

Artificial Sense Technology: Emulating and Extending Biological Senses

Jianwu Wang, Cong Wang, Pingqiang Cai, Yifei Luo, Zequn Cui, Xian Jun Loh, and Xiaodong Chen*



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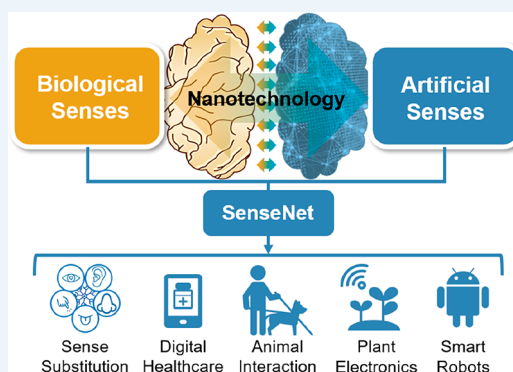
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ABSTRACT: Biological senses are critical for the survival of organisms. A great deal of attention has focused on elucidating the underlying physiological mechanisms of the senses, inspiring various sensing techniques. Despite progress in this area, gaps remain between the biological senses and conventional sensing techniques. In this Perspective, we propose the concept of artificial sense technology, which mimics the biological senses but differs in terms of objective sensing and intelligent feedback capabilities. We first summarize recent progress in the use of nanotechnologies to emulate the biological senses and then outline the advantages of artificial sense technology, which extend the capabilities of its biological counterparts. We envision artificial sense technology as a powerful perceptual interface that will play key roles in sensation substitution, digital healthcare, animal interactions, plant electronics, smart robots, and other areas that enrich the connections of the physical and virtual worlds.



Evolutionary adaptation to a changing environment is critical to the survival of a species. Traits that enable the effective sensing of an organism's external environment have thus been the focus of substantial evolutionary change across organismal groups. Hence, the biological senses, which play key roles in an organism's ability to perceive its complex external and internal worlds, have been in the spotlight of biological sciences. The Nobel Prize in Physiology or Medicine 2021 was awarded to David Julius and Ardem Patapoutian for their discoveries of thermal and mechanical transducers. To date, the Nobel Prizes in Physiology or Medicine have been rewarded to dozens of achievements relating to sensation or neuronal systems.¹ These breakthroughs revealed the stimuli transduction, signal transmission, and recognition processes of biological sensory systems, which enable organisms to perceive various environmental stimuli and to react appropriately for their survival.² However, despite this sensory organization, some issue of reliability and shareability remain. In human sensation, for example, we perceive the world in a subjective manner, and our perceptions can be affected by the environment as well as by our physiological or mental states.³

Researchers have developed a numbers of sensing techniques (e.g., optical fiber sensors, ultrasonic detectors, and wireless sensor networks) as supplements to biological sensory systems, which have provided valuable information for human activities, such as environmental monitoring, industrial manufacturing, and medical diagnostics.⁴ These conventional

sensors can respond to a wide range of stimuli and generate reliable and quantifiable signals; however, they lack adaptability, energy efficiency, error tolerance, and reliable sensation in the complex environment, among many other merits of the biological senses. As a result, gaps remain between the biological senses and conventional sensing techniques. Artificial senses, emerging at the convergence of nanotechnology, electronics, and computer science, have evolved from emulating biological senses to now exhibiting comparable or even more powerful functionalities than their biological counterparts (Figure 1).^{5,6}

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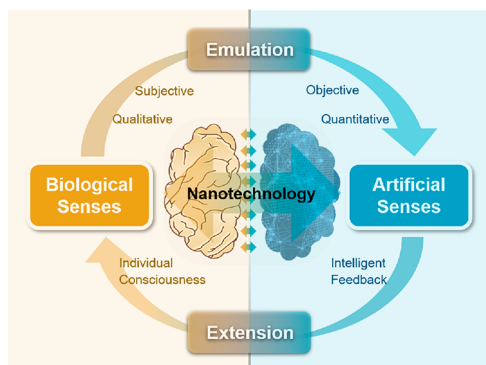


Figure 1. Illustration of the relationships between biological and artificial senses.

Artificial senses have two major components corresponding to their counterparts in biological senses: (1) systematic sensing techniques for converting various stimuli to quantizable signals and (2) digitalization processes for constructing holographic models of the physical worlds (Table 1). Nanotechnology, a highly interdisciplinary field that encompasses nanomaterials and nanomanufacturing, plays a critical role in constructing biomimetic structures of artificial sense technology and further establishes close connections with the biological sensory system at different scales.⁷ Artificial senses with objective sensing capabilities and intelligent feedback paradigms move toward a powerful perceptual interface with the biological senses, deciphering complex biological sensory processes into digitalized models.

NANOTECHNOLOGY FOR BIOMIMETIC ARCHITECTURES

Biological sensory systems consist of many highly organized structures ranging from the molecular scale to the nano-, micro-, and macroscales in a hierarchical manner. Sensory receptors exist at the nanoscale and implement their transduction functions through the organization of sensory organs.² As a consequence, nanotechnology is necessary to construct biomimetic sensing architectures.

Functionalization of Nanomaterials. Nanotechnology can be utilized to reconstruct matter at the nano level, endowing it with physicochemical properties superior to those seen in molecule states or bulk crystals. For example, nanoporous materials show catalytic and gas-sensing abilities higher than those of their bulk counterparts due to their large surface-to-volume ratio and high density of reactive sites.¹⁰ The Xu group fabricated a metal–organic framework (MOF) film with a spray layer-by-layer liquid-phase epitaxial method to mimic the olfactory gas-sensing system (Figure 2a).¹¹ The thickness of the conductive $\text{Cu}_3(\text{HHTP})_2$ film can be precisely controlled to ~ 2 nm per growing cycle. As a result, the obtained MOF film exhibited a smooth surface and high orientation, enabling it to act as the NH_3 reactive layer of a chemiresistor gas sensor at room temperature (Figure 2e).

In some cases, the responsiveness of materials emerges only at the nanoscale level. For example, carbon quantum dots exhibit adjustable fluorescence emissions derived from surface-related defects at the nanoscale.¹² Moreover, the organization of nanostructures could also impact the performance of materials. Zheng *et al.* reported an artificial basilar membrane based on the piezotriboelectric effect.¹³ They applied a multistep procedure to incorporate BaTiO_3 nanoparticle

Table 1. Definitions and Features of the Major Components of Biological and Artificial Senses

	definition	features
biological senses	sensory systems	the total structure involved in sensation, consisting of sensory receptors, neural pathways, and sensory areas in brain
	perception	the conscious mental registration of a sensory stimulus by organisms
artificial senses	sensing techniques	the integrated artificial sensing platforms involved in stimuli recognition, signal transmission, and data acquisition
	digitalization	construction of holographic models of physical world based on sensory data and Machine learning algorithms
		<ul style="list-style-type: none"> ◆ Pros: multiscale and exquisite architectures with high energy efficiency and superior multimodal integration (e.g., an adult brain has 10^{11} neurons with 10^5 synapses per neuron⁸) ◆ Cons: inherent limitations for stimuli transduction (e.g., detectable range of human naked eyes is 380–760 nm) and transmission (restricted to electro-neurographic signal); limited storage capacity, distorted memory, and labile information extraction ◆ Pros: subjective and qualitative experiences with superior plasticity and creativity ◆ Cons: individual feelings with limited consistency and shareability ◆ Pros: abundant responsive materials and sensing devices with extended sensing capability (e.g., electromagnetic wavelength 10^{-12}–10^3 m) and multiple signaling modes (electrical, optical, magnetic, etc.); massive volume of heterogeneous data, enhanced data extracting, and processing capability ◆ Cons: incompatibility of different data sources; preliminary integration-level of sensory modalities and densities (e.g., 347 transistors/cm^2 on the human skin⁹) ◆ Pros: objective, quantitative, and replicable virtual reality overcoming temporospatial limitations ◆ Cons: dubious fidelity of digitalized models compared with the actual scenarios

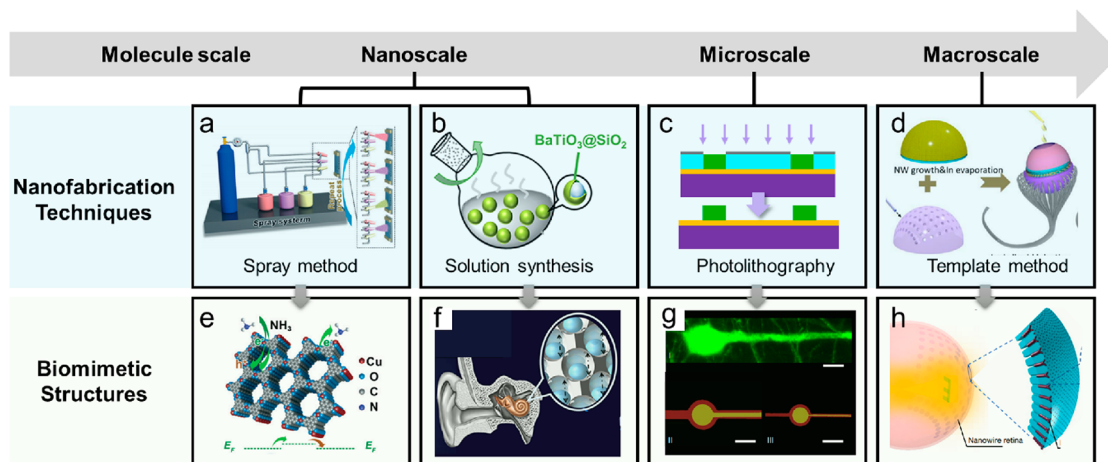


Figure 2. Nanofabrication approaches for emulating the hierarchical structures in the biological sensory system. (a,e) Spray layer-by-layer liquid-phase epitaxial method (a) for preparation of MOF thin film (e). Images a and e reproduced with permission from ref 11. Copyright 2017 Wiley-VCH. (b,f) Solution synthesis approaches (b) for preparing BaTiO₃/PVDF-TrFE membranes with core-shell nanostructures to mimetic basilar membrane in cochlea (f). Images b and f reprinted from ref 13. Copyright 2021 American Chemical Society. (c,g) Photolithography techniques (c) for fabrication of neuron-like electronics (g), scale bars, 10 μm. Images c and g reproduced with permission from ref 14. Copyright 2019 Springer Nature. (d,h) Template methods (d) to fabricate nanowire photodetectors to mimetic hemispherical structures of human retina (h). Images d and h reproduced with permission from ref 16. Copyright 2020 Springer Nature.

103 cores into porous poly(vinylidene fluoride-co-trifluoroethylene)
 104 (PVDF-TrFE) shells to fabricate a membrane with well-
 105 organized core-shell structures that can generate charge
 106 separation and a potential gradient under uniform pressure
 107 (Figure 2b,f). Current synthesis techniques make possible the
 108 ability to tailor active materials at different scales and to
 109 customize sensing properties, thus greatly enriching the
 110 material candidates for constructing structures in biological
 111 sensory systems.

112 **Construction of Hierarchical Structures.** To emulate
 113 biological sensory systems further, nanomaterials can act as
 114 building blocks to construct hierarchical structures at a higher
 115 level *via* nanotechnology. Lieber and co-workers reported
 116 creating neuron-like electronics (NeuE) *via* photolithography
 117 methods (Figure 2c) that mimic the subcellular structural
 118 features and mechanical properties of neurons.¹⁴ These NeuE
 119 consist of polymer/metal/polymer structures with polymer
 120 and metal widths of 4 and 2 μm or 1 and 0.6 μm, respectively
 121 (Figure 2g). The subcellular structures of the NeuE facilitate
 122 the migration of endogenous neural progenitor cells, which is
 123 promising for the interconnection of neuron systems and
 124 brain-machine interfaces.

Nanotechnology makes it possible to tailor active materials at different scales and to customize sensing properties, thus greatly enriching the material candidates for constructing structures in biological sensory systems.

125 Biomimetic eyes with a wide field of view, high resolution,
 126 and high sensitivity are desirable in robotics and visual
 127 prostheses.¹⁵ To achieve these targets, Fan and co-workers
 128 substituted visual receptors with high-density perovskite
 129 nanowire arrays through complex nanomanufacturing proce-
 130 dures, where the template method was the critical step to
 131 achieve structural similarity to the human retina (Figure 2d).¹⁶

The obtained hemispherical bionic eye exhibited capabilities to
 132 acquire image patterns that are comparable to the human eye
 133 (Figure 2h).
 134

Moreover, printing techniques (*e.g.*, screen printing, inkjet
 135 printing, and 3D printing techniques) have been widely used to
 136 engineer nanomaterial inks for sensing applications. In addition
 137 to responsive materials, these nanofabrication techniques can
 138 also be applied to modify substrates, electrodes, and
 139 encapsulation layers, which are all essential elements for the
 140 construction of artificial sensory architectures.^{17–19}
 141

EMULATING THE BIOLOGICAL SENSES

142 Research on biological sensory systems has revealed the
 143 organization and mechanisms of sensory processes whereby
 144 biological senses are disassembled into a series of phys-
 145 icochemical processes. Through the emulation of stimuli
 146 conversion, signal transmission, signal fusion, and recognition
 147 along the sensation generation pathways, artificial sense
 148 technology will gradually emulate the sensing mechanisms of
 149 the biological sensory systems and obtain the ability to
 150 interpret the codes of sensory processes following intrinsic
 151 biological sensory paradigms.
 152

Artificial Sensors for Stimuli Conversion. Stimuli
 153 transduction in biological sensory systems relies on specialized
 154 sensory receptors and well-organized sensory organs. Accord-
 155 ingly, artificial sensors are designed to emulate the biological
 156 stimuli transduction processes through the fabrication of
 157 stimuli-responsive materials or the construction of biomimetic
 158 structures. Researchers have designed many optically, mechan-
 159 ically, or chemically responsive materials to mimic sensory
 160 receptors using artificial sense technology. Whereas biological
 161 stimuli transduction processes convert stimuli into electrical
 162 signals, artificial sensors can convert stimuli into various types
 163 of signals, including electrical, optical, or magnetic signals
 164 (Figure 3a). The emulation of the biological sensory systems
 165 always follows the biological architectures to reproduce the
 166 signal transduction processes of the sensory organs. For
 167 example, the hemispherical retina structure with high-density
 168 photoreceptors fabricated by Gu *et al.* realizes imaging
 169

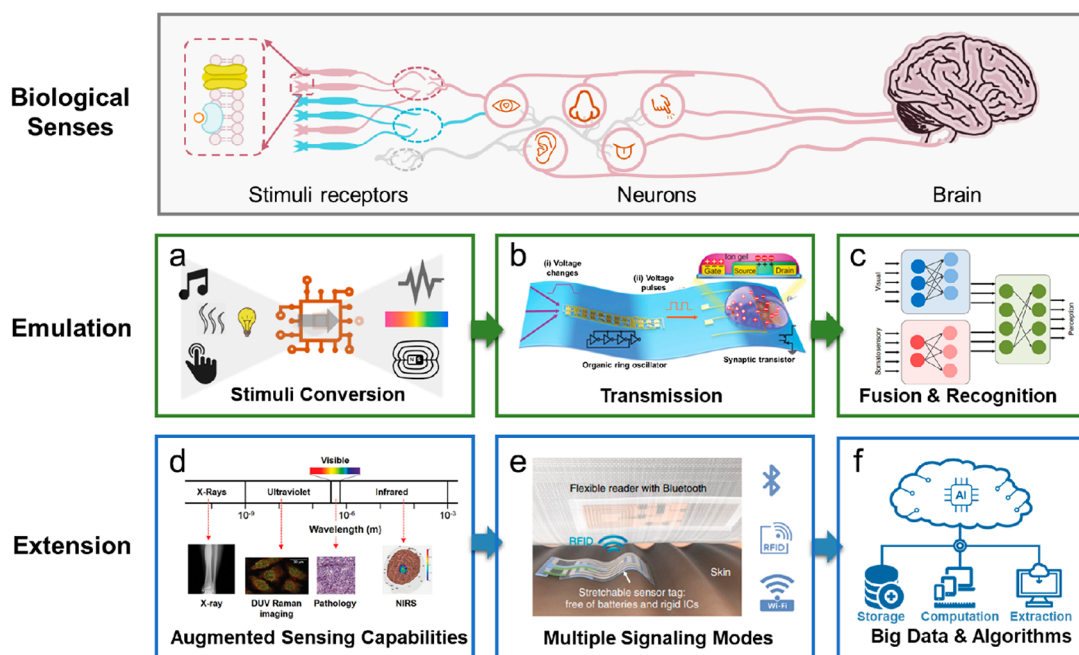


Figure 3. Emulation and extension of the biological senses along the stimuli perception pathway. (a) Stimuli conversion processes by artificial sensors. (b) Artificial afferent nerve consists of an organic ring oscillator that is connected to a synaptic transistor. Image b reproduced with permission from ref 22. Copyright 2018 AAAS. (c) Bioinspired somatosensory-visual associated machine-learning frameworks that mimic sensation fusion processes. Image c reproduced with permission from ref 23. Copyright 2020 Springer Nature. (d) Biomedical imaging technology at wavelengths ranging from X-rays to ultraviolet, visible, and infrared areas. Image d reproduced with permission from ref 26. Copyright 2021 Wiley-VCH. (e) Wireless interconnection between rigid and soft components. Image e reproduced with permission from ref 33. Copyright 2019 Springer Nature. (f) Illustration of the big data and intelligent algorithms that involve storage, computation, and extraction modules.

170 resolutions as high as those of the naked eye.¹⁶ Saadatzi *et al.*
 171 designed a spiral-shaped basilar membrane based on the
 172 human cochlea, which can generate a localized deflection for
 173 different frequency inputs for voice recognition.²⁰

Artificial sensors are designed to emulate the biological stimuli transduction processes through the fabrication of stimuli-responsive materials or the construction of biomimetic structures.

174 **Artificial Nerve Systems for Signal Transmission.** In
 175 biological sensory pathways, signals are first collected and
 176 filtered from multiple sources by the peripheral systems before
 177 being sent to the nervous centralis for perception.²¹ During the
 178 signal transmission processes, peripheral afferent neurons are
 179 critical for bridging the widely distributed network of receptors
 180 and the central nervous system. To improve understanding of
 181 the roles of peripheral afferent neurons, Lee and colleagues
 182 developed an artificial afferent nerve based on flexible organic
 183 electronics to emulate the biological slowly adapting type I
 184 (SA-I) afferent neurons (Figure 3b).²² They designed multiple
 185 organic ring oscillators to emulate the interneurons in the
 186 spinal cord, which can transduce signals from resistive pressure
 187 sensors to a synaptic transistor. The hierarchical artificial
 188 neurons enable the pressure sensors to combine simultaneous
 189 pressure inputs and to distinguish braille characters, greatly
 190 improving the ability of the artificial perception system to
 191 conduct sensory signals.

Intelligent Algorithms for Signal Fusion and Recognition. 192
 193 An organism's accurate depiction of its environment 193
 depends on systematic analyses of multiple sensory modalities. 194
 As a result, the fusion of multiple sources of cues is essential for 195
 perceptual capabilities. Bimodal fusion was first carried out to 196
 elucidate how to emulate the multimodal fusion seen in 197
 biological senses. Researchers constructed various binary 198
 sensing platforms together with different machine-learning 199
 methods (Figure 3c).^{6,23} We implemented ionic–electronic 200
 hybrid neuromorphic electronics to collect optic and pressure 201
 information for bimodal sensory fusion. The resistive pressure 202
 sensor and perovskite-based photodetector function as the 203
 mechanical and optical receptors, turning haptic and visual 204
 stimuli into electrical signals.²⁴ The isolation of different types 205
 of sensors in space or time may have correlation and 206
 synchronism issues, which will hinder the signal fusion 207
 processes. We further constructed a locally coupled electro- 208
 mechanical interface to record myoelectric and mechanical 209
 signals simultaneously at the same location, which enabled 210
 more precise perceptual communication between the human 211
 and robotic hands.²⁵ With the assistance of higher sensor 212
 integration levels and artificial intelligence, locally coupled 213
 interfaces could be greatly improved. 214

EXTENDING THE BIOLOGICAL SENSES 215

Despite a long evolution history, human biological senses have 216
 many limitations. For example, only light with wavelengths 217
 from 380 to 760 nm can be observed by the human eye, and 218
 only sound with frequencies from 20 to 20000 Hz can be 219
 captured by human ears. The senses of smell, taste, and touch 220
 also have detection thresholds. Based on simulated sensory 221

222 perception, artificial sense technology, which integrates
223 advanced sensing techniques, signal transmission, big data,
224 and intelligent algorithms, could extend the functionalities of
225 biological senses.

Based on simulated sensory perception, artificial sense technology, which integrates advanced sensing techniques, signal transmission, big data, and intelligent algorithms, could extend the functionalities of the biological senses.

226 **Augmented Sensing Capabilities.** Artificial senses have
227 been continuously optimized and now exhibit many
228 capabilities that exceed those of their biological counterparts.
229 First, the detection ranges and limits of artificial senses have
230 been expanded. For example, different types of artificial sensors
231 have been fabricated to detect ultraviolet light, infrared light,
232 and beyond, thus exhibiting a much broader detection scope
233 than the human eye (Figure 3d).²⁶ Second, the stability and
234 durability of sensing materials can be improved. Natural
235 enzymes play important roles in biological sensory systems,
236 whose activities may be influenced by temperature, pH, and
237 other physiological conditions. Researchers have constructed
238 many artificial nanoenzymes that show much higher stability
239 and durability than natural enzymes with comparable catalysis
240 efficiency.²⁷ Finally, sensory visualization that is reliable and
241 shareable becomes reality through the digitization of sensation.
242 Cui *et al.* developed a minimized fingertip modulus sensor
243 (FMS), which can haptically quantify the Young's modulus of
244 soft materials.²⁸ The FMS was used to monitor Young's
245 modulus variation of swollen tissues in patients who suffered
246 from bone fractures, indicating suitable surgery dates that
247 matched the decisions of an experienced doctor. In addition to
248 light, sound, chemical, and mechanical stimuli, a broad range of
249 physical (*e.g.*, electroencephalogram, electrocardiogram, and
250 electromyogram) and chemical (*e.g.*, volatile organic com-
251 pounds, ions, and other metabolites) information exists that is
252 closely related to humans but easily ignored by biological
253 sensory systems. These signals have been detected by various
254 wearable, implantable, or injectable artificial sensors, which can
255 provide valid and quantized data for healthcare applica-
256 tions.^{29,30}

257 **Multiple Signaling Modes.** In biological sensory systems,
258 stimuli input received by different sensory receptors must be
259 converted into electroneurographic signals and then trans-
260 mitted along with the neurons, which results in intrinsic
261 limitations of the single transmission pathway. In contrast,
262 signals from artificial senses can be transmitted in different
263 modes, notably with wireless transmission techniques, which
264 greatly increases flexibility in designing sensory devices and
265 systems.^{31,32} Connecting discrete devices with different soft-
266 hard characters or different spatial distributions has been
267 challenging. Tian *et al.* constructed a wireless body sensor
268 network by confining radiowaves onto metamaterial textiles.³²
269 The sensory network exhibited enhanced robustness and
270 transmission efficiency and could localize signals within 10 cm
271 of the body. Moreover, Niu *et al.* introduced an unconven-
272 tional radio-frequency identification technology that integrates
273 stretchable on-skin wireless sensors with wearable readout
274 circuits (Figure 3e).³³ This design demonstrates the synergistic

effects among different types of signal transmission techniques
by replacing traditional physical interconnections with wireless
hybridization.

Big Data and Algorithms. The cognitive functions of
brains may encounter limited storage capacity, distorted
memory, and labile information extraction.³⁴ In contrast,
cloud storage systems that have been developed for big data
applications can handle a massive volume of heterogeneous
signals and data (Figure 3f).³⁵ Moreover, data-processing
capabilities promote the development of artificially intelligent
algorithms, of which image- and voice-processing algorithms
have been investigated the most extensively. Graphics
processing units have greatly enhanced image-processing
capabilities and data-extraction efficiencies, which further
lead to advances in vision-related techniques, including
image recognition, edge video analytics, and automatic
drive.³⁶ In addition, machine-learning algorithms have been
widely applied to cochlear implants, which can optimize voice
signals to fit complex environmental scenarios and individual
patients.³⁷

PERSPECTIVES AND CONCLUSIONS

The organization and mechanisms of the biological senses
provide inspiration for artificial senses, which continue to be
optimized and may exhibit comparable or even better
functionalities than biological systems. Through the hierarchi-
cal architectures constructed with nanotechnology, artificial
sense technology has established preliminary connections to
biological sensory systems and the environment at different
scales. With further development, artificial sense technologies
could evolve into powerful interfaces that can encode
biological and environmental processes into holographic
models, ultimately forming nets of sensations (SenseNet,
Figure 4).

Sense Substitution. Investigation and emulation of the
biological senses have enabled scientists to capture, to
translate, and to transmit biological sensations *via* artificial
sense technology. Traditional sensory substitution, which
interprets certain signals into stimuli that can be perceived
by sensory-deprived subjects, has limited sensory capabilities

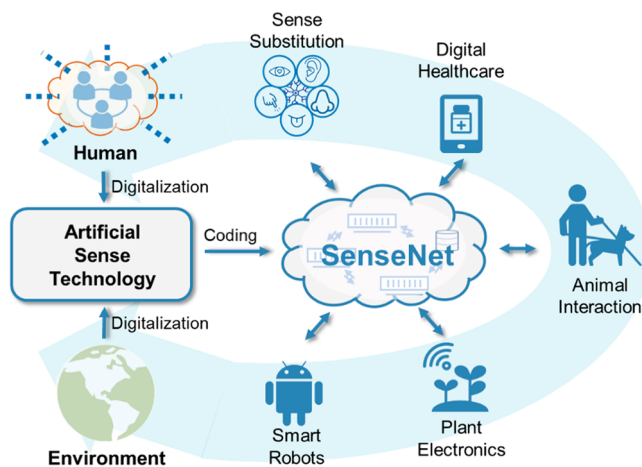


Figure 4. Digitization of human- or environment-related signals *via* artificial sense technology could be applied in the areas of sense substitution, digital healthcare, animal interactions, intelligent agriculture, and smart robots, forming the net of sensations (SenseNet).

314 due to the fundamental perceptual, attentional, and cognitive
315 discrepancies among different sensations.³⁸ Neural interfaces
316 that connect biological sensory systems with artificial sensing
317 devices provide more efficient routes to record, to analyze, and
318 to emulate neuronal activity during stimulation. **There,**
319 stimuli conversion, transmission, recognition, and other
320 sensory processes can be analyzed and recoded into digitized
321 signals that are easier to record and to reproduce, thus realizing
322 sense substitution within the same sensory modality.

With further development, artificial sense technologies could evolve into powerful interfaces that can encode biological and environmental processes into holographic models, ultimately forming nets of sensations.

323 **Digital Healthcare.** Traditional medicine relies on
324 experienced doctors to recognize symptoms and to make
325 judgments in an individual and subjective manner, which
326 greatly hinders the security and efficiency of treatment. With
327 the development of nanotechnology, electronics, and computer
328 science, researchers have designed a series of wearable or
329 implantable devices that comprehensively profile the physio-
330 logical states of a subject. Presently, healthcare data have not
331 been fully utilized due to incompatibilities across different
332 sensing techniques. Standards for artificial sense technology
333 should be established to unify sensor fabrication and evaluation
334 processes, as well as systematize the data collecting, trans-
335 mission, and calculation processes to provide valuable and
336 reliable digitalized profiling for healthcare applications. Various
337 physiological parameters could be continuously monitored and
338 analyzed to realize digital healthcare.

339 **Animal Interactions.** Animals have evolved diversiform
340 sensory systems, whose stimuli sensitivities or stimuli detection
341 limits are different from those of humans. Dogs have
342 particularly sensitive olfactory reception, which humans have
343 utilized for tasks including safety inspection, odor tracing, and
344 disease diagnosis.³⁹ The behaviors of insects (*e.g.*, reproduc-
345 tion, group membership, resource locations) can be affected by
346 pheromones.⁴⁰ Investigating these sensory processes *via*
347 artificial sense technology may improve our communication
348 efficiency with other species, and help us to interpret or to
349 intervene in the behaviors of other animals.

350 **Plant Electronics.** Plants have intricate functional micro-
351 structures and network-like communications that enable them
352 to respond to various stimuli, such as light, gravity,
353 temperature, and electrophysiological signals.^{41,42} Some
354 preliminary efforts have been made to connect artificial sense
355 technology to plant sensory systems. We used conformable,
356 transparent electrodes to communicate with plants without
357 affecting the plant's movement or physiology.⁴¹ Artificial sense
358 technology could also be applied to profile many other
359 important parameters, recoding plant sensory systems to
360 establish a plant electronic system, where plants can closely
361 integrate with artificial sensory systems, functioning as sensing,
362 transmitting, or storing components.

363 **Smart Robots.** A smart robot can perceive stimuli in the
364 environment and then learn from and respond to these stimuli.
365 Similar to biological organisms, a smart robot needs to collect
366 and process information from multiple sources to obtain a

comprehensive understanding of its environment. Artificial
sense technology plays critical roles in this process by detecting
environmental stimuli, analyzing the signals, and providing
feedback. Similar to biological evolution, artificial sense
systems should be able to optimize their sensing materials
and devices continuously, eventually to realize multimodal
sensation by smart robots that are comparable to that of
biological species.

In summary, artificial sensing technology has preliminarily
participated in profiling the environment and revealing
biological sensory processes. With ongoing development in
materials, nanotechnologies, electronics, data science, intelli-
gent algorithms, and other sensing-related areas, the
capabilities of artificial sense technology will continue to
expand, establishing closer ties with biological sensory systems
and evolving into powerful perceptual interfaces that connect
the physical world to the metaverse. We expect that, eventually,
immersive spaces will be constructed in the metaverse where,
through artificial sense technologies, all the biological senses
will be digitized and reestablished into holographic counter-
parts, and an extremely connected and expanded life will be
able to be experienced beyond current spatiotemporal
limitations.

AUTHOR INFORMATION

Corresponding Author

Xiaodong Chen – Innovative Centre for Flexible Devices
(iFLEX), School of Materials Science and Engineering,
Nanyang Technological University, 639798, Singapore;
Institute of Materials Research and Engineering, Agency for
Science Technology and Research (A*STAR), 138634,
Singapore; orcid.org/0000-0002-3312-1664;
Email: chenxd@ntu.edu.sg

Authors

Jianwu Wang – Innovative Centre for Flexible Devices
(iFLEX), School of Materials Science and Engineering,
Nanyang Technological University, 639798, Singapore
Cong Wang – Innovative Centre for Flexible Devices (iFLEX),
School of Materials Science and Engineering, Nanyang
Technological University, 639798, Singapore
Pingqiang Cai – Chemistry and Biomedicine Innovation
Center, Nanjing University, School of Medicine, Nanjing
210093, China; orcid.org/0000-0002-2665-5932
Yifei Luo – Institute of Materials Research and Engineering,
Agency for Science Technology and Research (A*STAR),
138634, Singapore
Zequn Cui – Innovative Centre for Flexible Devices (iFLEX),
School of Materials Science and Engineering, Nanyang
Technological University, 639798, Singapore
Xian Jun Loh – Institute of Materials Research and
Engineering, Agency for Science Technology and Research
(A*STAR), 138634, Singapore; orcid.org/0000-0001-8118-6502

Complete contact information is available at:
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Author Contributions

The manuscript was conceptualized by X.C. and J.W. and
written through contributions of J.W., C.W., P.C., Y.L., Z.C.,
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426 Notes

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