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Adaptation of sensor morphology: an integrative view of perception from biologically inspired robotics perspective

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Sensor morphology, the morphology of a sensing mechanism which plays a role of shaping the desired response from physical stimuli from surroundings to generate signals usable as sensory information, is one of the key common aspects of sensing processes. This paper presents a structured review of researches on bioinspired sensor morphology implemented in robotic systems, and discusses the fundamental design principles. Based on literature review, we propose two key arguments: first, owing to its synthetic nature, biologically inspired robotics approach is a unique and powerful methodology to understand the role of sensor morphology and how it can evolve and adapt to its task and environment. Second, a consideration of an integrative view of perception by looking into multidisciplinary and overarching mechanisms of sensor morphology adaptation across biology and engineering enables us to extract relevant design principles that are important to extend our understanding of the unfinished concepts in sensing and perception.

1. Introduction

Despite the rapid technological progress in sensor devices, machine perception is still regarded as one of the major challenges in robotics and information engineering: autonomous vehicles are, for example, still not able to visually identify objects in cluttered and dynamic environments as reliably as biological systems; robotic manipulators are not capable of discriminating subtle differences of objects as precisely as human hands; and robots are unable to perceive the subtle motions of fluids while swimming and flying for efficient and agile manoeuvres. While robotics engineers have been attempting to replicate the robust and adaptive capabilities of biological sensing systems, it is not trivial owing to the fundamental differences in the 'making' of physical bodies.

In all of these situations for which perception is a key challenge, a common theme is the sensor morphology for a specific sensing process. The importance of morphology has been recognized in several research areas, such as biology [1–5], cognitive science [6,7] as well as machine perception, which is the focus of this review. The term 'morphology' can be defined as the form and structure of an organism or any of its constituent parts [8], specifically it can be described by its geometrical and material properties. In biology, the term sensor morphology is defined as the morphology of an organism at the sensor level, with a variation in sensor morphology affecting the physiological and ecological performance of the biological being [1]. Sensor ecology is a subdiscipline of biology that focuses on the general principle of how organisms capture information from their environment, and the sensory systems involved in doing so [9,10]. This paper specifically focuses on sensor morphology, biological examples of which include: the structural variations of hair receptors in crickets, the viscoelastic properties of human tympanic membrane, as well as the two-dimensional shape and three-dimensional position and orientation of rat whiskers [1–5]. It was also emphasized that in any sensory modality, sensor morphology involves converting and shaping physical stimuli from surroundings to signals usable by the nervous system as sensory information [4].

Although there are many examples in nature, the issue of sensor morphology is still a scientific challenge, because the sensor must be integrated into a system. Sensing processes of an organism occur not only in the receptor cells that convert physical stimuli into electric signals, but also the physical stimuli can be already significantly shaped before reaching the nervous system. Physical stimuli can be, for example, structured by the locations of the sensory receptors in the physical bodies (depending on the locations of receptors in animals' bodies, the stimuli given to the receptors are very different [6,7]). Similarly, physical stimuli are also dependent on active motions and sensory–motor control of organisms such as animals or humans. When determining the roughness of a tabletop, for example, the sensation in our fingertips is dependent on the speed of the finger rubbing on the surface. Obviously, as also explained further in §3.2.1, the speed of the finger is also depending on the mechanical properties of the finger such as elasticity, tackiness and size of the fingertip. All of these mechanical properties are important to understand how humans or animals perceive the world and establish meaningful inferences from the sensory signals. Therefore, the problems of sensing and perception cannot be reduced down to a single mechanism that is part of a larger organism, but must be constructed as an integral part of the system. This integrative view has also been proposed for studying the general principles of animals locomotion [11], where it is important not only to understand how each component within a larger system operates, but also how they function as a whole.

In this context, biologically inspired robotics is a unique and powerful methodology that can take this far more integrated approach. Bioinspired robotics typically investigates a target behaviour in biological systems by extracting and formulating mechanisms that could be replicated in engineered systems. This formulation process is particularly important as it leads to abstract principles, and often they result in integrative views. It has been discussed that direct replication of biological systems is not necessarily advantageous, but an adequate level of abstraction can be used to provide meaningful inspiration or development of models [12]. Similarly, it was also argued that abstraction of design principles in biological systems depends on research objectives, and the synthetic approach (including the use of physical robots in the biological research) provides necessary components in our comprehensive understanding of nature [13]. These aspects of the use of robots in biological science should not be underestimated because it is necessary not only to obtain the aspects of biological systems that cannot be understood otherwise, but also to transfer some of the biological knowledge to engineering for developing innovative practical applications [6,14].

From this perspective, the goals of this article are to provide a structured review about the recent bioinspired robotics researches on sensor morphology, and discuss the underlying design principles we learned from them. By classifying the recent works, this review particularly focuses on the following four principles of sensor morphology that leads to an integrative nature of biological sensing processes from bioinspired robotics perspective. First, sensor morphology provides physical conversion, filtering and amplification of stimuli for reliable and precise sensing. Second, the bioinspired robotics research showed that the integration of sensing and motion control is the basis to understand sensing and sensor morphology in general. Third, the sensing processes need to be investigated in the context of embodiment of the target organisms at large, especially mechanical dynamics. Fourth, to cope with all these principles above, it is necessary to consider adaptation and optimization processes over multiple timescales. Section 2 explains the principles in more detail. More specifically, §2.1 first gives a general overview of the relevant research landscape, whereas §2.2 explains how the principles are exploited or investigated by using biologically inspired robotic systems.

Furthermore, we also extend our discussion towards a recent research trend about the adaptation of sensor morphology. Because of the recent rapid progress in robotics technologies, we are now able to investigate various aspects of sensor morphology, including the impact of adaptation of sensor morphology in a systematic manner. By introducing two recent case studies, we explain the state-of-the-art of researches on adaptive sensor morphology, and discuss challenges and perspective based on them.

2. Review of bioinspired sensor morphologies

Many bioinspired robotics projects can be regarded as sensor morphology research as every platform has well-thought morphological design that incorporates sensors in particular morphologies aiming to replicate biological systems. There is substantial work undertaken in this area [14–19] that provides a full overview of the field and includes discussions on the integrative nature of biological sensing processes from biological and cognitive science perspectives. The goal of this section, in contrast, is to provide a review of more recent sensor morphology research with a particular focus on the integrative design philosophy from bioinspired robotics perspective.

2.1. The research landscape

Table 1 summarizes the landscape of recent research on sensor morphology. The main body of previous literature on bioinspired robotics research focusing on sensor morphology can be classified by the following nine aspects. Let us first briefly overview the landscape of research, based on which we will discuss more abstract design principles in §2.2.

The first important aspect is the sensory modality, i.e. the type of the sensed physical phenomenon, such as visual (light) [20–27,32,33,35–46], somatosensory (touch and perception) [47,48,49,50–56,58–68], auditory (hearing) [71,72] and even electric [73–77] or magnetic field [78,79]. Some researchers also investigated sensor morphology of multimodal systems, where a combination of multiple sensors is used, each sensing a different physical phenomenon [80–84].

The second aspect is the sensory receptor types used by the systems, e.g. elementary motion detectors (EMDs) for visual modality [20–24] or artificial whiskers based on a capacitor microphone with glued natural hair for touch modality [51–53].

Third, it is also important to note that there are multiple definitions of sensor morphology. Sensor morphology could be defined as the number of receptors, spatial resolutions, angular orientation and acceptance angle of artificial facettes forming a compound eye [25,26], distribution of artificial

Table 1. The landscape of sensor morphology research in biologically inspired robotics.

no.	modality	sensors used	morphology definition	design goal	design methodology	corresponding biological systems	co-optimization between morphology, motor control	explicit motion for active sensing	implementation	references	investigated design principles
1	vision—light	EMDs	angles of the EMDs with respect to a target	confirming a biological assumption of how flies maintain a fixed lateral distance to target	biological inspiration	fly	no	no	real robot	[20–24]	1, 2
2	vision—light	an array of polymer microlenses moulded on a glass carrier, with photo detector, electromechanical layers	number, spatial resolution, angular orientation and acceptance angle of the artificial ommatidia	mimicking characteristics of biological compound eyes	biological inspiration	fly	no	no	real robot/device	[25,26]	1
3	vision—light	local motion sensors	number and orientation of sensors forming compound eyes	navigation in stringent corridor configurations	biological inspiration	bee	no	no	real robot	[27–31]	1, 2, 3
4	vision—light	an array of photodiodes	interommatidial angles	dynamic track and obstacle avoidance	biological inspiration	diurnal insects	no	no	real robot	[32]	1, 2
5	vision—light	PSD (an optic-based position sensor)	eight possible sensor locations	collision-free navigation in a maze	evolutionary algorithm	no specific correspondence	yes	no	both	[33,34]	1, 2, 4
6	vision—light	floor sensors, consist of an infrared light-emitting diode and a light receiver	number and sensor placement on a line following mobile robot	maximizing accuracy in line following task	reinforcement learning and evolutionary algorithm	no specific correspondence	yes	no	both	[35,36]	1, 2, 4
7	vision—light	camera	sensing distance, field of view and pan	formation control	systematic investigation	no specific correspondence	yes	no	both	[37,38]	1, 2, 4
8	vision—light	camera	retinal morphology described by log-polar transformation	induce statistical regularities and information structure in vergence behaviour	biological inspiration	human	no	yes	real robot	[39,40]	1, 2

(*Continued.*)

Table 1. (*Continued.*)

no.	modality	sensors used	morphology definition	design goal	design methodology	corresponding biological systems	co-optimization between morphology, motor control	explicit motion for active sensing	implementation	references	investigated design principles
9	vision—light	camera	placement of the sensors on different robots	induce statistical regularities and information structure	biological inspiration	no specific correspondence	no	yes	both	[41]	1, 2
10	vision—light	simulated distance sensor	orientation with respect to joints, range and activation timing of the sensors	collision free navigation in cluttered environments	biological inspiration, evolutionary algorithm	snake	yes	no	simulation	[42,43]	1, 2, 4
11	vision—light	simulated distance sensor	placement of the sensors	traversal of corridor-like environment and formation control of multiple undulatory robots	biological inspiration	snake	no	no	simulation	[44]	1, 2
12	vision—light	simulated visual sensor with particular angular view	position and visual range of the sensors	maintaining a certain distance from an object	evolutionary algorithm	no specific correspondence	no	no	simulation	[45]	1, 4
13	vision—light	simulated visual sensor with particular angular view	number of visual sensors	maintain a distance between a certain part of the body and an object	evolutionary algorithm	no specific correspondence	no	no	simulation	[46]	1, 4
14	somatosensory—touch and proprioception	artificial whiskers individually equipped with a motor, shaft encoder and three-axis Hall effect sensor	distribution, length, structure of the whiskers, and the degrees of freedom of the movement	constraining sensory range to increase the fidelity of sensing, and maximizing the number of whisker contacts	biological inspiration	shrew and rat	no	yes	real robot	[47–50]	1, 2, 3
15	somatosensory—touch and proprioception	artificial whiskers based on a capacitor microphone with natural hair glued to its membrane	position and length of the whiskers	collision free navigation in cluttered environments	systematic investigation	rodents	yes	no	real robot	[51–53]	1, 2, 3

(*Continued.*)

Table 1. (*Continued.*)

no.	modality	sensors used	morphology definition	design goal	design methodology	corresponding biological systems	co-optimization between morphology, motor control	explicit motion for active sensing	implementation	references	investigated design principles
16	somatosensory—touch and proprioception	commercially available pressure sensor	placement of the sensors	swimming speed control	biological inspiration	fish	no	no	real robot	[54,55]	1, 2, 3
17	somatosensory—touch and proprioception	fluid sensing through pressure	shape of the sensor	maximizing fluid sensing sensitivity in fluid sensing	biological inspiration	crayfish	no	no	simulation	[56,57]	1
18	Somatosensory—touch and proprioception	statocyst inspired tilt sensor	size and structure	maximizing sensing sensitivity	biological inspiration	jellyfish	no	no	real robot	[58,59]	1
19	somatosensory—touch and proprioception	additive manufacturing based shape-flexible strain sensor	path of a thread-like strain sensor	maximizing sensitivity of strain sensing in soft structure	strain vector aided	no specific correspondence	no	no	both	[60–62]	1
20	somatosensory—touch and proprioception	tactile sensor composed of thin rubber skins and a camera to track markers on the skins	the layered structure of the rubber skin	maximizing sensing sensitivity	biological inspiration	human	no	no	real robot	[63,64]	1
21	somatosensory—touch and proprioception	bending sensor based on electric capacitance	position and dimension of the sensors	maximizing sensing sensitivity	biological inspiration	plant	no	no	real robot	[65]	1
22	somatosensory—touch and proprioception	singe bit contact sensor	which sensors to use, out of eight positions	collision free navigation in cluttered environments	evolutionary algorithm	no specific correspondence	yes	no	real robot	[66]	1, 2, 4
23	somatosensory—touch and proprioception	camera for force and temperature sensing	depend on the sensed physical quantities	*in situ* adjustment for balancing sensing sensitivity and linear response	biological inspiration	human	yes	yes	real robot + hot melt adhesive	[67]	1, 2, 3
24	somatosensory—touch and proprioception	pressure, angle, inertia and motor torque sensors on a four-legged robot's hinds, body segments, joints	placement of the sensors	stable locomotion of four-legged dog-like robot	systematic investigation	no specific correspondence	no	no	both	[68]	1, 2, 3

(*Continued.*)

Table 1. (*Continued.*)

no.	modality	sensors used	morphology definition	design goal	design methodology	corresponding biological systems	co-optimization between morphology, motor control	explicit motion for active sensing	implementation	references	investigated design principles
25	Somatosensory—touch and proprioception	joint and pressure sensors	placement of the sensors	dead reckoning in four-legged dog-like robot	systematic investigation	no specific correspondence	no	no	real robot	[69,70]	1, 2, 3
26	auditory—sound	microphone	analogue electronic model of cricket's peripheral auditory morphology	phonotaxis	biological inspiration	cricket	yes	no	real robot	[71,72]	1, 2, 4
27	electric field	electrosensor	shape and placement	underwater navigation and docking	biological inspiration	fish	no	no	real robot	[73–77]	1, 2
28	magnetic field	Hall sensor (magnetic field sensor)	position of the sensors	self-assembly	systematic investigation	no specific correspondence	no	no	real robot	[78,79]	1, 3
29	multimodality	tactile and distance sensors (ultraviolet and infrared-based light sensors)	which sensors should be activated, the distance sensor range, and the sensor orientation	collision free navigation in cluttered environments	evolutionary algorithm	no specific correspondence	yes	no	both	[80–83]	1, 2, 4
30	multimodality	simulated distance, touch and proprioception sensor	number and types of sensors	maximizing directed displacement of the robot in a fixed amount of time	evolutionary algorithm	no specific correspondence	yes	no	simulation	[84,85]	1, 2, 4

whiskers [47–50] or number and types among distance, touch and proprioception sensor in simulation setting [84].

The fourth and fifth aspects are the relevant design goal and methodology, such as how sensor morphology can maximize sensitivity, and what is the methodology to design a particular sensor morphology (e.g. by imitating the morphology of specific biological system such as crayfish [56,57]).

The sixth aspect specifies target biological system in the research. Many previous publications focus on specific biological systems to investigate, whereas others do not. For example, a number of research relies on evolutionary algorithm to co-optimize sensor morphology and motion control [33,45], or on strain vectors in order to maximize sensitivity in sensing particular motions commonly performed by biological systems with soft and compliant body [60,61].

Seventh, it is also important to note the aspect of 'co-optimization between sensory morphology and motor control', which plays an important role in understanding the integrative nature of the issue. Here we specifically consider whether the parameters related to motion control and sensor morphology are being tuned simultaneously, e.g. by using evolutionary algorithm [33], in the designed artificial system [33,45]. A counter example of co-optimization could be a biomimetic navigation strategy based on bees' sensor morphology and motor control [27]. This case study is not considered as a co-optimization research, as there was no dedicated technique implemented to co-optimize motion control and sensor morphology in addition to imitating bees' sensor morphology and motor control.

Eighth, we have also noted that some experimental platforms emphasize explicitly controlling the motions of the sensors for sensing purposes, i.e. whether the system performs active sensing [30], such as examples shown in [47–50]. Section 2.2.2 has further explanations on active sensing as well as sensory motor coordination, i.e. the mutual coupling between sensing and acting [14].

Finally, it is also shown whether research was conducted in the physical robotic platforms or in simulation. With some exceptions [42–46,56,84], the majority of previous work shown in table 1 was investigated on the physical platforms, indicating the importance of real robot implementation for research on sensor morphology.

2.2. Design principles of sensor morphologies

The overview of sensor morphology research shown in §2.1 and table 1 provides several design principles across different species, sensor modalities and physical media comprising morphology. While the individual case studies of sensor morphology are highly interesting on their own right, it is also important to extract more comprehensive design principles as explained in the Introduction. The goal of this section is therefore to develop principles towards an integrative view, which are conversion and shaping of physical stimuli into sensory information, sensory–motor coordination, sensory–dynamics coupling and adaptation over timescales. While the design principles are not something that can be applied to all sensor modalities, and all robots or animals, it is argued that the aspects are important to extend our understanding of some of the unfinished concepts of biological system sensing and perception. In the last column in table 1, these four principles are denoted as principles 1–4, respectively. As also shown by table 1, not all design principles become the focus of the investigation for all modalities and robotic systems. Nevertheless, it is shown that the first principle, i.e. the conversion and shaping of physical stimuli, is involved in each research. However, as will explained further in §§2.2.1–2.2.4 (i.e. principles 1–4), some researches only show the importance of the filtering and amplification process of the signal, whereas others also emphasize the importance of using a suitable approach to co-optimize sensor morphology and motion control and therefore also involve sensory motor control principle.

2.2.1. Physical conversion, filtering and amplification of stimuli

Biological systems make use of sensory signals for large diversity of purposes, but they need to be pre-processed physically for the given requirements such that physical stimuli can be used to produce useful sensory information [4]. In this situation, sensor morphology usually plays an important role by mechanically converting, filtering and amplifying physical stimuli for robust and precise identification.

For instance, crustaceans are known to have a great variety of sensilla along their antennules as chemomechanoreceptors to properly sense both hydrodynamic and chemical stimuli in aquatic environments and convert them into useful sensory information [86–88]. It was observed that, along the antennule of the freshwater crayfish, there were four predominant mechanosensory sensilla, which were crucial for detecting their predators, mates and varying environmental substrates [88]. In this regard, a numerical model was proposed to confirm the relationship between the four sensilla morphologies and the sensitivity in sensing the flow perturbations within the crayfish's surrounding fluid [56] (figure 1*c*).

A similar concept was applied to robotics applications, in which strain gauge sensors employing conductive thermoplastic elastomer (CTPE) [62] were used for sensing deformation in robots mainly composed of soft material like their biological counterparts. Owing to its low Young's modulus and flexible shape, CTPE can be integrated into a robot soft body with suitable shape for particular purposes such as maximizing strain sensing sensitivity. More specifically, a soft robot sensorized with CTPE can be made to be sensitive to certain motion patterns based on the sensor morphology, instead of having any additional filtering or amplification algorithms [60,61].

A miniature curved articial compound eye was also presented in [25] (figure 1*d*). The compound eye possessed morphological characteristics similar to the eye of the fruitfly *Drosophila*, such as number and spatial resolution of facets represented by an array of highly transparent polymer microlenses. The sensor possesses similarities in converting optical flow cues into useful sensory information as its biological counterpart, and therefore will be advantageous for biomimetic experiments.

This design principle demonstrates the importance of an integrative view of sensing problems, because physical conversion, filtering and amplification of stimuli make sense only when sensing targets are known. Without knowing the targets, we are not able to optimize sensor morphology for the required sensing performance, e.g. sensitivity or sensing range.

2.2.2. Morphology for active sensing and sensory motor coordination

It has been suggested that the separation of perception from action in theoretical analyses of intelligent behaviour may be

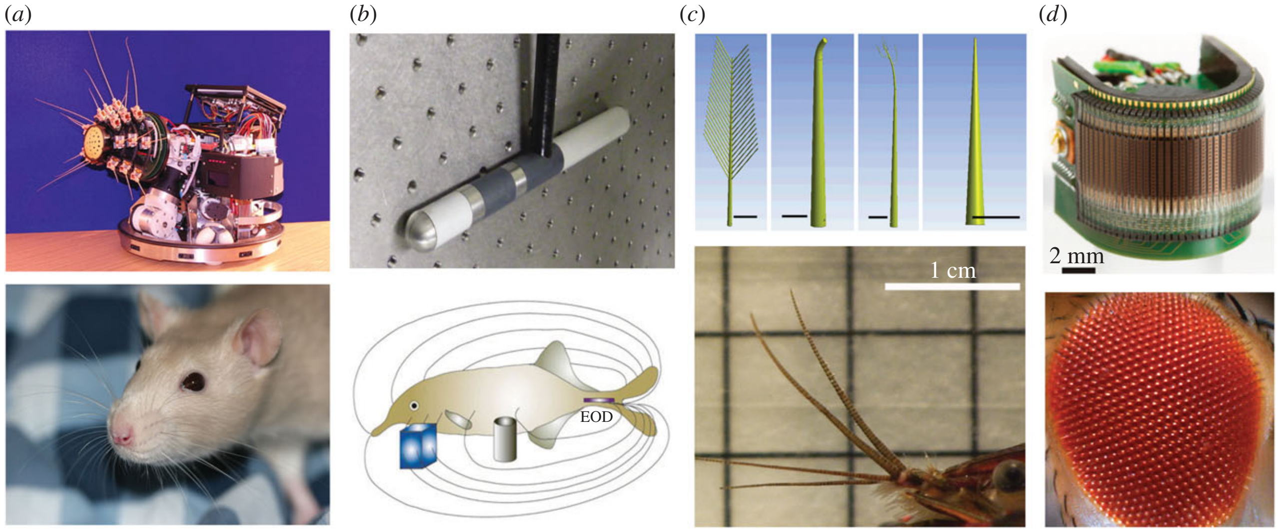

Figure 1. Examples of human-made sensors (top) inspired by biological ones (bottom) that demonstrate the importance of sensor morphology. (*a*) Biomimetic vibrissal sensor for robots inspired by facial whiskers of rodents [47]. (*b*) Electrode sensor for underwater robots inspired by the ability of electric fish with electric organ discharge (EOD) to sense distortions in the surrounding electric fields due to the presence of objects [76]. (*c*) Four idealized simulated models used to investigate the effects of sensilla morphology on mechanosensory sensitivity in crayfish antennular flagellum [56]. (*d*) Artificial curved compound eyes [25] inspired by natural ones such as those possessed by fruitfly *Drosophila melanogaster* [89]. Figures are reproduced by the permission of the authors and publishers, or used under the Creative Commons License. Panel (*c*) copyright IOP Publishing. Reproduced with permission. All rights reserved. (Online version in colour.)

misleading and sensing of most kinds is best considered as an 'active sensing' process rather than as a passive one [18,30]. The term active sensing itself is defined in literature as purposive and information-seeking sensory systems that usually entails sensor movement to maximize information gain, whereas passive sensing is defined oppositely [30]. While active sensing's concept and application has been a long-standing research topic over the last decades [30,90], the implications of it can reach even further when considering sensor morphology, which has been intensively explored both in biology and recently in robotics.

From table 1, several examples that demonstrate the importance of an integrative view can be highlighted. For example, a CCD camera was used in humanoid [39,40] and other types of robots [41] to demonstrate the importance of sensor morphology in an active vision system, along with its interaction with the environment, to induce statistical regularities and information structure in sensory inputs and within the neural control architecture. In the context of somatosensory modality, i.e. touch and proprioception, biomimetic vibrissal sensing, inspired by shrews and rats, was proposed in quite a number of works [47–50]. The definition of sensor morphology therein was the distribution of developed artificial whiskers on a mobile robot's head, the length and the structure of the whisker shafts and the degrees of freedom of the movement (figure 1*a*). The robot was able to individually control each whisker, as the whiskers consisted of a motor, shaft encoder and three-axis Hall effect sensor. Based on a proper sensor morphology and suitable motion of each whisker to perform the sensing process, it was shown that the robot was able to maximize the number of whisker contacts, as well as to increase the fidelity of sensing within certain sensory range.

More generally, it can be said that sensing problems in nature are largely combined with motor functions. To encapsulate the concept, the term sensory motor coordination is defined in the literature as mutual coupling of sensing and acting [14]. It has been shown that through sensory motor coordination, an agent is able to obtain more structured sensory information, rather than to 'passively' registering sensory information [14]. Table 1 lists relevant researches that demonstrate the importance of sensory motor control, but also points out whether dedicated motion for active sensing purpose is explicitly employed in the research through the ninth column from the left. As can be seen, there are quite a number of works that focused on visually mediated motor control and navigation in flying insects [20–27,32]. An important design principle of their sensory systems is found to be the so-called motion parallax, that is, the motions of further objects projected on the insects' retina appear to be slower than those of nearer objects. This essentially means that a flying insect experiencing fast optic flow on its retina is most likely to fly closer to a large obstacle, which usually triggers an obstacle avoidance action to avoid crashing. Similarly, when an insect is about to touch down on a flat surface, the flight control tries to maintain the optic flow constant which automatically gives slowing down function as the insect approaches the surface and finally touches down at zero velocity eventually.

The most pioneering works that demonstrated the importance of sensor morphology in flying insects to facilitate the motion parallax design principle were probably those presented in [20–24]. Inspired by the knowledge that insect eyes consist of many facets or ommatidia, and therefore commonly known as compound eyes, a robotic system consisting of EMDs to represent the facets was proposed therein. It was known that in certain species of flies the facets are more densely spaced towards the front [24]. In order to investigate the benefits of this morphology, the robotic system was able to adjust the angles between the EMDs by using an evolutionary algorithm. The result confirmed the theoretical predictions: the facets ended up with an inhomogeneous distribution with a higher density towards the front in order to compensate motion parallax, during an effort to maintain a fixed lateral distance to an object. If a standard CCD camera with evenly spaced light-sensitive cells was used, then the compensation for the motion parallax had to be performed at the computational level. However, in this case, the morphology of the sensors was adjusted, whereas the explicit computational effort was kept.

There is also research that exploits the design of sensor morphology and how it is coupled with a suitable motor control strategy in other modalities. For example, inspired by electrolocation ability of electric fish, underwater navigation and docking techniques based on electrosensing were proposed [73–77]. The approach exploited a bioinspired morphology for the developed sensors, i.e. slender shape and bilateral symmetry (figure 1*b*), which sense the surrounding electric field perturbations, as well as a suitable sensor-based reactive control law. Although the importance of sensory–motor control has been known in biology for a long time, the issue of sensor morphology under highly dynamic feedback control is still not fully uncovered and remains for investigations both in biology and robotics.

Finally, without any specific corresponding biological systems, evolutionary algorithm was commonly used to couple motor control and sensor morphology [33,66,80–84]. An example is shown in [66], where the speed level and positions of single bit contact sensors mounted on a mobile robot are co-optimized to accomplish a collision free navigation task in a cluttered environment.

2.2.3. Sensing through mechanical dynamics

The fact that sensing processes are highly coupled with the agents' motions leads us to consider more general design principles of autonomous systems in relation to mechanical entities, namely 'embodiment'. Physical motions of embodied systems are not only limited to active and actuated ones, but also applicable to more general motions including those generated by mechanical dynamics such as elasticity and deformability of physical structures. This principle therefore refers to the class of sensing processes that relate to mechanical dynamics of organisms.

A representative example was shown in the robots with elastic whiskers that the dynamics of morphology and materials significantly influence the identification processes of the environments and a success rate of collision free navigation in cluttered environments [51–53]. In these case studies, it is found that appropriate mechanical stiffness in whiskers plays an important role in reliable and accurate sensing of the objects in the environment. A similar mechanism was also shown on a larger scale, i.e. a dynamic four-legged robot with elastic feet and passive joints [68]. In this case study, attractor states derived from mechanical dynamics can be used for the recognition of its own dynamic behaviours as well as physical properties in the environment through proprioceptive sensing [68]. The research direction to take advantage of the interaction between the elastic feet, passive joints and the environment for proprioceptive sensing purpose is continued afterward where a dead reckoning technique based on joint and pressure sensors for legged robots is proposed [69,70].

Mechanical dynamics also help sensing processes underwater. A commercially available on-board pressure sensor was used in a robotic trout with bioinspired morphology to detect the laminar flow speed [54,55]. It was shown that owing to the similar mechanical dynamics arising from the interaction between the robot's body and the environment, it was possible to derive a linear control law between the tail-beat frequency and the swimming speed, which holds for both the real and artificial fish.

In general, it is essential to consider the mechanical dynamics derived from morphological properties and an interaction between an embodied system and its environment in order to gain proper insights into the underlying mechanisms of sensory–motor coordination, and more generally the nature of perception. This principle nicely illustrates the importance of an integrative study of sensing as it is strongly coupled with motor control as well as mechanical dynamics.

2.2.4. Adaptation over multiple timescales

The case studies introduced in this section indicated the power of morphology in sensing purposes, but we have not so far discussed how it can adapt to the given tasks and environment autonomously. There is however an increasing interest in the study of sensor morphology adaptation.

For design and optimization of sensor morphology, a consideration of multiple timescales is essential. While designing sensor morphology, it is necessary to consider the fact that every morphology has limitless dimensionality in design choices, as well as their relations with motor control, mechanical dynamics and overall purposes of sensing as stated in the previous principles.

There have been a series of investigations that explored the adaptation principle on the phylogenetic timescale. For instance, in vision (light) modality, an approach to co-optimize motor commands and sensor morphology, i.e. eight possible locations of position sensitive detector (PSD), by using genetic programming [34] was proposed to enable a mobile robot to navigate in a maze [33].

Other researches also attempt to determine the morphology of sensory systems involving more than one sensor. In a hexapod robot, an evolutionary algorithm was proposed to concurrently evolve control, i.e. walking gait, and sensor morphology: which among tactile, ultraviolet and infrared-based distance sensors should be activated, their orientation and the range of the distance sensors [80–83]. Here, the task for the robot is to perform collision-free navigation in cluttered environments. Evolutionary algorithm was also used to concurrently evolve a neural network controller, namely compositional pattern producing networks [85], and sensor morphology for achieving a task of maximizing directed displacement of a simulated robot in a fixed amount of time [84]. The sensor morphology was defined as the number and type of sensors that should be used which include distance, touch and proprioception sensors.

On a phylogenetic timescale, it is worth mentioning that evolutionary algorithm has also been used for various optimization problems including optimizing the shape of sensors for applications more general than robotics, e.g. optimizing the thickness of convex lens to minimize ray scattering [91]. However, as also shown by examples [33,34,80–85], there are more aspects to consider in the problem of optimizing sensor morphology from bioinspired robotics perspective, such as co-optimization between motor control and morphology, gaps between simulation and real-world implementation, or how factors such as material properties or multiagent setting affect the design (see [92] for a review of the current progress of evolutionary algorithm applications

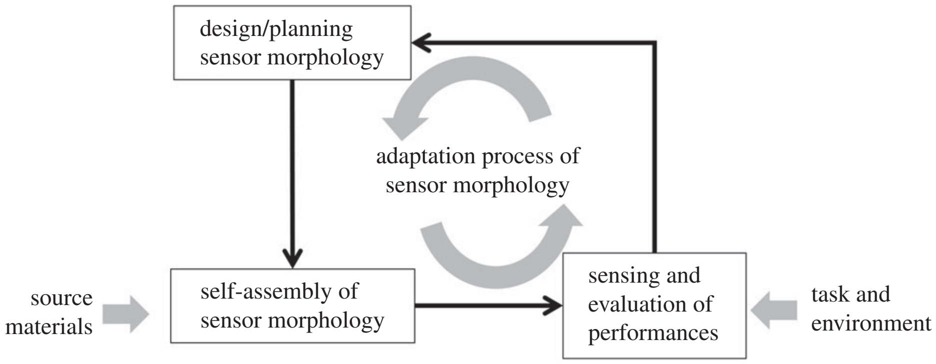

Figure 2. The integrative view of sensor morphology adaptation from bioinspired perspective that includes the design/planning of the morphology, the ideal self-assembly process by using the necessary source materials, as well as the sensing and evaluation of performances based on task–environment interactions.

in robotics), which also shows the importance of an integrative view.

Last but not least, instead of only exploiting phylogenetic adaptation by using evolutionary algorithm, there is also research that demonstrated two types of adaptations, ontogenetic and phylogenetic, to co-optimize control and sensor morphology [35,36]. More specifically, reinforcement learning was used to search for the optimal policy as part of the ontogenetic adaptation, whereas in phylogenetic adaptation, a genetic algorithm is used to select morphologies with which the robot can learn its tasks faster.

The principle of adaptation over multiple timescales is particularly important for the integrative view of sensor morphology because it implies the ways to deal with the large (if not infinite) dimensionality in the optimization problem of sensory morphology.

3. Adaptation of sensor morphologies

From the principles of sensor morphology we discussed in §2.2.4, we attempted to explain the integrative nature of the sensor morphology problems. Sensing of autonomous systems is significantly related to motor control, mechanical dynamics and overall control objectives of the systems, and morphologies are playing considerable roles in this context. Having these design principles, the goal of this section is to provide a more specific discussion on the topic of morphological adaptation in bioinspired robotics research, which we think is one of the most important research directions in the field.

3.1. Basic concept

Adaptation of sensor morphology is a fundamental question because it explains how the aforementioned principles can emerge in autonomous systems, and more broadly, the adaptive nature of organisms' sensing and perception. However, the adaptation processes have not been investigated in detail until recently because of the intrinsic complexity of the processes.

Figure 2 illustrates a 'mechanistic' view of the adaptation of sensor morphology, in which there are two key elements to determine morphology, i.e. 'what morphology to build?' and 'how to build it?'. If we implement such a mechanism in a robot, then the machines should be able to design or plan the sensor morphology by themselves and construct it somehow physically through an iterative adaptation process based on the necessary source materials and ideally self-assembly processes [93]. The term self-assembly here refers to an ideal condition that the process of physically adapting the sensor morphology is performed spontaneously and autonomously by the machine with minimal human intervention, through the utilization of the necessary source materials (e.g. hot melt adhesives (HMAs); see §3.2.2). Finally, the system's performance should be evaluated through its interaction with the task–environment, by using real physical systems, i.e. robotic systems, or in some cases through simulation. The performance is fed back to the next iteration of the design and planning process, which makes use of this information for the update of the design.

3.2. Case studies

Although the adaptation processes of sensor morphology are challenging to replicate in robotic systems, the recent case studies, which are discussed in this section, revealed the importance of careful investigations about them.

Although the adaptation of sensor morphology is still performed manually by humans, the first case study is chosen to demonstrate the importance of properly coupling the sensor morphology and motor control, and how careful imitation of relevant biological systems by using robots can help to reveal the relationship among the sensor morphology, motor control and the expected behaviour. The second example describes a proposed technological solution to enable iterative adaptation processes of sensor morphology by robots, with a focus on how to properly use soft and unconventional materials to imitate their biological counterparts (see [94–96] for recent reviews of this emerging research area). It will be shown that by properly using soft thermoplastic adhesive material, a robotic system is able to repeatedly fabricate, attach and detach various structures with flexible placement, stiffness, size and shape, and use them for sensing purpose. Another direction shown by the second case study is the investigation of how a robotic system could autonomously come up with suitable morphology through design automation or self-organization. Both case studies also demonstrated physical processes that facilitate information processing and control of adaptive motions. The challenges and perspectives learned from the case studies and the adaptation of sensor morphology in general will be discussed in §4.

3.2.1. Biomimetic vision-based hovercraft

As shown in table 1, sensor morphology of insects' compound eyes is a popular investigation. One of the latest results was

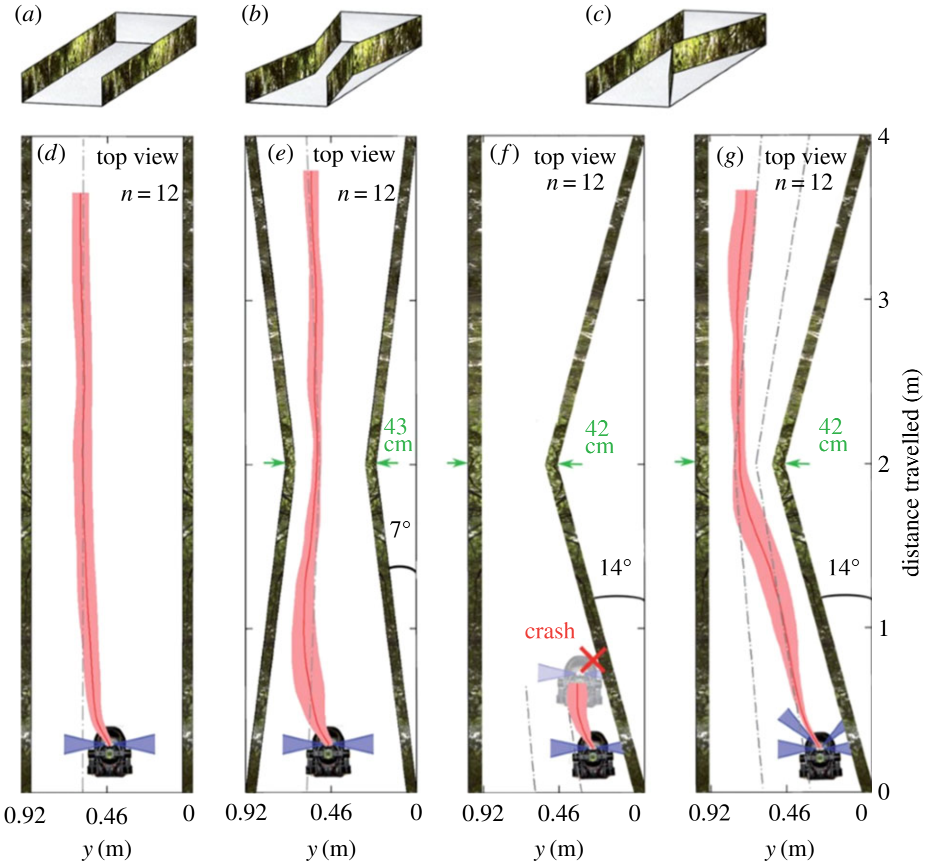

Figure 3. The navigation performance (*d–g*) of a biomimetic vision-based hovercraft in stringent corridor configurations (*a–c*) with different sensor morphology represented by its compound eye [27]. The mean trajectory (solid red line) and the standard deviation of the mean (pink shaded area) were computed from a set of 12 trajectories and plotted with the expected/predicted steady-state position (grey dashed–dotted line). The obtained flying behaviour of the robot was similar to bee behaviours observed in the last 25 years of ethological studies [28–31]. Figures are reproduced under the Creative Commons License and also by the permission of the authors. (Online version in colour.)

reported in [27], where a biomimetic hovercraft robot was able to travel safely along corridors with various configurations by carefully adapting the sensor morphology (figure 3).

It is well known that flying bees are able to fly through unknown and unpredictable environments by relying on the optical flow cues generated by their own motion, instead of using any emissive sensors to gauge their own speed or the distance to obstacles [97]. In [27], it was shown that the key to this ability was the compound eye morphology along with the coupled navigation control strategy. More specifically, the authors developed minimalistic bee-inspired compound eye by using local motion sensors (LMS), consisting of an optical assembly composed of a lens and a pair of photosensors. At first, two LMS were used with $\pm 90^\circ$ azimuthal angles, i.e. the sensors oriented laterally, one on either side. Afterwards, two LMS were added, facing forward with $\pm 45^\circ$ azimuthal angles. It was also explained that the values of the angles $\pm 90^\circ$ and $\pm 45^\circ$ were comparable to those measured in the honeybee's compound eye. In terms of control strategy, the importance of a heading-lock system that enabled the robot to experience a purely translational optical flow, also possessed by bees [98], was emphasized.

As a result, they demonstrated that the developed hovercraft robot was able to fly safely in various configurations of long straight and tapered corridors. It was also discussed that the two extra frontal eyes were useful to help the robot navigate in more demanding corridor configurations by improving the ability to detect lateral optical flow. Moreover, it was also explained therein that the obtained flying behaviour of the robot was similar to bee behaviours observed in the last 25 years of ethological studies [28–31].

Although the adaptation of sensor morphology was not conducted autonomously (the addition of LMS was conducted manually by humans and therefore is not a self-assembly process as ideally proposed in figure 2), this case study provides valuable implications about the importance of sensor morphology adaptation. First, this case study further supports our argument about the power of sensor morphology. That is, the locations of LMS in this case study were particularly important in a sense that only eight pixels of photoreceptors (four pairs of LMS) are sufficient to steer the hovercraft successfully in the relatively complex environment. Second, the adaptation of additional pixels improves the performance of overall navigation capability, in a sense that two pairs of lateral LMS are sufficient to navigate in many environments, but the addition of two more LMS improves the performances in more complex environment.

The underlying adaptation mechanism is actually quite complex, because the sensor morphology is actually coupled with the sensory–motor coordination. Nevertheless, this case study shows how the capacity of sensor morphology adaptation could trigger the improvement of behavioural performance, by achieving tasks that are not possible otherwise.

3.2.2. *In situ* adaptation of sensor morphology based on thermoplastic adhesive material

A robotic system capable of adapting its sensor morphology *in situ* by using soft thermoplastic adhesive material, i.e. HMAs, has been proposed in [67]. The approach taken was to equip the robot's end effector with an HMA handling unit. The unit was composed of a solid HMA block that was fed to an HMA supplier. Through additive manufacturing process, a passive structure with particular shape and size could be repeatedly fabricated, attached and detached to the end effector. The fabrication of the passive structure is shown in figure 4*a*.

A camera was mounted to perform visual processing tasks during sensing. As can be seen from figure 4*b*, by performing suitable dedicated motion, i.e. active sensing, the robot used the structure to physically probe a target object and transduced the physical stimuli into information usable by the camera. Here, the softness of the object was sensed through force applied to a developed stick (top figure) and the temperature was sensed through the known weight and the attachment area between the built object and robot's end effector (bottom figure).

Through a developed model that explained the interaction between the robot's end effector and the object, it was explained further therein how the sensing sensitivity and linear range depended on sensor morphology. Referring to figure 4*c*, it was shown that when the stick pushed the object with a possible distance Δx, the function that relates the force F (either the original force F_s or the reaction from the object F_o) which caused the deflection of the stick with angle θ detected by the camera was proportional to the Young's modulus E and certain morphological parameters. The parameters consisted of width w of the fabricated stick, the thickness h and the stick's length l (see [22] for more detailed explanation). It was also shown that the sensing sensitivity and linear range of the sensing depended on these morphological parameters w, h and l. As the robot was able to fabricate the passive structure, i.e. HMA stick, *in situ*, it can therefore adjust the sensitivity and linear range of the sensing process by tuning one of the parameters such as h as shown in figure 4*c*.

Owing to the thermoadhesive property of HMA, its mechanical characteristics were also exploited for sensing temperature where the physical interaction is shown in figure 4*c*. When the robot touched the object with its end effector, owing to heat conduction Q, temperature T will increase as T_o is increased. As a result, the fabricated mechanical structure will be detached from the robot's end effector. It was also shown that T is an exponential function of bonding strength B, where B was proportional to the weight W of the object and inversely proportional to its area A, defined as a square with length d. Again, the sensitivity and linear range of the sensing process were adjustable through the morphological parameters W and d. Figure 4*d* shows how they are adapted through the weight W, by building appropriate number of layers in an additive manufacturing process.

In this case study, it can be observed that the design adaptation shown in figure 2 was being conducted *in situ* by the robot due to its ability to repeatedly fabricate various detachable passive structures using HMAs, as it source material. Furthermore, the definition of the sensor morphologies here not only includes their size and shape, but also the attachment points that affect how the passive structures would be used by the robot to interact with a target object. Based on the real-world evaluation, i.e. the sensing sensitivity and linear range, the design of the sensor morphology for a particular motion is adapted.

Some aspects listed in table 1 can also be clarified further. For example, in this work, the interaction between the robot and the object was inspired by what could be performed by humans when they attempted to sense an object's softness and temperature. In addition, the dedicated motions performed by the robot to accomplish the sensing process, i.e. active sensing, were chosen to be suitable with the physical quantities need to be sensed and therefore the relevant sensor morphology. More specifically, the motion for each sensing process was fixed by the robot's user, whereas the robot attempted to adjust the sensor morphology *in situ*.

4. Challenges and perspectives

Throughout the case studies in this review, we discussed how the use of robotics technologies could provide significant additional insights into the complex problem of sensor morphologies and their adaptation. As the robotics technologies advance, there are more possibilities of unconventional experiments and analyses for the purpose of complex phenomena as represented by adaptation of sensor morphology. This section discusses the lessons learned from the case studies we reviewed in this article, and elaborates further implications.

4.1. Self-organization, self-assembly and design automation

With the progress of robotics technologies, we are now more accessible to the automation processes that are capable of fabricating a large variety of mechanical structures autonomously out of variations of materials. These processes are particularly important and interesting from the perspectives of morphology adaptation, i.e. the system is able to develop mechanical structures, test them in the real world, and update the designs for improvement [99]. The model-free search of mechanical designs is an important research direction because it allows us to systematically explore the principles behind self-organization of physically adaptive systems, regardless of whether biological or artificial.

Being able to adjust sensory morphology is crucial for autonomous adaptive systems for many reasons. As one of the reasons, the case study in §3.2.2 has stated that the mechanical sensor has the trade-off between maximum linear sensing range and sensitivity, and the trade-off can be coped with by introducing the mechanical adjustability. By physically adjusting the morphology (e.g. autonomously varying dimensions of physical structures such as varying widths of whiskers), the system is able to obtain an optimum sensing range and sensitivity that is necessary for the given tasks (or survival in the given environment in nature). Such adjustability between sensing range and sensitivity is an important function for many autonomous systems, because the trade-off is fairly general among many sensor modalities. As every sensory receptor has its own sensing capacity limits, the trade-off between sensing range and sensitivity is an intrinsic problem that has to be coped with by mechanical structures for filtering and amplification of physical stimuli. By analogy, the adaptation of sensor morphology will offer the 'optics' of photosensors to the other sensor modalities such as tactile and auditory sensing.

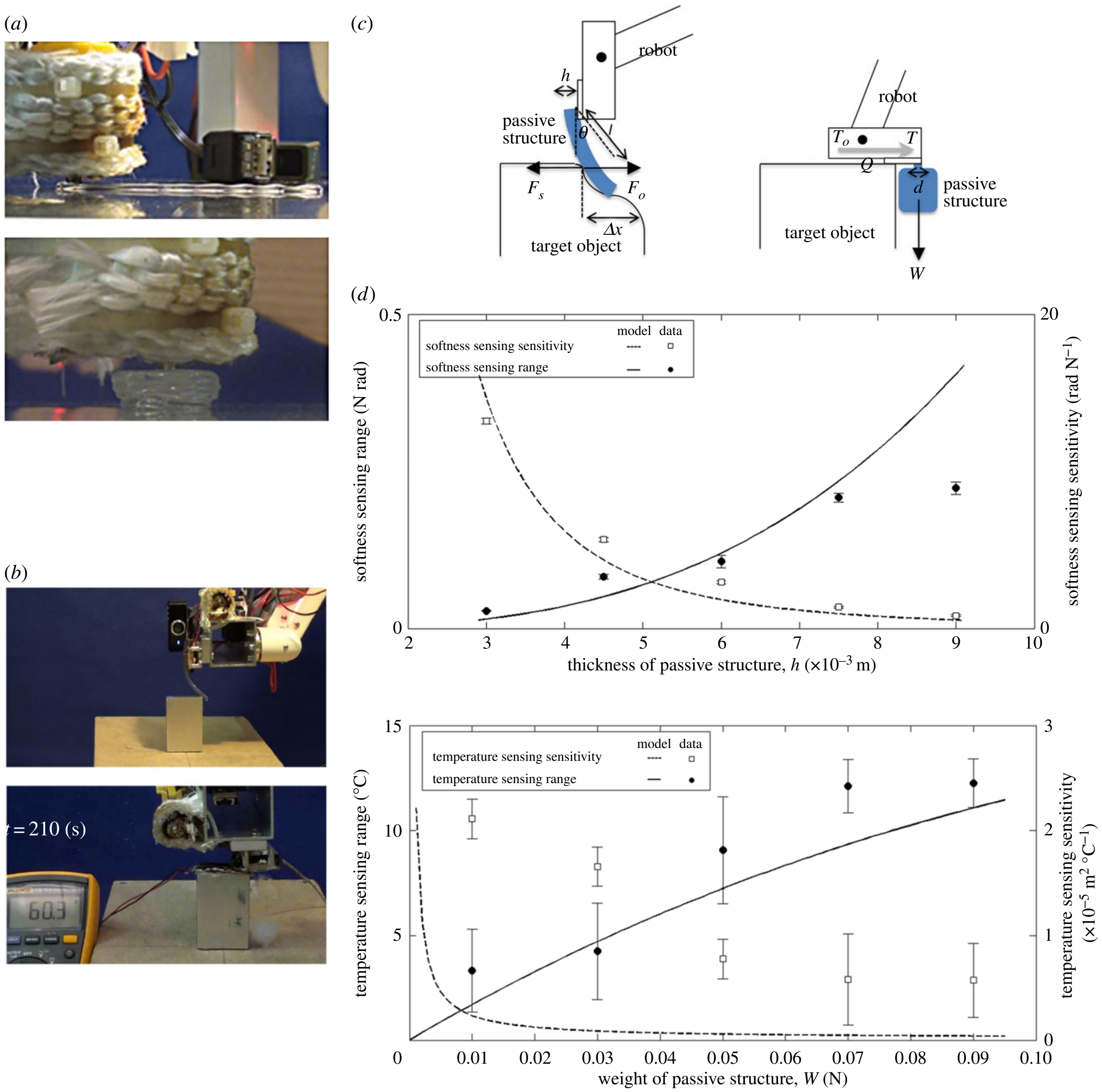

Figure 4. Example of how adaptation in sensor morphology can be implemented in a robotic system owing to the use of proper material [67]. In this case, using soft thermoplastic adhesive material, i.e. HMA, the robot is able to repeatedly fabricate, attach and detach passive structures with a variety of shapes and sizes to its end effector for sensing purpose. The figure shows the fabrication process of the structure by the robot for force sensing (top) and temperature sensing (bottom) (*a*), how the sensing is performed (*b*), the adaptive morphological parameters of the sensor (*c*), and how they affect the sensing sensitivity and linear range (*d*). Figures are reproduced under the Creative Commons License and also by the permission of the authors. (Online version in colour.)

On the other hand, the adaptation function of sensor morphology does not come for free because it requires specifically designed mechanisms and processes onboard. In the platform we introduced in §3.2.2, for example, there was a specifically designed process of thermoplastics to be structured through extrusion processes that required significant amount of efforts (physical energy, control and space for implementation) that are not negligible.

Considering these costs and benefits, automated design processes without (or with minimum) human intervention provide interesting perspectives for the investigations of sensor morphology. In particular, mechanical adjustment of sensor morphology is significantly related to the processes of sensory signals, and associated motor actions for active sensing. Conversely, the actions and signal processing could also influence the way mechanical adjustment could take place. While it still remains for further investigations in the future, such an over-redundant nature in perception dynamics would be necessary for understanding some of the very sophisticated sensing capabilities in nature.

4.2. Soft technologies and functional materials

The problem of sensor morphology adaptation is, in many ways, related to soft functional materials, because deformation of morphologies is the underlying driving force for biological systems (and some of the robots in this article) to exploit morphologies for sensing purposes. More specifically, in the case studies of active whisking and sensing through body dynamics, deformation of physical structures is the amplifier of physical stimuli, and for adaptation of sensor morphology, the structures have to be deformed (e.g. by temperature control for thermoplastic).

In the discussions so far, the sensor morphologies are implicitly assumed to be separately considered from their given receptors (e.g. photoreceptors, cameras or pressure-sensitive probes), but the distinction between receptors and mechanical structures becomes more ambiguous if we consider advanced functional materials such as deformable photo-sensitive devices [25,26] or deformable pressure-sensitive materials. It is of crucial importance to consider deformation of structures and stimulus-sensitive functional materials especially when we would like to consider high density of sensing points or miniaturization of autonomous systems.

Furthermore, in many case studies introduced, it is important to note that material properties are the practical limitations of sensing performances. For the sensing of vibration, deformation, and pressure, in particular, the Young's modulus of the materials used determines the ultimate range of sensitivity, which is something the geometrical adaptation as in §3.2.2 cannot overcome. In this sense, the materials are one of the most important determinants of the limits of adaptability.

4.3. 'Morphological computation' as a common currency

This review attempts to provide a landscape of sensor morphology research that spans over many physical aspects, including diverse sensor modalities, geometrical and mechanical constraints, as well as changes of them over time. Developing an integrative view of sensing is an important effort because, on the one hand, these physical aspects (such as physical motions, morphologies and interactions with the environment) are closely related to each other as shown in the principles we discussed in this article, and on the other hand, they cannot be fully understood if being investigated in isolation. Having said that, there is also a similarly important question as to whether this integrative view could reach to a unified theory of autonomy and adaptivity, or whether it is leading to a framework with limitlessly complex processes and mechanisms.

In the effort of answering these questions, the aspect of mechanical dynamics used for computational purposes has been investigated as the so-called morphological computation, and the concept was previously explored through a number of case studies in robotics and complex systems (see more details in [6,17,100,101], for example). In this context, sensor morphologies can be viewed as physical structures that perform 'pre-processing' of signals before they are being passed to the other computational processes. A particularly interesting fact is that morphology is not only playing the role of pre-processing for sensing, but also for motion control: having a well-designed physical body was found to be very important to facilitate motor control processes, and with a pertinent body design, a complex walking, hopping or swimming dynamics, for example, can be achieved with very simple control [68,102–106].

More generally, every information processing system has its physical entities on top of which computational processes are running as exemplified by electrons running in silicon wafers or spike trains in neurons and synapses. In the context of physically embodied systems such as animals or robots, while many interdisciplinary researches are currently being investigated, it is still not fully understood how computational processes can emerge from the dynamics of the physical systems. Although the entire landscape of this research direction requires another review of itself, this article provided a few important examples that contribute to this broad and stimulating research area. An important contribution of sensor morphology research lies in the fact that it offers various case studies of morphological computation in concrete physical terms. The geometry of EMDs, for example, provides a case study of how pre-processing can be achieved for motion control [20–24,27]. In addition, the material properties (elasticity and geometry) of whiskers and their changes over time play a role of filtering of physical stimuli for identification tasks [47–50]. These case studies showcased the physical processes that facilitate information processing and control of adaptive motions, on top of which we are able to quantitatively analyse the degrees to which morphologies do 'computation' [70,107,108]. For example, in the second case study explained in §3.2 [67], we are able to estimate how much information was lost if the *in situ* adaptation of whisker morphology were not possible. In this sense, future research should highlight systematic analyses of sensor morphology to quantify morphological computation by using information theoretic tools.

5. Conclusion

Sensor morphology is a long-standing research topic in both biology and robotics, and there have been a number of case studies reporting the importance of physical structures in organisms' perception of the world. Such examples span various species, physical principles, target behaviours and functions.

In addition to the diversity of sensor morphology, this article considers an additional dimension, i.e. adaptation processes of sensor morphology, in order to develop a more integrative view for our comprehensive understanding of biological sensing and perception. Even though this is a challenging methodology, it is now more feasible to conduct such research systematically by employing the state-of-the-art robotic technologies.

Bioinspired robotics is a powerful approach to identify specific design principles for the complex problem of sensor morphology, and this article proposes four general principles that should be the fundamental guideline for systematic investigations. Adaptation of sensor morphology is, from this perspective, a necessary part of the concept to understand how adaptability and more generally sensory–motor control can develop over different timescales. Although this investigation is still in a nascent stage, this integrative view of bioinspired perception will be structured into a more general understanding of autonomous adaptive systems in both nature and engineering.

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Competing interests. All authors have no competing interest to declare.

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