biological environment and realize a wider range of applications. In the work of Liu *et al.*, composite films of magnetic iron particles dispersed in a SMP matrix were demonstrated, and the composite films responded to both magnetic fields and light for reconfigurable remotely actuated soft robots[97].

4. DESIGN AND CONTROL BASED ON OPTIMIZED HMI

4.1. Design

In recent years, tremendous progress has been made in the development of small, untethered soft robotic systems that are capable of programmable shape deformation via magnetic fields, chemical cues, temperature, light, and other forms of external or environmental stimuli[98]. Jin *et al.* prepared and characterized a class of crystalline shape memory networks consisting of temperature-reversible and photoreversible covalent bonds using programmable crystalline SMPs with thermo- and photoreversible bonds[99]. Wang *et al.* proposed a small and dexterous flexible robot, which is based on a dielectric elastomer artificial muscle and consists of a pair of asymmetric feet, and a pair of chiral subfeet[100]. The flexible manipulation of target molecules is achieved by chiral modulation. Tang *et al.* integrated a soft electrofluidic pump, actuator, healing electrofluid, and e-skin[101]. And synthesized a healing electrofluid that can form a self-repairing membrane with excellent stretchability and strong adhesion, which can realize rapid self-repairing of soft materials without complex repair process when encountering accidental breakage, especially in dealing with large-area damage scenarios showing significant technical advantages.

When designing the structure of a soft robot, its passive flexibility is a key element[102]. This flexibility can be carefully designed into a safe and reliable human-robot interaction, allowing the robot to interact with humans in a natural and harmless way. Through this design, machines and humans can communicate closely without physical constraints, thereby increasing productivity and reducing the risk of potential accidents. However, passive pliable systems suffer from low control accuracy and complex dynamic processes. Yang *et al.* proposed tensile interference fibers, by quickly adjusting the tensile stiffness and maintaining the bending stiffness in all directions, when stuck, its tensile stiffness increased by more than 20× in less than 0.1 s, but the bending stiffness only increased by 2×[103]. Simulation and experimental results verify that the interference technique can achieve adaptive behavior of soft robots during interaction. Combined with HMI technology, Li *et al.* investigated bionic stretchable fiber optic strain (BSOS) sensor; combined with machine learning techniques such as BP neural network, the sensor is able to recognize the user's gestures, and the experimental results show that the sensor can reach 80% of the degree of stretch, and the accuracy of gesture classification is as high as 96.36%[104]. Experiments also confirmed the sensor's temperature resistance and water resistance. Figure 8 shows the structure of the system and the rules for transforming information.

Sensing is crucial for planning and performing safe physical human-robot interactions; e.g., combining robotic visual sensing with haptic feedback can greatly enhance navigation and manipulation[105]. How to establish an efficient and sustainable method that can be applied in real-world environments has been an important research topic in the field of human-robot interaction. Most of the current research on soft robots is limited to existing soft robots and is not applicable to real sensing systems[106]. Nguyen *et al.* designed a haptic proximity sensor based on the combined inductive-capacitive proximity sensing principle to provide distance information in the form of impedance between the sensor and the approaching object[107]. The experimental results show that the sensor can detect the actual distance up to 300 millimeters from the human body, and can also effectively identify conductive and non-conductive materials. The impedance change is very stable with an accuracy of up to 90%. Also, as a non-contact HMI, Le *et al.* complemented the information collected by the humidity sensor and the friction electric sensor with each other, which empowered the simultaneous collection and recognition of information in several different directions while satisfying a stable continuous response[108]. The results show that the complementarity of the two types of sensors provides excellent performance, with high signal strength (Q = 1,729.5) and low signal noise level (±0.31% RH) ensuring an effective and stable interaction with nearby fingers. Figure 9 illustrates a schematic of the HMI.

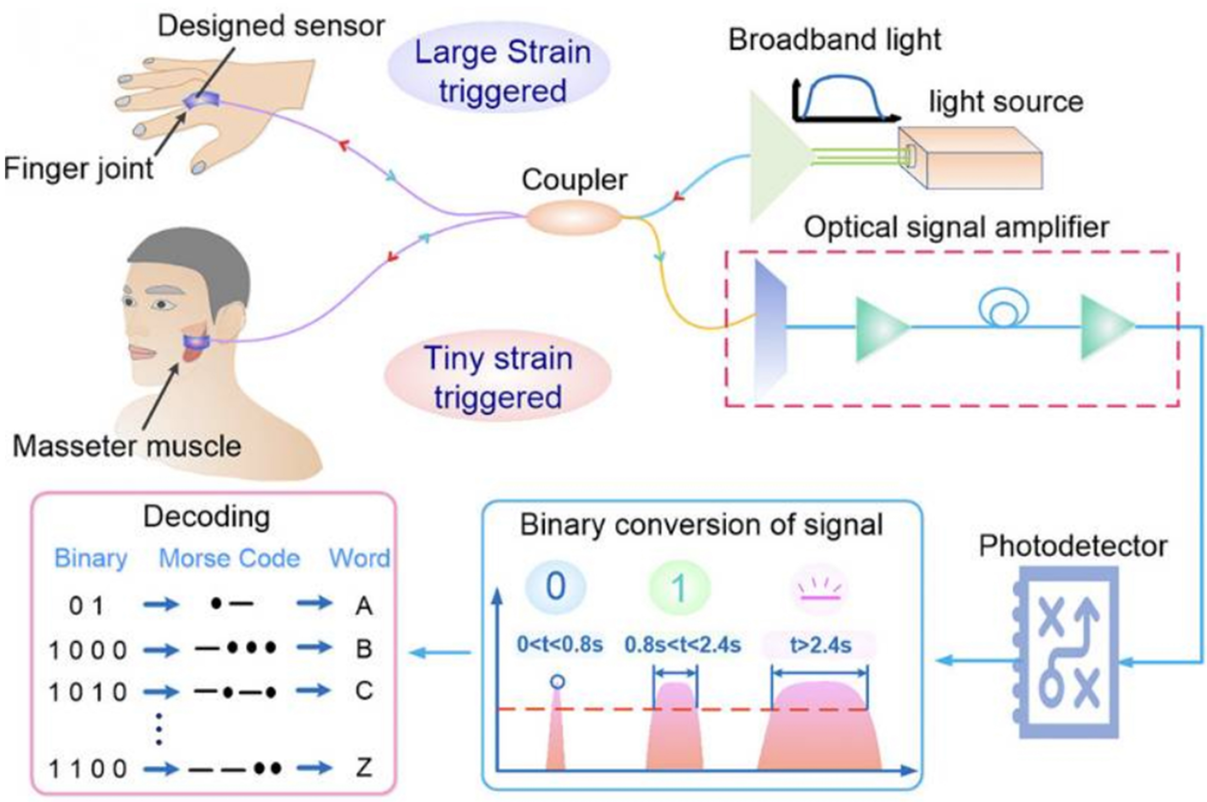

Figure 8. Internal structure of the system and the definition of information conversion rules[104].

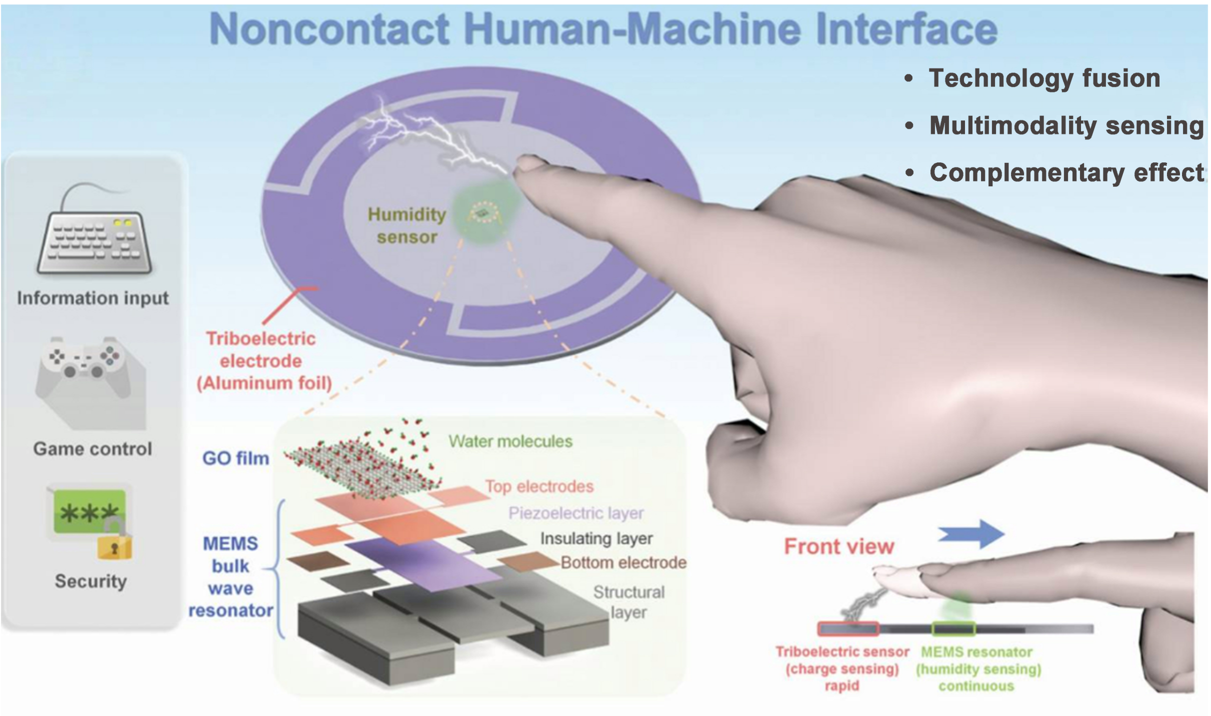

Figure 9. Schematic illustration of the HMI consisting of a MEMS bulk wave resonant humidity sensor and a triboelectric sensor[108]. HMI: Human-machine interfaces; MEMS: Microelectromechanical system.

4.2. Modularization

The use of new materials has driven modular design and customizability of soft robots. By adopting modular design, researchers can rapidly prototype and iteratively optimize soft robots. At the same time, by adjusting the number of modules, arrangement and size parameters, *etc.*, soft robots can be customized to adapt to different environments and tasks. This modular design and customizability greatly improves the flexibility and adaptability of soft robots. Dong *et al.* embedded programmed magnetization modules into adhesive sticker layers to construct soft robots with programmable magnetization profiles and geometries within a driving magnetic field, where the three-dimensional deformation of the soft robots is mainly driven by magnetic moments driven by magnetic forces[68]. This strategy simplifies the fabrication of multifunctional soft robots with more freedom in specifying the magnetization profiles and expands the range of possibilities for functional integration.

The modular design makes the soft robot easily expandable, allowing for expansion and upgrading of functionality by replacing or upgrading different modules, thus providing a more flexible and scalable HMI. In terms of maintenance, the modular design allows damaged modules to be replaced individually, reducing repair costs and time[109]. Null *et al.* designed a modular underwater soft robot arm driven by hydraulic actuators[110]. The whole soft arm is composed of several independent components, in which the circuit network and fluid network can be connected with each other. On this basis, forward and backward kinematic forward and inverse models are established to provide a basis for the modeling and control of the robot. The robot is not only easier to assemble, but also has the characteristics of modularization and controllability, which can be used in the desktop environment.

The modular design can also be extended to a variety of soft robot effectors[111]. He *et al.* utilized responsive liquid crystal elastomers to modulate multiple modular control units[112]. The sensing and response to external stimuli (e.g., light, heat, solvents, *etc.*) is realized by detecting the external stimuli (e.g., light, temperature, solvents, *etc.*), and the autonomous adjustment of the robot's motion trajectory is realized. By merging different kinds of control modules, complex responses can be accomplished, e.g., multiple events must be logically analyzed before an operation can be performed.

4.3. Sensor

HMI have received growing attention in recent years, and the design of flexible sensors has been a major mainstream nowadays due to their good biocompatibility, stretch rows; researchers have attempted to fit flexible and stretchable electronic devices to the surface of human skin, gloves, or other soft objects in order to accurately collect deformation signals. Dong *et al.* proposed an HMI based on stretchable smart gloves[113]. The glove is embedded with stretchable sensors made of polydimethylsiloxane-carbon black (PDMS-CB) nanocomposites, and five sensors correspond to the motion data of each of the five fingers to realize the monitoring of the finger gestures, and the motion data are processed on Matlab software, which can in turn control the motion of the robot's fingers. According to the results of the experiments, the strain sensors satisfy a large deformation (> 30%) and maintain a high stability (GF ~15.2) in the electrical performance tests. Unfortunately, the authors lack an overview of the performance of the glove-controlled robotic hand. In another experiment, Zheng *et al.* designed an HMI for controlling the robotic hand with a soft elastic fabric worn to the arm, and monitored the user's muscle change state by electrical impedance tomography (EIT), and in a controlled experiment, the authors compared the volunteer's own grasping force with the grasping force fed back to the robotic hand through the muscle signals, obtaining an average coefficient of determination R2 of 0.83 ± 0.04, while the relative root mean square error (RRMSE) averaged 0.31 ± 0.10[114].

Multi-sensing data and increasing the type or number of sensors to a certain extent can not only satisfy the comprehensive collection of signals, but also predict the user's behavior more accurately and give timely feedback, which is an advantage that using a single sensor does not have. Zhang *et al.* designed an HMI system that contains EMG and pressure-based myogram (pFMG) sensors, and the system recognizes seven commonly used gestures such as clenched fist, open, *etc.*, and the results measured an average accuracy of 94.6%, compared with 87.95% using only EMG and 80.11% using only pFMG, the multi-sensor has a clear advantage in the recognition of gestures[115]. Zhao *et al.* integrated the features of two physiological signals, namely EEG and eye movement, and the extracted feature signals were respectively subjected to the SVM algorithm, and then make a synthesized decision based on D-S evidence theory[116]. The results show that the accuracy of intention recognition of the integrated decision can reach up to 93.54%, and the average recognition accuracy reaches 89.22%, which is higher than the 84.60% of EOG data and 73.60% of EEG data. The above studies are all based on two or more sensors of HMI; they have the advantages of their constituent sensors at the same time, but their defects should not be ignored, such as the noise signal's may interfere with the work of one of the sensors, resulting in the inability to make decisions. Therefore, more in-depth research is still needed for the practical application of multi-sensor data.

4.4. Algorithmic control

In order to achieve more flexible human-robot interaction, scientists need to not only achieve autonomous learning for soft robots[117], but also do a good job of controlling the dynamics of the robots in a sophisticated manner. Nazeer *et al.* proposed a control scheme based on the performance difference between the training environment and the robot by using data-driven dynamics modeling of the soft robot that learns to track the trajectory in offline mode with appropriate accuracy to track the desired trajectory[118]. This scheme bridges the simulation-to-reality gap and paves the way for online policy adaptation when the original environment changes. Haggerty *et al.* advance the modeling and control of soft robots to inertial, nonlinear states[119]. The method is capable of exploring the dynamics of a complex, nonlinear inertial system, thus providing advantages in the modeling and control of myriad robotic systems. In addition, its speed, generalizability, low computational cost, and ease of use may expand the accessibility of robotics to new user groups. Table 5 briefly describes the three calculation methods in terms of principles, computational costs, *etc.*

In order to achieve an electronics-free soft robot capable of making autonomous decisions and switching between different behaviors or programs based on its interaction with the environment, Picella *et al.* drew inspiration from mechanical programming[120]. In order to implement mechanical programming, a generic library of pneumatic circuit modules was designed to achieve programmability of pneumatic soft robots for more complex programming by taking inspiration from modular coding statements used in software programs. Tang *et al.* introduce a learning-based data-driven approach[121]. The method employs probabilistic modeling to explicitly capture system nonlinearity and uncertainty. The learning-based data-driven control method can face the challenges of nonlinearity, uncertainty and high dimensionality.

5. FUTURE WORKS

Thanks to the extensive research on HMI for soft robotic systems in recent years, significant progress has been made in this area. However, there are still some challenges that need to be worked on in future research.

The multi-sensing mode of HMI needs to have higher stability. Although current studies have confirmed that HMIs with multiple sensors can combine the advantages of single sensors to achieve more comprehensive and accurate information acquisition and identification, they also introduce greater

Table 5. Principle and computational cost of the three calculation methods

Calculation methods	Principle	Computational cost
PID control	Weighting the proportional (P), integral (I), and differential (D) parts of the error, thus calculate the control quantity	Low computational cost, does not require high hardware computing resources
Adaptive control	Extract information about the model and adjust the controller parameters according to object model changes	Complex design and high computational resource requirement
Neural network control	The combination and output of the model is realized through the connection and computation of multiple nodes (artificial neurons)	The training phase requires a large amount of computational resources and time

drawbacks. For example, EOG and EEG are susceptible to signal noise interference. When one category of sensor is affected, it can influence the performance of the entire HMI. Understanding what kind of impact this causes, and how to reduce or avoid such situations, is an important direction for integrating HMIs into everyday life.

The withdrawal and overwriting of information has not been described more in existing research, and although the response time of human-robot interaction was rapid in many experiments, the need for immediate termination or reissuance of commands due to special circumstances (e.g., user's decision-making errors, or unexpected surprises in the execution of a task) was rarely mentioned. Therefore, the necessity of adding a period of time for buffering between analyzing and transmitting signals and the execution of the task by the robot, as well as the setting of the length of the buffer time, is something that needs to be considered in future work.

With the rapid development of artificial intelligence, future HMI systems may integrate AI assistants. Through AI voice prompts coordinated with HMI operations, human-computer interaction will become simpler. We can imagine a future where people "communicate" with HMIs through AI, achieving harmony between humans and robots.

6. CONCLUSION

The emergence of soft robots undoubtedly marks a leap forward in the field of robotics. These robots, unlike traditional rigid robots, are designed to be softer, more flexible and able to integrate more naturally into a variety of complex and changing environments. This advancement is not only in their physical form, but also in the way they interact with people and the environment. In order to better integrate soft robots into human daily life and give users a better interactive experience, researchers are working hard to push them to the forefront of intelligence. Starting from various aspects such as material selection and design concepts, soft robots with more diversified functions are continuously developed. At the same time, a well-developed learning algorithm is also an indispensable element, which can help the robot understand and adapt to changes in its surroundings more intelligently and improve its autonomous decision-making ability. In addition, optimization of the control system is crucial to ensure that the robot can achieve the desired results and maintain stability when performing tasks. Ultimately, by optimizing the HMI of soft robotic systems, i.e., the way humans and robots communicate with each other, we can create a more humane and adaptive robotic ecosystem.

DECLARATIONS

Authors' contributions

Investigation, data curation, writing - original draft: Gao, Z.

Investigation, data curation: Liao, Z.
Conceptualization, methodology, resources, supervision: Li, C.

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Li, C. is a guest editor of the special issue "Human-machine Interface for Robotic Systems" of the journal *Intelligence & Robotics*. Li, C. was not involved in any steps of editorial processing, notably including reviewers' selection, manuscript handling and decision making. The other authors declared that there are no conflicts of interest.

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Not applicable.

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