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Review of the Intelligent Sensor-Memory-Control Fusion Systems

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The ability to sense light, heat, and touch is vital for human beings, underpinning the interaction between humans and the environment. To mimic the biological perception system, the sensory system converts external light, heat, and mechanical inputs into electrical signals, then processing and storing the data in digital hardware before providing feedback. However, modern digital sensing-processing systems based on the von Neumann architecture are facing significant challenges in power consumption and latency due to the unprecedented increase in data size and algorithm complexity. A promising solution is to integrate sensors, memory, and control. Here the "state-of-the-art" fusion systems involved in the sensing of visual, olfactory, tactile, visual signals, and control is reviewed. The challenges in high performance and reliability are also discussed.

1. Introduction

The human perception system is an ideal intelligent sensory system. When the receptors receive a particular stimulus, a bioelectric signal is generated and transferred to the actuator. During transmission, the signal is processed simultaneously. The actuator responds to the stimuli signals. To mimic the human perception system, various types of sensors[1–6] and actuators[7–10] bridge the robotic sensing and real world. A complete perception system contains sensors, memory, processors, and actuators. Most traditional sensory systems simply connect the functional modules without providing feedback. Besides traditional discrete systems face the von Neumann bottleneck, where separated modules consume significant power. To break the von Neumann bottleneck, neuromorphic devices are proposed. Neuromorphic devices fuse the function of memory and computing, owning the capability of processing signals and storing data simultaneously. The memristor is one of the widely used neuromorphic devices. In addition to the memristor, the complementary metal oxide semiconductor (CMOS) devices by system integration packing are also proposed.

In this work, an in-depth understanding of the working mechanism of the human perception system brings the inspiration for sensor-memory-control fusion systems will be reviewed. The "state-of-the-art" with fused system on the sensing of visual, olfactory, tactile, visual signals, and potential paradigms of control. The challenges in high performance and reliability are also discussed.

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2. Intelligent Sensor-Memory-Control Fusion Systems

The human perception system is an ideal intelligent sensory system to feel light, heat, and touch. To mimic the human perception system, sensors are used to convert external physical excitations including optical, mechanical, and chemical stimuli into electrical signals. **Figure 1** shows the representative sensory systems including visual, tactile, olfactory, auditory, and nociception perception. Feedback control is needed to close the loop of perception.

2.1. Visual Sensing-Memory-Control System

Visual sensing enables awareness of the color, brightness, and contrast of light. Light carries rich information such as frequency, wavelength, and amplitude, which can be harvested in recognizing objects and determining spatial locations. Visual sensors are capable of detecting and acquiring certain information from

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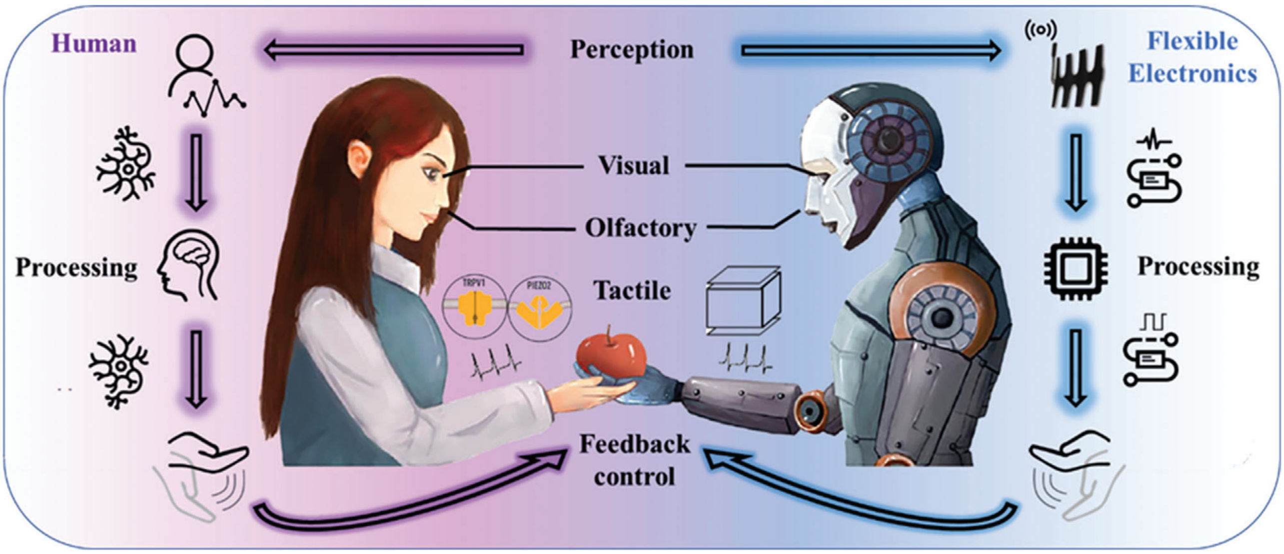

Figure 1. Schematic of processing data about five sensory systems of machines inspired by human neural networks. Reproduced with permission.[11] Copyright 2021. Springer Nature.

light. The biological counterpart in humans and many other mammals is the eye. The retina of the eye receives the light signal and transmits it to the brain. The brain processes the light signal. This is the basis of the perception of mammals in seeing and reacting to the scene captured by their eyes. Artificial electronic visual sensors detect light signals and convert to electrical signals. **Figure 2**a shows a flexible sensing material that converts light to electrical signals based on the photoelectric conversion effect.[12] Figure 2b–d shows the camera circuit and its related transistor structures.[13,14]

With the development of integrated circuit technology, certain devices are used in sensors to increase photosensitivity.[16] In the past, most visual sensors were used to analyze the spectrum and derive the elemental composition of an object. However, with the development of photodiode and neural network computation, functionalities of visual sensing systems are also advancing. These functionalities include object classification, motion recognition, and image optimization. A visual signal processing architecture for image recognition that has two parts. The sensing part is responsible for detecting, converting, and memorizing the input light signal. Benefiting from the memristive nature, certain simple signal processing (such as filtering, noise reduction, and feature extraction) can be completed while the data is stored. Such front-end memristive architecture can reduce the multiply-and-accumulate operations of the back-end computing part. Besides, Figure 2f proposes another novel visual sensing architecture to process light signals.[15] The sensing system directly processes the current signal generated by the photodiode array in the analogue domain. Such a processing scheme eliminates power-consuming Visual systems with sensing, processing, and control have seen a wide spectrum of applications in daily life. The presentive work of controlling visual signal is review. Through massively distributed edge visual sensing systems with image recognition functions, the agencies can track a certain person or vehicle. Figure 2g shows the contrast between original images and images after enhanced,[14] while Figure 2h shows the contrast before and after noise reduction. In additional to the visible light region, visual sensing system based on infrared radiation (IR) is being widely used in night vision device. Such a visual sensing system may bring dim or noisy vision to clearness, making people possible to see in dark areas or even bring vision to blind people.

2.2. Tactile Sensing-Memory-Control System

Tactile sensing which measures information arising from physical interaction with the environment is commonly seen in touch sensation. Human-being rely on tactile sensing to measure the hardness, temperature, weight, roughness, and shape of objects, thus providing rich information about the environment in addition to that offered by visual sensors. Skin consists of numerous sensory receptors including pain, cold, and warmth, and four mechanoreceptors that measure innocuous mechanical stimuli.[17,18] Among mechanoreceptors, mechanically activated ion channels are distributed in mammalian Merkel cells, which serve as the afferent nerve terminals under the skin surface.[19–21] These mechanoreceptors convert mechanical signals to voltage changes, powerful in sensing tiny pressure changes, which is further benefited from high-speed data shuttling at low energy cost. These receptors are the basis of how humans touch and react to the environment.

Pressure sensitive material is a vital part of new tactile sensation. Favorable materials choices include graphene, a two-dimensional carbonation with excellent flexibility, high toughness,[22] and ideal conductivity.[23] Additionally, it shows high intrinsic carrier mobility (200000 cm^2 V^{-1} S^{-1}), decent mechanical properties (an in-plane tensile elastic strain of up to 25% and Young's modulus of 1 TPa), optical transmittance, chemical inertness, and low-cost mass production.[24] **Figure 3** shows the mimic tactile and control system. Figure 3a show various tactile gloves, some of them are composed of heterogeneous

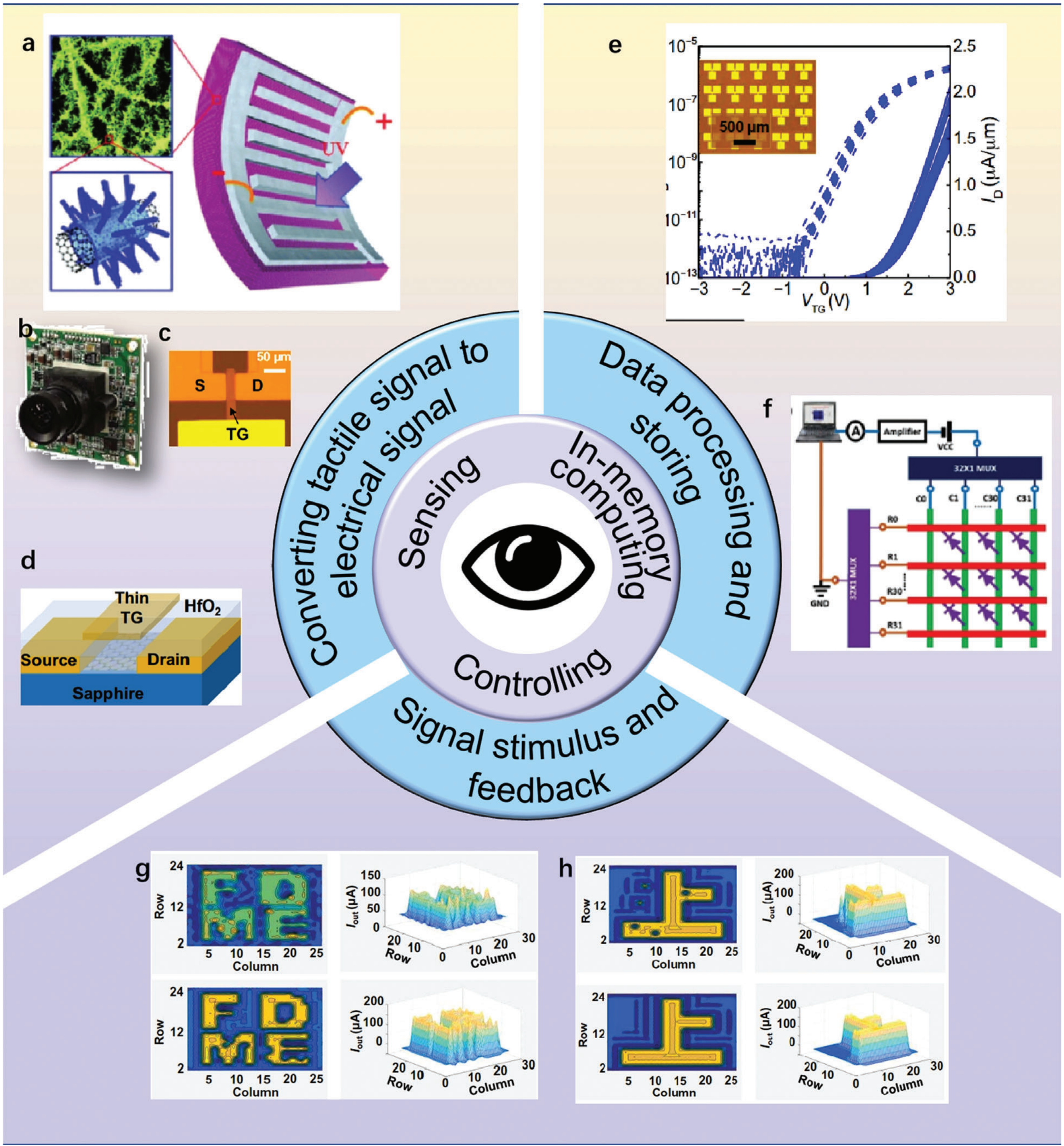

Figure 2. Schematic of sensing, processing, and controlling flow in visual perception. a–d) Recent works on optical sensing methods. Reproduced with permission.[12–14] Copyright 2017, Wiley. Copyright 2015, Korea Institute of Science and Technology Information (KISTI). Copyright 2022, American Association for the Advancement of Science. e–f) Optical signal processing algorithms and architectures.[14,15] Copyright 2022, American Association for the Advancement of Science. Copyright 2016, Wiley. g,h) A kind of biomimetic imaging system integrating the function of sensing, processing, and controlling.[14] Copyright 2022, American Association for the Advancement of Science.

mechanoluminescent materials and some are polymer matrix can identify five kinds of gestures without power supply.[25] More portable and wearable sensor array systems including a wireless sensor glove consisting of yarn-based stretchable sensor arrays for monitoring stress changes under a human finger and a wireless printed circuit board for further processing. It can be regarded as the backbone for wearable devices, such as the gesture recognition gloves (Figure 3b),[26] and the graphene-based layered percolative film strain gauge (Figure 3c).[27] With the development of graphene sensors, sensor arrays are often used to ensure high precision detection and postprocessing using machine-learning algorithms. Sensors can also be designed with bionic inspiration, such as the artificial mechanical transducer skin inspired by piezoelectronic materials and internal data lines.[28]

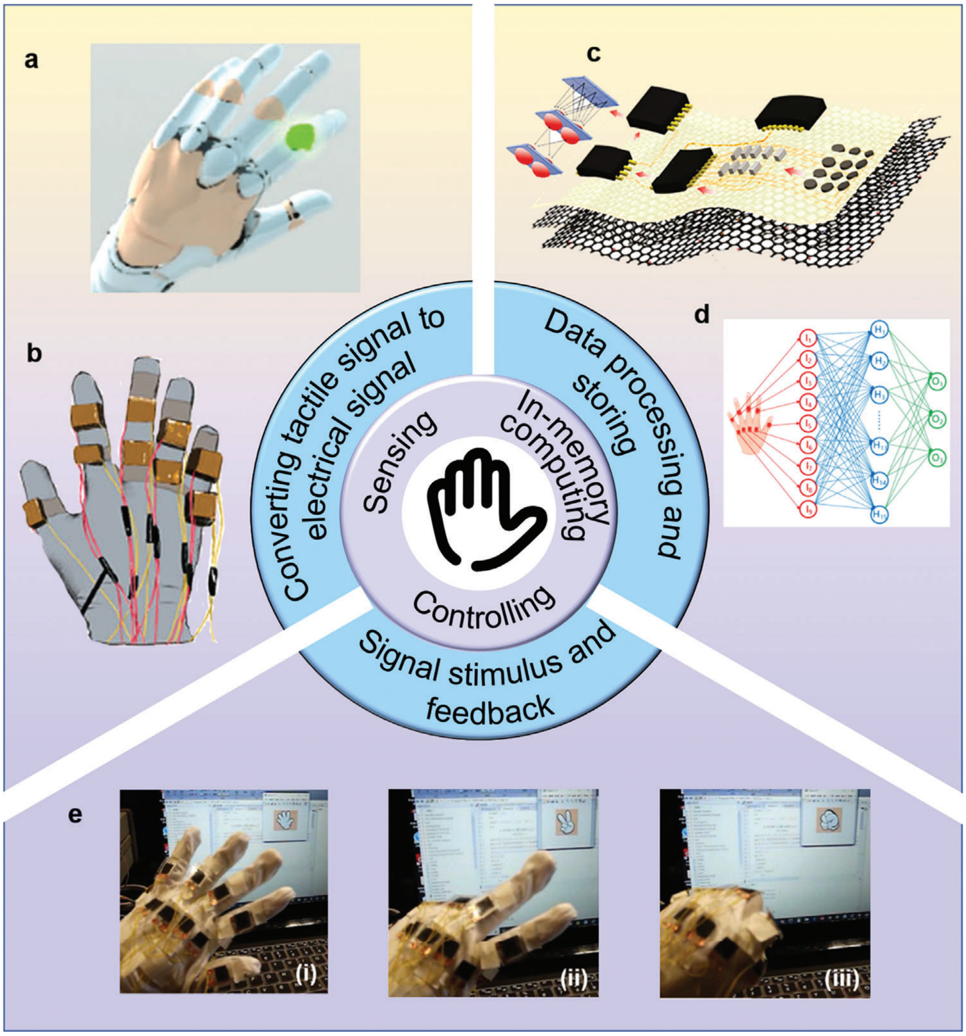

Figure 3. Schematic of sensing, processing, and controlling flow in tactile perception. a,b) Recent works on tactile sensing methods. Reproduced with permission.[25,26] Copyright 2022, Wiley. Copyright 2020, Wiley. c,e) Tactile signal processing algorithms and a complete tactile sensory system for object recognizing. Reproduced with permission.[27] Copyright 2019, IEEE Xplore.

Researchers developed a bioinspired flexible organic artificial afferent nerve consisting of pressure sensors, an organic ring oscillator, and a synaptic transistor.[29] Conventional computing units process data with a von Neumann architecture. However, it usually suffers from massive data flows travelling between memory and processing units, leading to large power consumption and latency. This effectively imposes a restriction on the bandwidth of data, also known as the von Neumann Bottleneck. In recent years, computing methods have been developed to circumvent the two problems. Processors can process a large amount of data with a low power consumption and improved speed at the same time thanks to the bioinspired algorithms running on both CMOS circuits and memristors.[30] Combining these two methods, researchers developed artificial intelligence (AI) systems for tactile processing. In these systems, data are pre-processed to digital signals, then directly put into intelligent algorithm models, for example, multilayer perceptron (MLP) used in a dual-model sensory (Figure 3d),[27] without being stored in memory devices, therefore avoid the massive data transference. Large amount of data detected by sensors can also enable researchers to build a large tactile dataset of the hand and analyze the spatial correlations and correspondence between finger regions that represent the tactile signatures of the human grasping strategy, and also help to explain the collaborative relationship among different regions of hands when gesturing and grasping. As Figure 3e shows, a circular map illustrates the correlation between areas on the hand extracted from the data of scalable tactile glove.[27]

The flexible materials and methods of near-sensor or in-sensor computing equip tactile sensing systems with a wide range of applications.[31] The human–machine interface (HMI) benefits significantly from tactile sensing devices. The potential usage in stretchable touch panels may overcome the typical shortcoming of receiving limited range of touch signals[32] and largely increase the endurance of the screen.[33] Moreover, a more efficient HMI system, which can give feedback and automatically react, has been developed. This outstanding performance provides tactile sensing with a great potential for health monitoring,[34] robotics,[35] and industrial automation.

2.3. Olfactory Sensing-Memory-Control System

Olfactory sensory system could sense the concentration of molecules. By analyzing the odor molecules, the olfactory sensing system can identify the gas type and concentration. Olfactory sensors are devices sensitive to gas molecules. The biological counterpart for humans and many other mammals is the nose. The odor molecules are captured by the olfactory receptor cells in the epithelium of the nose. Then, the cells bind to the molecules and generate neural spikes transmitted to the brain. The brain finally processes the signal and forms the sense of smell.

Artificial electronic olfactory sensors can detect odor molecules and convert them to electrical signals. **Figure 4**a shows a typical flexible olfactory sensor, including the gas-sensitive material and memory arrays.[36] By integrating different kinds of sensitive materials (Figure 4b,c), the olfactory sensing system can identify the composition of the gas.[37,38] Due to the rapid development of integration techniques and classification algorithms, the function of the olfactory sensing system has changed from detecting the type of a single gas to concentrations of multiple gases in recent years. Figure 4d shows a common architecture of olfactory systems, composed of an olfactory sensor array and a processing module.[37] The olfactory sensor array contains several sensitive materials corresponding to different odor molecules. When these materials capture corresponding odor molecules in the gas, they generate electrical signals whose amplitude depends on the molecular concentrations. Next, the complex electrical signals are transferred to a processing module, where a classification algorithm is deployed. Through the classification algorithm, the type and quantity of odor molecules in the gas can be estimated, as shown in Figure 4e.[39] A great breakthrough of such olfactory systems is the integration of different sensitive materials, reducing the area of sensors while improving the energy efficiency of the system. Meanwhile, using a classification algorithm reveals the gas composition more intuitively and directly than using multiple discrete gas sensors.

There are many application scenarios for olfactory systems with sensing, processing, and controlling functions. An important application scenario is safety. Chemical plants need to detect the content of multiple gases in a single confined space to ensure that the underlying chemical reaction proceeds correctly. Figure 4f,g show one of the olfactory sensing systems suitable for this purpose, which can determine six kinds of odor molecules.[39] If the output signal reveals that a certain molecule exceeds the threshold concentration, the controller can shut down the reaction in time and send out a warning. Such an olfactory system can also be integrated with kitchen stoves. By analyzing the concentrations of methane and sulfide, the olfactory system can respond to natural gas leaks and turn off the natural gas stove in time.

2.4. Nociception Sensing-Memory-Control System

Nociception is a subjective and multidimensional feeling when living organisms suffer from harmful stimuli. It is the nature of creatures to avoid danger. Although pain often leads to an unpleasant mood, it serves as an alarm of the potential risk. Pain also shares an inherent overlap with cognition, which endows pain with a cognitive-evaluative ability, requiring learning, recall of past experiences, and active decision-making.[40] Without the ability to detect pain, it may be difficult for human beings to be aware of risks such as extreme temperature, objects hitting or piercing, or too much pressure, all cause pains.

In the human body, pain is signified by chemical neurotransmitters sent from dissociating nerve endings. When an afferent nerve receives those chemical signals, there is a temporary change in the membrane potential of the nerve, and the change is propagated forward until it reaches the brain. Recent studies found that transient receptor potential (TRP) channels are vital in diverting stimuli and conducting needed cations to cause changes in membrane voltages. David Julius et al. studied the structure of the capsaicin receptor TRPV1, proving its role in sensing "spicy" (in fact a kind of pain).[41] Additionally, when nociception comes from mechanical forces, it has been proven that an ion channel named Piezo2 plays the part of the major transducer of mechanical stress signals in mouse Merkel cells and thus can be used in both nociception and tactile detection.

Since pain is a subjective and ambiguous feeling that is differentiated from the other senses with clear physical quantities to benchmark, it is usually difficult for researchers to sense and quantify pain. Traditional methods include monitoring heart rate variability (HRV),[42] muscular electric activities,[43] electrocardiography,[44] recognition of facial expressions, skin temperature, and blood pressure to indirectly measure the pain level. With the rapid development of flexible electronic sensors in recent years, scientists have been able to directly monitor the impact of certain kinds of harmful stimuli, such as stress, temperature, and chemical substances, with either electronic or bionic means.

Conventional indirect wearable sensing usually employs sensors of different types. When measuring temperature, sensors are typically built on thermistors,[45] the resistance of which changes with temperature. When measuring heart rates, polymer, carbon nanotube, stretchable elastomer, and textile-based skin electrodes are frequently used to pick up the depolarization signals from the heart muscles or electrocardiography (ECG).[46] A typical blood pressure measurement device is a sphygmomanometer with a pump linked to a cuff placed around the arm and a manometer to measure the pressure.[47] On the other hand, facial expression detection usually involves computer vision systems.[48]

Compared to diversified indirect sensing techniques, the method to directly probe pain is relatively straightforward. Past efforts mainly relied on sensor arrays to detect the environment, such as the bionic stretchable and conformable matrix networks (SCMNs) introduced by Hua et al.,[49]which was inspired by human skin for in-plane strain, pressure, and temperature detection. However, traditional methods may not always be effective in tracing the action of external objects, making it difficult to provide feedback and react to harmful stimuli. Recent research has addressed these shortcomings. For example, inspired by a bioluminescent jellyfish, Zhang et al. developed a dual-mode electronic skin for the static and dynamic pressures by combining electrical and optical responses.[50] The working mechanism is illustrated in **Figure 5**a. Under low pressure loading (<5 kPa), the electronic skin brings high pressure response sensitivity through rapid saturation of the microstructure. Under high pressure

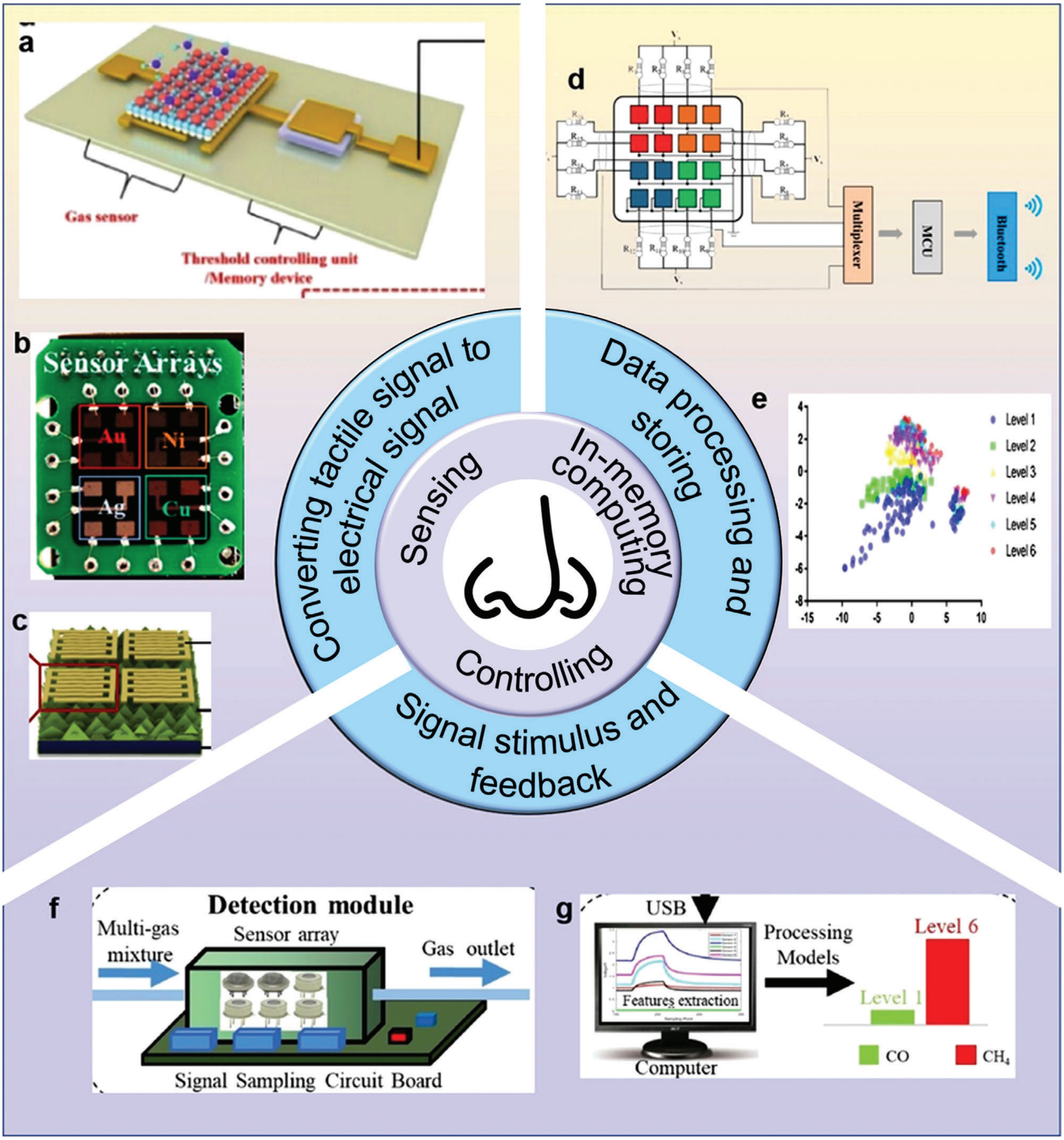

Figure 4. Three steps for machines to perform a "smelling" action. a) Overall board structure of an olfactory sensing system with sensing, memory, and self-protection capabilities. Reproduced with permission.[36] Copyright 2021, Elsevier. b) Integrated wireless self-powered nanostructured gas sensor arrays. Reproduced with permission.[37] Copyright 2021, American Chemical Society. c) The overall structure of the WS_2 nanowalls with yellow Cr/Au electrodes has excellent performance in gas sensing. Reproduced with permission.[38] Copyright 2020, American Chemical Society. d) Schematic of the future smart indoor light-driven system with nanostructured gas sensors. Reproduced with permission.[37] Copyright 2021, American Chemical Society. e) Schematic of concentration level classification of CH_4 after adding all interfering samples detected by a miniatured electric nose with PCA models.[39] f.g) Schematic diagrams of a gas classification system. Gases are sent from a gas blender and pass through a detection module consisting of MOS sensors (f), and the signals are analyzed to determine the level of each kind through neural network models (g). Reproduced with permission.[39] Copyright 2021, Elsevier Science Sa.

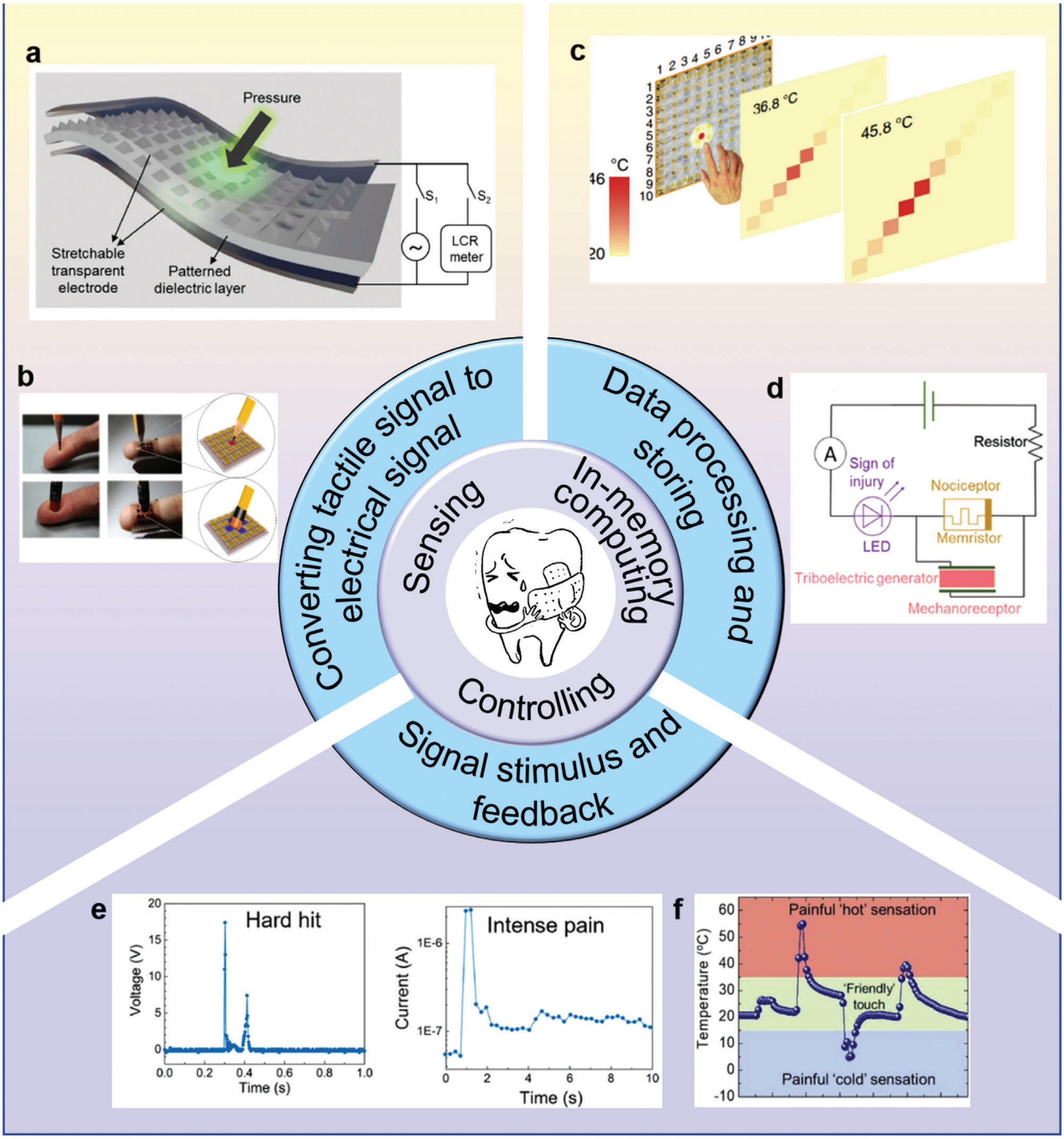

Figure 5. Three steps for machines to perform a "pain sensing" action. a) Schematic of a pain sensor that combines electrical and light responses. Under small compression, the device has high pressure sensitivity. Under large compression, the device realizes the perception of the pain site based on optical localization. Reproduced with permission.[50] Copyright 2017, American Chemical Society. b) Schematic diagram of the working of piezoelectric nanowire sensor array. Reproduced with permission.[51] Copyright 2015, Royal Society of Chemistry. c) Visual result of the matrix network used for temperature sensing. Reproduced with permission.[49] Copyright 2018, Springer. d) Circuit diagram of the artificial injury response system.[55] e) The voltage output generated by a hard hit on the triboelectric generator and the corresponding memristor circuit current. Reproduced with permission.[55] Copyright 2022, Wiley. f) Distinction between human friendly touch, painful hot, and cold feelings. Reproduced with permission.[56] Copyright 2022, Wiley.

loading (>60 kPa), the phosphor particles embedded in the PDMS matrix can be triggered by enhanced inspired electric field, the bright luminescence enables the pressure profile to be visualized instantly. Jeong et al. reported a piezoelectric sensor based on ZnO nanowires (Figure 5b).[51] Stimulation of sharp objects was used to simulate pain-generating scenarios. The sensor array senses the precise distribution of dynamic forces, expected to enhance the protection mechanism from harsh environment.

Regardless of whether the sensory information is acquired in indirect or direct ways, their postprocessing is quite similar and involves signal pre-processing, feature extraction, feature selection, and classification. Data collected and pre-processed by the sensors are then transferred to processing units to extract their useful features according to multiple sensory signals (as shown in Figure 5c).[49] This method could be highly efficient in classifying data that are close to each other. Another way to study the intensity of stimuli signal is to use piezoresistors to change their persistence along with signal changes. For example, the persistence gradually drops with an increase in hitting object diameters. The typical processing algorithm to perform the classification often uses cross-validation to train a model and use it into a set of new data. Frequently used algorithms include decision trees (DT),[52] Bayesian networks (BN),[53] and K-nearest neighbors (KNN),[49] which are derived from neuromorphic computing.

The overall purpose of pain sensing is to detect, keep away of dangerous stimuli, and protect humans. Xu et al. reported a triboelectric generator (artificial nociceptor) based on a copolymer of chlorotrifluoroethylene and vinylidene fluoride (FK-800).[54] Bioinspired injury response systems have been developed by integrating susceptors, memristors, and light emitting diodes. A triboelectric generator, a light emitting diode and an ammeter are connected in series. The triboelectric generator is connected in parallel with a memristor (Figure 5d). After being hit hard, the triboelectric generator generates a high voltage and sets the memristor to a low resistance state to simulate the conduction of pain (Figure 5e). Chen et al. reported a distributed, highly sensitive miniaturized temperature sensor based on vanadium pentoxide nanowire printing process.[55] The robot's temperature-induced pain perception based on this device is obtained through local learning at the hardware level. Gentle touch, noxious heat, and cold stimuli can be distinguished (Figure 5f).

3. Challenges and Outlook

The intelligent sensor-memory-control fusion systems benefit the advancing technology. However, challenges remain:

i. Fabricating sensing and processing modules on the same substrate. Fabricating sensing and processing modules on the same substrate can further reduce the cost of data shuttling, thus reducing latency and power consumption. At the same time, such fabrication technology can improve system integration and area utilization. The integration methods include 3D monolithic integration, planar SoC, and 3D heterogeneous integration.[31]
ii. Integration of various sensors. The integration of various kinds of sensors can make a sensory system more attractive. With an increase in the amount of data sampled, more information can be harvested and analyzed. Combining different sensor data can lead to more accurate conclusions. For example, PPG, ECG, bioimpedance, and pulse-wave signals can be used to determine blood pressure. Analyzing more of them can further reduce errors.
iii. Power sources with long battery life or self-powered capability. Power sources with long battery life or self-powered capability. The power consumption of intelligent sensory systems varies from microwatts to several watts mainly depending on the complexity of processing algorithmic. On this basis, introducing energy-harvesting sensing materials[57] can enable the system to have self-supplying capability.
iv. Innovative material design. Traditional materials are facing challenges in highly integrated system due to their rigidity and large size. Introducing innovative material design such as low-dimensional material to sensing system has potential opportunity. For example, low-dimensional material has the advantages of high ductility, and flexibility.

4. Conclusion

In this review, we summarized current flexible sensory systems for different signals. Traditional digital sensing based on the Von Neumann architecture faces the problems of time delay and large power consumption due to frequent data transfer between storage and computing units. To overcome this challenge, new methods of in-sensor or near-sensor computing are widely used, mostly based on neuron networks, to circumvent the "Von Neumann Bottleneck." CMOS and TRPMEMS technologies guarantee that the new algorithms are hardware encoded into the integrated circuits.

The rapidly developing flexible sensory systems including visual, tactile, olfactory, auditory, and nociception perception can form a "sensing-memory-control" three-stage loop. At the beginning, flexible sensors convert light, pressure, odor, sound, and pain signals into electrical signals. Finally, the systems give feedback to the mentioned steps, aiming at automatic real-time control. In this way, present programs can be efficiently adjusted, thus improving human-computer interaction. Such an all-in-one system has numerous potentials uses in future smart living and healthcare.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

All authors contributed to writing the manuscript.

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