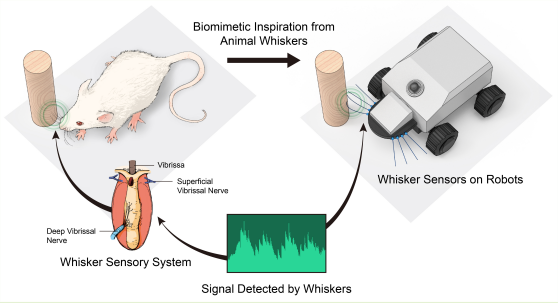
Whisker Sensor for Robot Environments Perception: A Review

Zhenhua Yu*, Peter R.N. Childs, Yukun Ge, Thrishantha Nanayakkara

***Abstract*— Nocturnal mammals such as rats heavily depend on whisker based tactile perception to find their way through burrows and to identify objects. There is diversity in the whiskers in terms of the physical structure and nervous innervation. The robotics community has developed many different whisker sensors inspired by this biological basis. They take diverse mechanical, electronic, and computational approaches to use whiskers to identify the geometry, mechanical properties, and texture of objects. Some work address specific object features and some others address multiple features. Therefore, it is vital to have a comprehensive discussion of the literature and to understand the merits of both bio-inspired and pure engineered approaches to whisker based tactile perception. In this paper we report and discuss the progress in following areas: The body of mammalian whisker follicle, unimodal whiskered sensors, multimodal whiskered sensors with variable stiffness that can capture tactile sensory stimuli of different frequencies, obstacles detection, shape detection, texture classification and robot navigation using whiskers.**



***Index Terms*— Whisker sensors, Tactile sensors, Soft robotic sensor, Bio-inspired sensors, Stiffness controllable sensors, Multimodal sensors.**

I. Introduction

The primary focus of this paper is to conduct a unified review of biological and engineered whiskers to identify future whisker design opportunities and to provide useful design guidelines. Despite the insightful review discussions on whisker design and fabrication and their applications in engineering, previous literature has not fully addressed the broader context, especially in biological mechanisms. To our knowledge, no previous attempts have been reported to provide a comprehensive and in-depth review that explores the discussion on the relationship between the biological mechanisms and experimental observations of animal whiskers and the technological aspects of sensor engineering—encompassing transducers, materials, design, fabrication, and applications.

We conducted a literature search using whisker sensors, whisker follicles, and whisker applications mainly in the Nature Publishing Group, IEEE, Elsevier, Springer-Verlag, data bases. Then we shortlisted 21 papers on mammalian whiskers based on the depth of details of anatomy, whisking behaviour, and functionality. We also shortlisted 71 papers on engineered whiskers based on the depth of details of mechanisms, transduction, control and perception.

Whisking is a behaviour observed in several mammalian species, particularly rodents, where they use their vibrissae as navigation inputs and gather complex environmental information by brushing their whiskers against surfaces. For example, seals use their whiskers to detect information about water streams and to prey by sensing the slightest water disturbance left by passing objects in the dark, deep-sea environment [1]. Furthermore, nocturnal mammals, such as cats and rats, rely heavily on tactile perception based on whiskers, also called facial vibrissae, to move quickly in dark environments, avoid obstacles, and prey [2].

Nature's whiskers possess advanced and robust features, each equipped with intricate multidimensional sensing mechanisms [7]. These whiskers facilitate a sophisticated interpretation of their mechanics by utilizing the densely populated sensory cells within the follicles. When external stimuli act upon the whiskers, they transmit forces and moments through their structure, leading to the deformation of the whisker follicle. This deformation subsequently generates neural signals for the mechanoreceptors [8]. Animals employ a process known as "whiskering" to actively gather information about encountered objects, such as shape, size [9], distance [10], and surface texture [11] [12]. This process involves sweeping the whiskers

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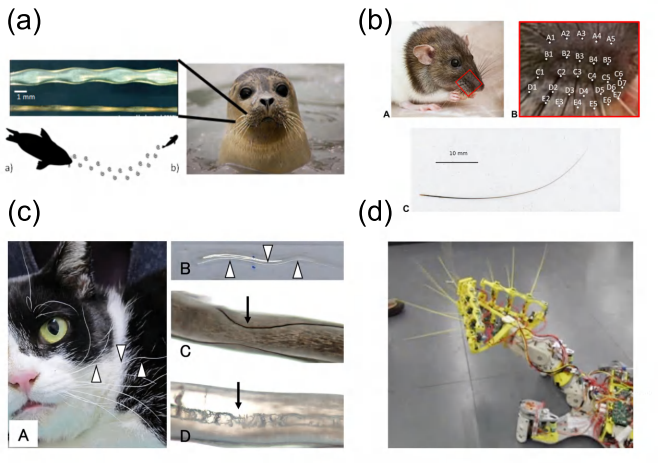


Fig. 1. Example of whiskers. (**a**) Seal whiskers [3], (**b**) Rat whiskers [4] , (**c**) Cat whiskers [5], (**d**) Robotic whisker sensors [6].

forward and backwards through coordinated head movements, allowing the whiskers to make contact with and explore the objects [13].

However, external stimuli need not be limited to direct contact but can also arise from the flow of fluid or gas around the whiskers. Research on animal behaviour has demonstrated that various animals, such as seals, rely on the flow-sensing ability of their whiskers to perceive hydrodynamic conditions [14]–[16]. Additionally, animals such as cats, leopards, and rats actively vibrate their whiskers and employ active sensing methods to ascertain wind direction and speed in their surroundings.

The aforementioned research on animal behaviour and whisker mechanisms have led to the proposal of diverse whisker sensors. Early designs of whisker sensors exhibited relatively homogeneous structures and functions, predominantly measuring the force or torque acting on the sensor's base to gather information [17], [18]. Subsequently, various types of whisker sensors utilizing piezoelectric [19], piezoresistive [20], and capacitive [21] sensing principles were developed to detect external stimuli. Figure 5 illustrates that the advancement of materials science and nanotechnology has expanded the range of materials employed in whisker sensor fabrication. From traditional materials like steel beams, [22] and springs [23], the field has progressed to encompass nanomaterials such as polymers [24]. The adoption of novel materials and sensors has facilitated the evolution of whisker sensor fabrication techniques from conventional assembly methods [25] to more advanced approaches like 3D printing [26] and 3D air assembly [27].

Compared to other sensors, whisker sensors offer heightened sensitivity, smaller contact areas, and enhanced reliability and environmental robustness. These advancements have significantly improved the performance and expanded the application scenarios of whisker sensors, which have transitioned from initial deployment on fixed platforms to their current utilization in mobile robots, aerial drones, underwater unmanned robots, and other domains [28], [29].

The subsequent sections of this paper are organized as follows: Section II explores the bio-mimetic mechanisms of animal whiskers and presents the findings of animal behavioral experiments conducted to study their performance. In Section II-C, we review and analyze the various mechanoreceptors used in whisker fabrication, along with different operating modes of whisker sensors. Section IV discusses the strengths and weaknesses of specific manufacturing techniques and materials employed in the production of whisker sensors. In Section V, we highlight typical application scenarios of whisker sensors and their recent advancements. Finally, in Section VII, we bridge the research gap between engineered whisker sensors and natural whiskers, while proposing future directions and potential applications based on the comprehensive literature review.

II. Biological Principle of Whisker Sensors

The reliance of animals on their whiskers for survival in low-light environments has been a topic of great interest among biologists. Researchers have been studying unimodal whisker sensors and their potential applications since the 1970s. In this section, we will provide a concise overview of the biological structure of whiskers, the mechanisms involved in information transmission, the mechanics of bionic sensors, and the animal behavioral experiments conducted to investigate the performance of animal whiskers. Gaining a deeper understanding of animal whiskers can greatly assist us in the design and fabrication of versatile and high-performance whisker sensors.

A. Biological mechanisms of whisker sensor

Many mammals, including aquatic seals, terrestrial rats, and mice, rely on mechanosensitive whiskers to perceive information about their environment and objects. Whiskers are a specialized type of hair that protrudes from the skin and are densely packed with nerve endings within their follicles. The mechanical interaction between the whisker and external stimuli results in stress being exerted on the hair follicle. The follicle, illustrated in Fig.2 (c), not only anchors the whiskers to the skin but also provides them with tactile sensitivity and mobility. It plays a crucial role in gathering environmental information [31]. Within the whisker follicle, nerve terminals enter different locations through superficial and deep vibrissal nerves. The specific location of these nerve terminals may be closely related to the type of vibrissa movement that triggers their activation [34], [35]. Thus, whiskers typically measure the forces and pressures causing deflection by converting external mechanical strains into electrical signals and transmitting these signals to the brain's nervous system. Following the same principle, they can be used to measure flow, viscosity and strain by underwater animals, such as harbour seals.

Figure 2(a),(b) depicts the arrangement of whiskers in rats, where approximately 30 large and long whiskers are present on each side of the nose. These whiskers are organized in a grid-like pattern with five rows labelled A through E. Importantly, this whisker array is consistent across all rats [32].

Tactile information gathered from each whisker follicle is mapped to specific groups of neurons that are topographically

TABLE I
COMPARISON OF REPRESENTATIVE KINDS OF ANIMAL WHISKERS AND THEIR FUNCTIONS

Representative Animals	Whisker Shape	Motion Control	Remarks
Terrestrial Large Mammals (e.g., Cats)	Conical Whisker	Motion by head movements and also with extrinsic muscles	This shape of the whiskers can measure object distances by the curvature of a single whisker. The main whisking frequency of cats is between $25-150$ Hz.
Aquatic Mammals (e.g., Harbour Seals) [16] [30]	Elliptical cross sections with an undulating diameter	Motion by head movements and also with extrinsic muscles around the follicles	Unique whisker shape structure for water flow detection. Responds rapidly to low-frequency hydrodynamic stimulus between $10-50$ Hz [16].
Rodents: Rats & Mice [31] [32]	Conical Whisker	Motion by head movements and also with extrinsic and intrinsic muscles around the follicles	The different abundant innate and learned whiskers move actively or passively, allowing them to collect specific types of information. Whisking periodically between $5-10$ Hz for rats and $15-20$ Hz for mice [33].
Hypothetical Cylindrical Whiskers (or Human Hair)	Cylindrical Shape		This shape would get stuck in small imperfections on surfaces compared to conical shape.

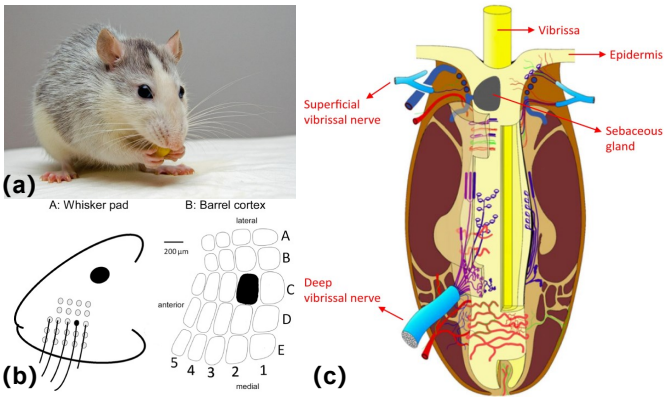


Fig. 2. (a) A rat with whiskers on both sides of its face. (b). The whiskers consist of up to five rows on each side of the nose, each containing five to nine whiskers between 15 and 50 mm in length, forming a two-dimensional grid [36]. (c). Schematic view of the whisker follicle of a rat or mouse [37].Picture courtesy of Frank Rice.

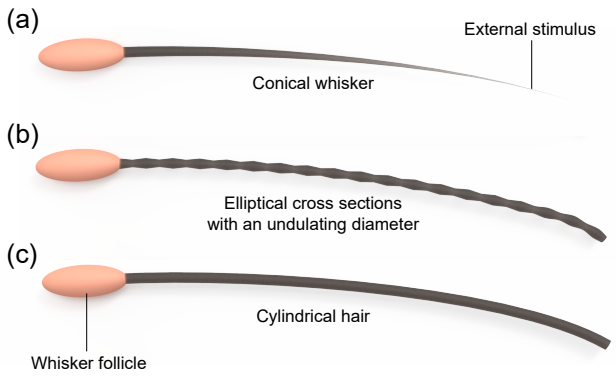


Fig. 3. Schematic of different shapes of animal whisker interacting with an external stimulus. (a) Rodent and large terrestrial animal whiskers are typical conical shapes. (b). The whiskers of aquatic animals (seals) are usually elliptical cross sections with an undulating diameter. (c) Hypothetical cylindrical hair or human hair

arranged throughout the brainstem. Rodents possess a dedicated region in the brain known as the barrel cortex, which is responsible for processing tactile information obtained through whisker-based touch. This underscores the significance of whiskers as a primary sensory modality for these animals.

However, in order to extract meaningful information from the whisker follicles, rodents must decode various aspects such as the location, direction, and magnitude of forces applied to the whisker beams. This decoding process allows them to simultaneously discern multiple characteristics of objects, including their shape and texture. Therefore, it becomes evident that our focus should extend beyond the design of whisker sensor arrays. We must also consider the design of the whisker follicle itself, such as incorporating features such as stiffness control, as highlighted in the concept of a stiffness-controllable whisker follicle [38]. By addressing the design aspects of both the whisker sensors and their follicles, we can enhance the ability to replicate and mimic the complex sensory capabilities observed in natural systems.

However, it is worth noting that the shape of whiskers plays a crucial role in the acquisition of sensory information. Different terrestrial and aquatic animals have evolved distinct shapes and arrangements of whiskers, which, to some extent, are reflective of their respective habitats. For instance, harbour seals possess whiskers with elliptical cross-sections and undulating diameters, as depicted in Fig.3(b). This particular structure enhances their ability to analyze fine-scale water currents associated with the movements of their prey [39].

On the other hand, rodents possess facial whiskers known as macro vibrissae, which exhibit conical shapes. These whiskers have a diameter close to the follicle of approximately 100 µm and extend to a length of about 20 mm, as shown in Fig.3(a). The conical shape enables rodents to estimate object distance using a single whisker, explore rough textures, and prevent the whiskers from becoming trapped in tight spaces. The gradation in size along the whisker allows for bending and aids in locating the object that comes into contact with the whiskers. In contrast, cylindrical whiskers as depicted in Fig.3(c) may lack these advantageous characteristics and are more prone to getting stuck in narrow spaces. The tapered tips of conical whiskers easily glide over surfaces due to the relatively stiff base of the whisker, which helps pull the wispy tips out of potential entrapments in rough textures [42].

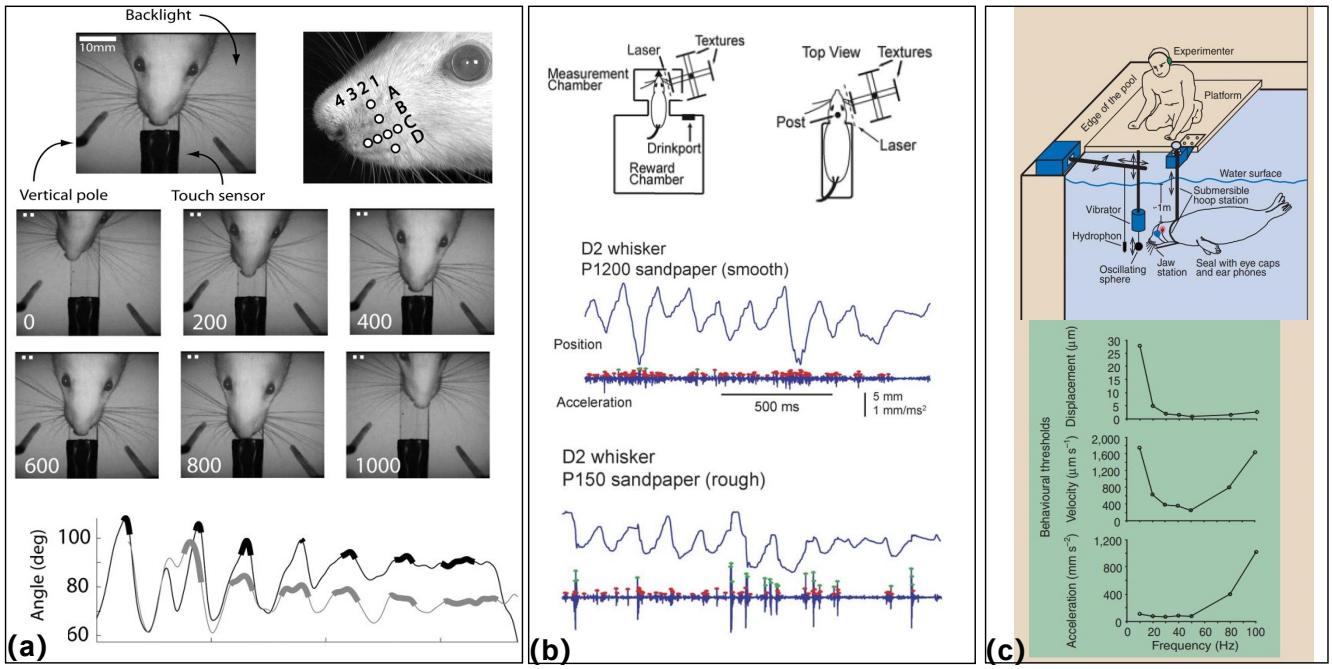


Fig. 4. Animal behavioural experiments on whiskers. (a) Rats were trained to discriminate the relative positions of the rods placed on either side of the head. The angle change in whiskers resulting from contact between whiskers and objects is indicated by the thicker areas on the lines [40]. (b) Rats' whisker micromotion during whisking on a smooth and rough sandpaper surface respectively. Red dots represent low-acceleration whisker motion; green dots represent high-acceleration whisker motion. This suggests that high acceleration events may occur systematically more frequently on rougher surfaces [41]. (c) Harbour seals are trained to test their responses to stimuli that disturb changes in external flows [16].

These examples highlight the importance of whisker shape in optimizing sensory capabilities and facilitating interactions with the surrounding environment. By studying and replicating these unique shapes, we can advance the design and development of whisker sensors that possess similar functionalities and performance characteristics.

B. Animal whiskering behaviors

Whisker movements in animals such as cats and seals consist of head movements and extrinsic muscles that move the entire whisker pad back and forth relative to the head, as shown in Table I. Additionally, many rodents possess a specialized system of intrinsic muscles, with each whisker having its own dedicated muscle, enabling fine control of whisker movement. These muscles allow the whiskers to move in an arc primarily in the cephalad direction, enabling rapid motion at approximately 10,000 degrees per second for shape and position recognition. Furthermore, the morphological deformation of whiskers induced by external stimuli provides comprehensive information about the sensory forces in the whisker follicles [33].

In addition, the whisking frequency and speed of the animal's whisking play a crucial role in the conversion of mechanical stimuli into neural excitation. Typically when rodents move, rodents move their whiskers forward (extension) periodically over dozens of cycles at well-defined frequencies (5-10 Hz for rats, 15-20 Hz for mice) and periodically adjust their whisker position around this extension position. Animal experiments have shown that rhythmic whisking is associated with running: the faster the rodents run, the faster they whisk and the farther their whiskers extend. For the seal, behavioural experiments show that seal whiskers respond rapidly at low-frequency hydrodynamic stimuli ($10 - 50$ Hz) to adopt the detection of hydrodynamic information [16].

The whisking frequency and speed of the animal's vibrations play a crucial role in converting mechanical stimuli into neural excitation. When rodents are in motion, they periodically extend their whiskers forward over dozens of cycles at well-defined frequencies (e.g., 5-10 Hz for rats, 15-20 Hz for mice) and periodically adjust their whisker position around this extended state. Animal experiments have shown that rhythmic whisking is associated with running, where faster running speeds result in increased whisking frequency and greater whisker extension. Behavioural experiments on seals demonstrate their rapid response to low-frequency hydrodynamic stimuli (10-50 Hz) for detecting hydrodynamic information [16].

Animals also utilize their whiskers for object exploration and tactile discrimination. During this process, rats make multiple attempts to adjust their whisker trajectory by extending and pressing the length of their whiskers against objects at different angles. The feedback between whisker movement and touch allows for the integration of information from multiple touches with varying stiffness and bending, crucial for exploring object shape, and roughness, and improving perceptual accuracy during decision-making [16], [33]. These whiskering behaviours provide valuable biological inspiration for future sensor design, particularly in terms of signal decoding and processing. Emulating the principles underlying whisker movement and touch-mediated perception can en-

hance the capabilities of sensor systems and contribute to advancements in various fields.

C. Animal behavioral experiments on real whisker

There are several modes of whisker movement, including rapid bilateral whisking movements of 5-12 Hz, and slow movement of large whiskers between objects by head movements [43]. The contact of the whisker with the object generates micromovements of the vibrissae that are transmitted by nerves to the primary somatosensory cortex (S1; barrel cortex, Fig.2(b)), where the neural information will be processed.

Numerous animal behavioral experiments have used psychophysical methods to study how animals use whiskers to obtain information about the position, shape, and texture of an object, fluid information, and the relationship between stress at the follicles and the whisker axis. In 1986, Hutson *et al*. published a classic paper using the ablation-behaviour method to prove that the rats needs a complete path from a whisker to a specified cortical barrel in performing the task [44].

Dehnhardt *et al*. used a trained harbour seal to demonstrate that seals can use their whiskers to detect small, low-amplitude water movements [16]. As shown in Fig. 4 (c), using a 'go/no-go' response paradigm, the seal demonstrates its response to a simulated hydrodynamic stimulus generated by an oscillating sphere with a frequency of $10 - 100$ Hz by leaving the hoop station. The results of behavioral experiments show that seal whiskers respond rapidly to low-frequency hydrodynamic stimuli ($10 - 50Hz$) and that they can detect water velocities as low as $245\ \mu m/s$. This animal behavior study also laid the groundwork for the subsequent design of underwater whisker sensors to detect hydrodynamic information [45]. Furthermore, if the special shape of the seal's whiskers can be taken into account in the design of this underwater sensor, it will further improve its application capabilities.

Regarding a whisker's perception of object information, animal behavioral experiments have focused on the use of rats. As Fig. 4(a) shows, Knutsen, *et al*. performed a bilateral comparison experiment of horizontal object localization to observe the angular variation of whiskers with the same number C2 on both sides [40]. By comparing the angular changes of the whiskers on the left and right sides, as indicated by the thicker areas on the graph, rats can determine the position and distance of the object. After that, Wolfe *et al*. trained rats to study how whiskers extract feature information by observing the movement of whiskers in contact with sandpaper of different roughness [41]. As illustrated in Fig. 4(b), D2 whisker movement usually consists of regular, 5-15 Hz whisking, and the high acceleration whisker motion is more prevalent systematically on rougher surfaces (sandpapers) compared to smoother surfaces. Psychophysical methods were used by [46] to study how fixed-head mice to locate an object along the axis of a single whisker and how the stress at the follicle relates to the stiffness of the whisker axis.

These animal behavior experiments elucidate that animals employ their mechanosensitive whiskers for a multitude of tactile behaviors, including navigation, object identification, and social interactions. There is a context-dependent modulation in the movement of these whiskers. The morphological characteristics of the whiskers and follicles, coupled with their kinetic adaptations, are intricately aligned for tactile exploration within their specific ecological niches. This remarkable adaptation in nature has not gone unnoticed by researchers and technologists, who have drawn inspiration from these biological systems for the development of advanced sensory technologies.

The nuanced understanding of how animals use their whiskers in diverse environmental contexts has led to the conceptualization and creation of biomimetic sensors. These engineered sensors mimic the mechanosensitive capabilities of animal whiskers, aiming to replicate their ability to detect and interpret tactile information. By integrating principles from biology with cutting-edge materials science and engineering, researchers have developed sensors that can perform tasks such as object detection, terrain mapping, and even air or fluid flow analysis with heightened sensitivity and accuracy. In the following section, we systematically analyze and summarize the design, materials, assembly process and application scenarios of various engineered whisker sensors.

III. Engineered Whisker Sensing Mechanism

The prior section's analysis of whisker biomechanics revealed a pivotal characteristic: the whisker shaft lacks sensory capabilities, with sensation primarily emanating from the base of the follicle. This leads to a comparative examination of various transduction methodologies within the whisker sensor base, categorizing them into magnetic [47] [48] [49], resistive [50], contact-resistive [34], capacitive [21], and optical [51] sensors. In the realm of whisker sensors, the choice of sensing mechanism significantly influences their ability to perceive static and dynamic changes. As shown in Table.II, magnetic, piezoresistive, capacitive, and strain sensors each offer unique capabilities and limitations in this regard. Magnetic sensors are versatile, capable of detecting both static and dynamic changes, making them suitable for a wide range of applications. Piezoelectric sensors, while excellent for dynamic sensing, fall short in static detection. Piezoresistive and capacitive sensors offer a balance, adept at sensing both static and dynamic changes. Strain sensors, with their high resolution, are particularly sensitive to both types of changes. Understanding these characteristics is crucial in selecting the appropriate sensor type for specific applications, whether it be for environmental monitoring, tactile feedback, or fluid dynamics.

TABLE II
Summary of Static and Dynamic Sensing Capabilities of Whisker Sensors

Sensing Type	Static Sensing	Dynamic Sensing
Magnetic Sensing	Capable	Capable
Piezoelectric Sensing	Limited	Highly Capable
Piezoresistive Sensing	Capable	Capable
Capacitive Sensing	Capable	Capable
Strain Sensing	Highly Sensitive	Highly Sensitive

A. Sensing Mechanism

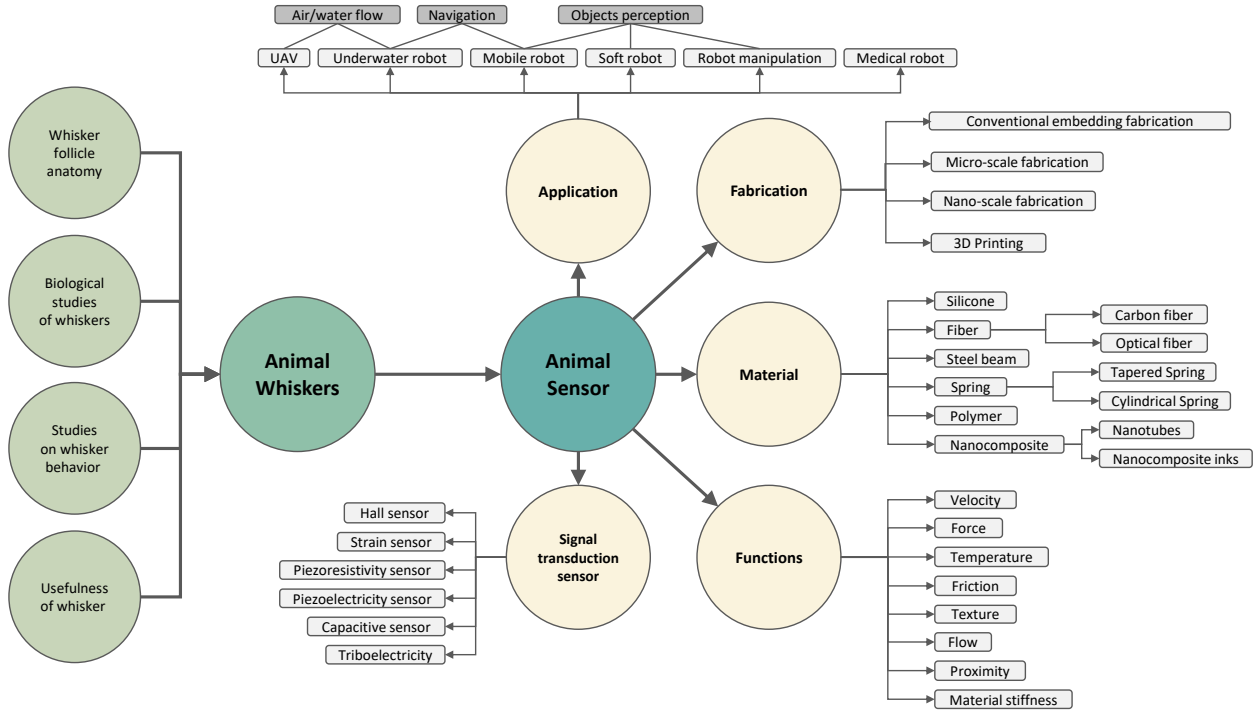


Fig. 5. A map of whisker sensor from the biological studies of animal whiskers to the bio-inspired sensor design, materials, fabrication, function, and application.

1) Magnetic Sensing: Hall sensors based on the magnetic transduction effect have been widely used in the design and manufacture of whisker sensors due to their ready availability and low cost. The basic design principle is to install a magnet at the base of the whisker beam and to have a Hall sensor nearby to measure the interference applied to the sensor due to external disturbances. Such measurements can often be made from a single point to two dimensions or even extended to three dimensions. For example, a bio-inspired 'Biotact' sensor was fabricated for classifying the surface textures, which include a small permanent magnet and Hall Effect sensor [52], as shown in Fig.6(a). In addition, it is also possible to accurately calculate moments, angular momentum, etc. by modelling the variation in magnetic fields, whisker beam motion, and Hall sensor outputs in relation to each other [47]. Inspired by the ease with which magnets can be quickly reconfigured in position, a novel re-configurable whisker was proposed which uses the magnetic attachment to achieve fast whisker array reconfiguration [48]. Although Hall sensors can provide accurate low-frequency information, such as shape information, they are at a disadvantage compared to piezoelectric sensors in terms of high-frequency information, such as texture information.

Incontrast to the magnetostrictive effect, another approach based on magnetic sensing is the reverse magnetostriction effect, which demonstrates the benefits of operating under static or low-frequency conditions when compared to piezoelectric and capacitive whiskers, as highlighted in previous studies [53]. These sensors employ magnetostrictive materials like Galfenol and Alfenol [54], enabling bidirectional tactile perception especially for both stress and vibration signals. Raghunath et al. have made significant strides in sensor technology with the development of a magnetostrictive whisker, utilizing the magnetoelastic effect for detecting stress and vibration. This innovative sensor is adept at capturing both static and dynamic data and exhibits excellent adaptability to various environments [55]. In [56], the authors present a valuable study on the impact of whisker thickness on Alfenol-based sensor performance, providing critical insights for sensor design. However, the research is somewhat limited by its exclusive focus on Alfenol and a specific range of thicknesses, which may restrict its applicability to other materials and broader contexts. However, there remains a gap in understanding the dynamic performance of the sensor, specifically in terms of dynamic sensitivity and resolution. In that case, Zhao et al. further study the relationship between vibration frequency and the whisker's response [49]. The novel whisker-like tactile sensor can perceive both static and dynamic information like stress and vibration signals, but it still exhibits limitations compared to piezoelectric and capacitive pressure-sensitive sensors, particularly in high-frequency signal ranges and high-frequency response intervals.

2) Piezoelectric Sensing: Different from Hall sensors and force sensors requiring an external power supply, a piezoelectric sensor can be self-powered because when external mechanical pressure is acting on its surface, it will induce rapid charge changes. This characteristic makes them indispensable in applications where dynamic information is paramount, such as in fluid dynamics or high-speed tactile feedback systems, but less effective for static condition monitoring. In 1986,

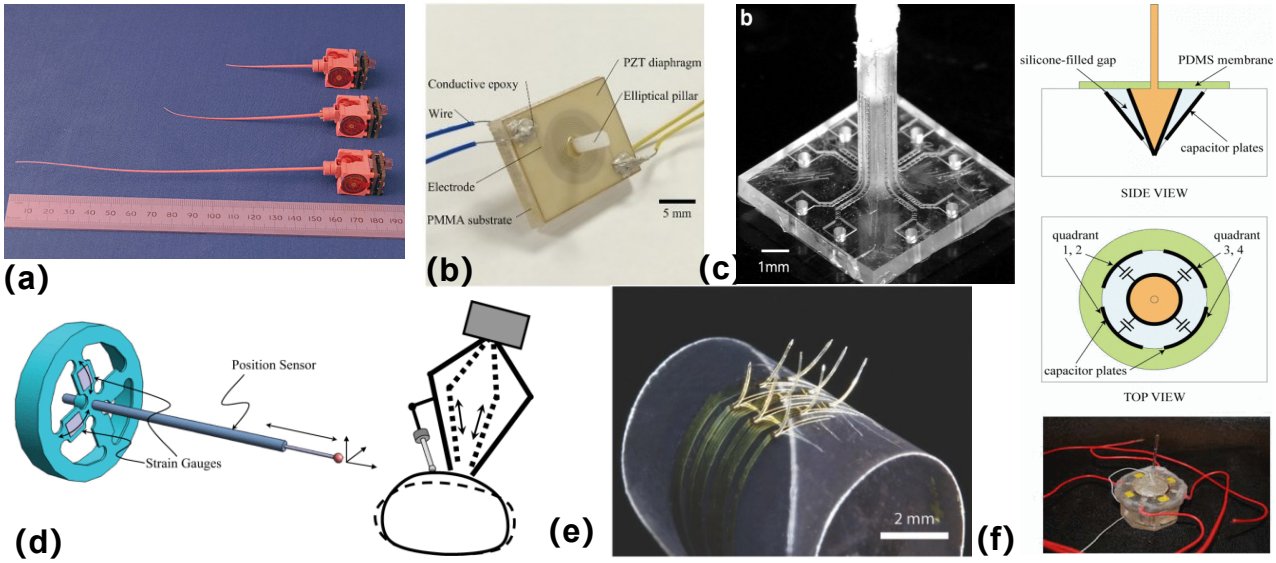


Fig. 6. Different mechanoreceptors used for whisker fabrication. (a) Hall sensor based [52]; (b) Piezoelectric sensor based [57]; (c) Piezoresistive sensor based [58] ; (d) Strain gauges based [59]; (e) Nanomaterials based [27]; (f) Capacitive sensor based [60]

Schiebel et al. [61] used a piezoelectric actuator and a straight whisker to provide information about the foot of an active suspension vehicle relative to its surroundings by monitoring the whisker's natural frequency. Takarada *et al* derived a numerical contact vibration model between the piezoelectric sensor and the contact surface for liquid density and viscosity measurement [19], and [62]

A piezoelectric whisker transducer (PWT) which acts simultaneously as both the actuator to excite the sphere tip to oscillate in the fluid and the sensor to measure the force, velocity and mechanical impedance was proposed by [63]. Asadnia et al. designed a self-powered piezoelectric sensor-based whisker arrays for localizing the underwater stimulus [64]. External water flow can cause the whisker sensor to vibrate, thus creating a voltage change in the piezoelectric sensor output. Inspired by the harbour seal whisker, a self-powered light-weight whisker based on the piezoelectric sensor was proposed for unmanned underwater vehicles to detect the underwater flow angle of attack and velocity [57], as demonstrated in Fig.6(b). This could achieve high sensitivity at $1.445\ m/s$. Even though piezoelectric sensors are unable to measure static force due to the rapid dissipation of charges, the piezoelectric sensor provides an alternative for self-powered robot perception, especially for air, and liquid flow measurement. In addition, considering the size of piezoelectric sensors, MEMS whisker sensors of miniature piezoelectric materials may be a future direction.

3) Piezoresistive Sensing : Piezoresistive sensors are highly capable of sensing both static and dynamic changes, making them versatile in a variety of applications. Because of the high sensitivity and high response frequency of piezoresistive sensors, they have been applied to make whisker sensors for water flow detection. Beem *et al*. have designed a whisker-inspired sensor by using four resistive bend sensors. When the whisker detects the flow pressure, that will create a resistance change in the bend sensor and thus cause a change in the output voltage [45]. A multi-material whisker sensor has been manufactured by 3D printing, with components including a polyurethane rod with four piezoresistive graphene patterns perpendicular to each other [65]. Piezoresistive strain gauges are also used to subtly measure the two-dimensional deviation of four steel whiskers [20]. However, these strain gauge or displacement sensor-based whisker sensors are relatively bulky and cumbersome to fabricate. Therefore, Liu *et al*. used a directional liquid spreading method to create an undulating morphology whisker sensor by using the nanocomposite ink as the piezoresistive material, and the whisker can detect flow velocities with a threshold of $8\ mm/s$ [58], as demonstrated in Fig. 6 (c). Compared to the use of large-size piezoresistive sensors, the use of new piezoresistive materials can effectively reduce the size of the sensors, resulting in miniaturization and applications in tight spaces.

4) Capacitive Sensing: Capacitive sensors are adept at detecting both static and dynamic changes, a trait that makes them particularly suitable for fluid dynamics applications. They excel in high-resolution and sensitive measurement of fluid flow, capable of discerning both slow and rapid fluid movements, thus providing comprehensive flow information. Barbier *et al*. demonstrated the feasibility of using parallel plate capacitors as a means of sensing and measuring the offset of artificial whiskers, and its sensors can obtain a sensitivity of several picofarads per 0.5° of angular displacement [66]. They further improved and expanded their design to create a multi-directional whisker sensor, which is mounted on a cone-in-cone parallel-plate capacitor base [60], shown in Fig.6 (f). Compared to the previous version, the sensor, can be sensitive to fluid compression forces up to millinewtons and can acquire both directional and velocity information of the fluid ranging from $0 - 1.0\ m/s$. In contrast to the use of polydimethylsiloxane (PDMS) to provide damping and restoring force by Eberhardt *et al*, a Silicon-on-Insulator (SOI) wafer technology was used to measure the small capacitance changes induced by

the air-flow. It could achieve high-resolution air-flow pattern observations of about 1 mm/s [21]. In addition to detecting fluid information, the capacitor-bases whisker can also be used to detect obstacle information for fast evasion [67]. In these applications, whisker sensors based on high-precision capacitive sensors are exceptionally sensitive to changes in the flow rate of water, reflecting their superiority over other sensors, such as Hall sensors. However, the information provided by a single underwater whisker is limited, and a multifunctional whisker array can better help the robot adapt to the underwater environment.

5) Strain Sensing : Strain gauges, known for their high resolution, can sensitively detect both static and dynamic changes. This attribute is beneficial in applications that demand precision in measuring minute variations in pressure or movement, ranging from mechanical displacements to physiological movements in medical applications [59], as shown in Fig.6 (d). Two separate designs have been developed for measuring large and small displacements of the heartbeat, respectively, with a 12 mm peak-to-peak maximum displacement operation range to fit the heart motion. Instead of using a cylindrical beam, Collinson *et al*. used a tapered beard beam, which detects the three-dimensional contact point between the whisker and the target using only three strain signals mounted at the base [24]. The experimental results demonstrated that this whisker could detect the contact point with a median distance error of only 0.47 mm. Considering that a whisker sensor can easily be damaged during the task, Ho *et al*. proposed a morphological compensation method that allows the sensors to adjust their morphology in order to get as close as possible to their original state of sensitivity [68]. A strain gauge mounted on the outer wall of the chamber is used to record strain changes during whisker contact, which could average achieve about 20.385% compensation error. Instead of using a mechanical structure, Eijking *et al*. used a 3D printing method that simultaneously uses two strain sensors to detect the magnitude of the force and the location of the force [62]. This can greatly reduce the cost of manufacturing and assembly of whisker sensors. While new strain materials or 3D printing technologies can reduce manufacturing costs and enable rapid fabrication of whisker sensors, their fragility is a challenge worthy of attention in order to adapt to the complex reality of the environment.

6) Other Sensing Mechanism : In addition to the above common conventional sensors, the emergence of new nanomaterials and their combination with 3D printing technology has further expanded the versatility of beard sensors and simplified the assembly process. As shown in Fig.6 (e), Reeder *et al*. used a shape memory polymer (SMP) to build a multimodal whisker, which could achieve sensing of force, distance and stiffness et al. at the same time [27]. Taking advantage of a similar approach, a multi-material whisker was designed and built by using the polyurethane rod as the whisker beam and graphene to measure the resistance changes for underwater vortex detection [65]. In addition, nanomaterials have been tried to make whisker sensors. For example, Takei et al. employed a carbon nanotube (CNT) as the conductive base with the silver nanoparticles (AgNPs) to improve its conductivity and strain sensitivity [69]. In general, the emergence of new

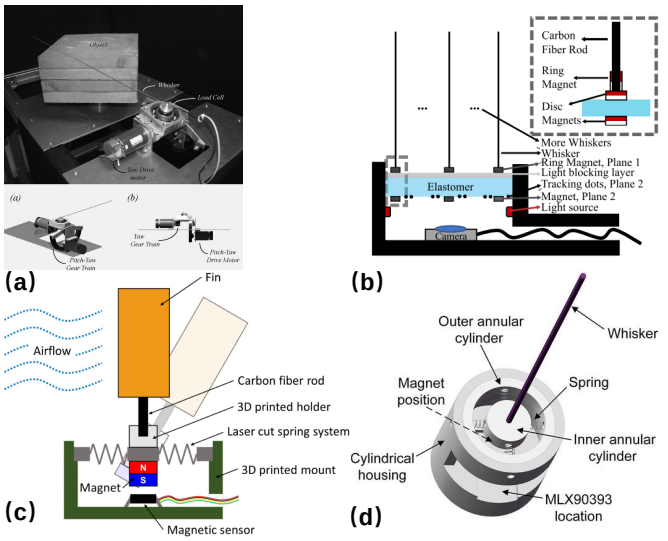


Fig. 7. Conventional embedding whisker fabrication. (**a**) Steel beam [22], (**b**) Carbon fiber [48], (**c**) Carbon fiber and spring [29], (**d**) Spring [23].

materials has fueled the development of whisker sensors from a single function to a multifunctional one, which will be discussed in the next subsection.

According to the findings from this literature review, the need to make a trade-off between sensing range, sensitivity, durability, stability and system integration is apparent when choosing different transducer type depending on the application scenario. In fact, whisker sensor systems may contain hundreds of such single highly sensitive mechanoreceptors that can simultaneously encode information about small offsets, velocities, directions, and amplitudes of offsets. Therefore, while the above illustrates that simple sensor designs can achieve good results, it is important to realize how to achieve simultaneous multimodal information acquisition. The future direction will be discussed in Section VI.

B. Multimodal transduction based whisker sensors

An animal whisker can provide environmental contextual information from air currents to provide indications of speed and direction, small vibrations or movements, to air pressure and temperature changes, as we discussed in Section II. Inspired by these, by incorporating multiple modalities such as vibration, and temperature into a single whisker device, applications of such multimodality whiskers could have significant potential in the future.

A fully printed whisker array incorporating temperature and strain sensing was manufactured by printable nanocomposite inks to detect the whisker's displacement and the object's temperature in [26]. In [27], through using warm air to heat the shape memory polymer into 3D space, a 3D multimodal electronic whisker was proposed to sense various objects information including the temperature, proximity, friction and material stiffness. Significantantly, their technique could achieve batch assembly and its low cost will further expand its application.

In [76], a piezoelectric transducer and Hall sensor were used simultaneously to construct a biologically inspired multimodal

TABLE III
WHISKER SENSOR MATERIALS AND FABRICATION

Reference	Material	Sensor	Methodology and Remarks
Harada [26]	Nanocomposite inks	Strain/Temperature sensor	Fully printed multifunctional E-Whiskers integrated with strain and temperature sensors
Reeder [27]	Shape memory polymer	Strain gauges	3D air assembly method is used to construct the re-configurable, multi-modal E-Whiskers
Eijking [62]	Thermoplastic polyurethane (TPU)	Strain gauges	Conductive TPU is utilized to provide resistive read-out to detect both the force applying on the whisker and the contact point
Emnett [24] [70]	Polymer (polycarbonate)	Strain gauges	Tapered whiskers based on polycarbonate to do three-dimensional tactile feature detection, successfully mimic the geometric and mechanical properties of rat whiskers
Takei [69]	Patterned carbon nanotube	Contact-resistive sensing	The carbon nanotube-based e-whisker work as a conductive network matrix for strain detection
Scholz [71]	Superelastic Nitinol beam	Hub load cell	The actuated whisker determines contacted object 2-D profiles by measuring hub angle, displacement, forces, and torque
Clements [22]	Steel beam (1.19mm diameter)	Load cell	3-D object profiles were imaged by measuring hub angle and torque
Yu [72] [73]	High-carbon tapered spring	Hall Sensor	Tapered Whisker provided morphological computation power for signal procession
Kim [74]	Steel beam (0.5 mm diameter)	Hall-effect magnetic sensors	By actively measuring both vertical and horizontal deflection of a single whisker, it could provide the localization information and object shape information
Will [75]	Steel beam (0.5 mm diameter)	Force/Torque Sensor	Modal analysis of the whisker one-sweep scanning process based on Bernoulli's bending theory for objects contour scanning
Zhao [23]	Plastic optical fiber	Fiber Bragg grating (FBG) sensors	Objects distance and shape information will be obtained by processing the FBG wavelength shift data
Wegiriya [76] [38]	Carbon fiber	Piezoelectric transducer and Hall sensor	The piezoelectric sensor and the Hall sensor will capture the high frequency and slow frequency vibration signals of the whisker sensor respectively
Kent [48]	Rigid carbon fiber rods	Camera	The camera was used to track a whisker array motion for contact, airflow, and inertial discrimination, and it used the magnetic attachment to achieve whisker array reconfiguration
Shi [77]	Silicon-on-insulator	Piezoresistor sensor	The small-scale whisker sensor mounted on a robotic rat for different texture surfaces discrimination and wall-following move
Bergbreiter [47] [29]	Planar serpentine spring	3D Magnetic sensor	Whisker's angular deflection would be detected by the changes of the magnetic field and the applied moments at the whisker base could be calculated by the mechanical stiffness change of the spring beam
Yang [34]	Conductive elastomer	Contact-resistive sensing	The highly scalable and streamlined whisker could detect contact and flow based on bending mechanics at the same time
Lepora [28]	Silicone rubber	CCD camera	3D printed soft optical whisker array motion was tracked by the camera for passive and active tactile perception

whisker follicle, in which the piezoelectric sensor will capture the high-frequency signals and the Hall sensor will collect the low-frequency signals. After this previous research, a novel variable stiffness multimodal whisker sensor has been designed and built by Wegiriya [38]. This study shows that using the multimodal follicle is able to capture different vibration frequencies by controlling the stiffness of the follicle together with the whisking speed. This research demonstrates that the robot could acquire texture and geometry information of an object in real time, just like the rodents.

Although a wide variety of sensors are used to make whisker sensors have achieved versatility ranging from texture recognition to robot navigation. However, the limitations of sensor size and the use of electric motors as actuators still make whisker sensors bulky and heavy. Therefore, future research will focus on the miniaturization, lightness, and multifunctionality of whisker sensors, such as MEMS.

IV. WHISKER SENSOR FABRICATION

Although whisker sensors are a recent emerging type, different specific fabrication techniques have been used. From the early traditional method of embedding the whisker beam within a base plate, some emerging processes, especially 3D printing, are also used to fabricate the whisker sensors. Some other methods such as Polymethylsiloxane (PDMS) moulding, and screen printing are also tested for manufacturing. Advancements in materials science have also contributed to the evolution of the whisker sensors from a single function to a multi-functional model. This section discusses representative whisker sensors in further detail in terms of design and manufacturing as well as materials listed in Table III.

A. Conventional Embedding Fabrication

Conventional whisker sensors are fabricated by mounting a whisker beam on a pedestal and measuring the vibrations generated by external stimuli at the base of the sensor by using different transduction methods such as a force, Hall, piezoelectric or piezoresistive sensor, and even a camera. In previous research, scientists have used fibre, springs, steel beams and silicone rubber to manufacture the whisker beam.

1) Steel beam: Inspired by the shape of animal whiskers, the initial materials used to try to make whisker tactile devices were generally long slender beams, such as the Dupont Dymetrol monofilament beam [61], Superelastic Nitinol beam

[71] and steel beam [75]. Scholz used an actuated whisker made by a superelastic nitinol beam to determine contacted object 2-D profiles by measuring hub angle, displacement, forces, and torque [71]. Clements made further improvements by mounting the whisker on a two-axis robot through a load cell to acquire 3-D object profiles [22]. The main improvement compared to previous research is the switch from the linear approximation of the curvature to the description of the problem in natural coordinates. Distinct from using a load cell, Hall effect sensors are used to actively measure both the vertical and horizontal deflection of a single steel beam whisker, which can provide the localization information and object shape information in [74]. It is worth noting that when choosing to use steel beams, it is important to choose the right stiffness so that bending information can be obtained, compared to using springs.

2) Fiber: Fibers are lighter and less deformable than steel beams, thus improving the accuracy of the whisker as shown in Fig.7 (b). The mobile robot could detect the object distance and shape information by processing the Fiber Bragg grating (FBG) wavelength shift data [23]. Compared to its sensors which are fixed, a novel reconfigurable whisker was proposed that uses the magnetic attachment to achieve fast whisker array reconfiguration [48]. The camera was used to track a whisker array motion for contact, airflow, and inertial discrimination. Although a delicate connection enables more sensitive transmission of information, such as force and deformation, when the whiskers come into contact with an object, some previous designs have not focused on the connection between the whiskers and the sensor body.

3) Spring: Due to the springs' good deformation properties and the simplicity of analyzing the forces applied through deformation models, Kim utilizes a planar spring system including four serpentine-shaped springs for micro aerial vehicle airflow sensing as shown in Fig.7 (c) [29]. Obviously, the four springs connected in a criss-cross configuration are a very stable mechanical suspension structure in Fig.7 (b), therefore Zhao in [78] uses a similar principle to better transfer the deformation produced by the whisker tip when it comes into contact with an object. Through finite element simulation, they further optimized the structural design of the whisker for precise positioning of the object. In contrast to using a spring for better signal acquisition in [47] [78], Yu employed a nonlinearly tapered spring as a reservoir computer that can provide morphological computational power, thus significantly reducing the computational power required for signal processing [72] [73]. The advantages of springs over steel beams and fiber optics are their good deformation properties and the convenience of calculating the magnitude of external forces. However, inspired by the fact that rodents can adjust the stiffness of their whiskers and hair follicles, it will be worthwhile to explore how to design spring-based stiffness-adjustable whisker sensors in the future [79].

Moreover, the challenge associated with fabricating whisker sensors in previous is usually to integrate the sensitive element in the base with the whisker beam while maintaining good sensitivity, accuracy, and durability under cyclic motion. To better improve the structural stability, 3D printing of the entire whisker sensor was attempted and will be discussed in the next subsection, and it will reviewd in the later subsection.

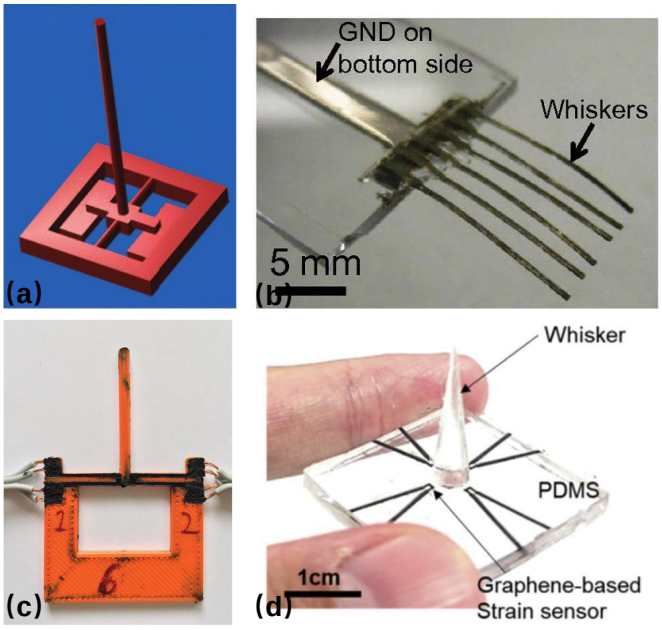


Fig. 8. Whisker fabricated through 3D print methods. (**a**) Fully 3D printed whisker [80], (**b**) Nanocomposite-based 3D printed whisker [62] , (**c**) PDMS-based whisker made by deep reactive ion etching methods [69], (**d**) Whisker made by 3D printer mold [81].

B. Advanced materials in micro/nano fabrication

This subsection explores the integration of advanced materials in micro and nanoscale fabrication, showcasing methods like 3D printing, deep reactive ion etching, and the use of conductive inks to develop bioinspired tactile whiskers. The combination of these techniques demonstrates how advanced materials are crucial in improving the performance and durability of whisker sensors, driving innovation in the field.

Micro-level fabrication methods have already been applied to the production of bio-inspired whisker sensors. 3D printing at the micrometre level is utilized for manufacturing moulds and structures for whisker sensors. A mould for the whisker and basement was firstly manufactured by a 3D printer, after which the direct laser writing method was to form a graphene film above the whisker base for the strain perception [81]. Lepora presented a soft optical whisker array made through dual-material 3D printing that is easy to customize and quick to manufacture, and whose motion was tracked by the camera to passive and active tactile perception [28]. A simple whisker structure and its base are fully 3D printed to detect the forces by measuring the coplanar capacitance change when mounted on a PCB [80]. Takei also adopted the deep reactive ion etching methods to fabricate a silicon mould which will be filled with PDMS. By attaching composite thin films of carbon nanotube (CNT) and silver nanoparticles (AgNPs) on both sides of PDMS, it could achieve high sensitivity and even 10 times higher than these capacitive or resistive pressure sensors reported reviously [69].

Compared with micro-level fabrication, nanoscale methods allow for the incorporation of materials like nanocompos-

ite inks and graphene, which can significantly improve the sensor's sensitivity and functional capabilities as a result of their exceptional electrical and mechanical properties. The use of conductive inks opens up new possibilities for creating sensors with complex geometries and integrated sensing elements, Harada proposed a 2D fully printed multifunctional E-Whiskers by using nanocomposite inks. By using the strain and temperature sensors at the same time, the E-whisker could simultaneously capture multiple pieces of information [26]. Xie et al. developed a durable and sensitive leather-based electronic whisker using conductive ink made of zero-dimensional nanomaterials to create a three-dimensional conductive pathway within the porous leather, enabling the e-whisker to withstand physical tests and sensitively detect surface texture variations as small as 50μm [82]. Furthermore, a fully 3D printed whisker composed of a polyurethane rod with conductive graphene patterns working as the sensing element has been developed for underwater vortex detection [65].

Regarding nano scale whiskers, the nano-scale vibration physics are not yet well understood, and hence a study of them is outside the scope of this paper related to bio-inspired whisker though some nano material studies use the term "whisker" for crystal growth.

In conclusion, while both microscale and nanoscale fabrication techniques are crucial for the advancement of sensor technology, the leap to nanoscale presents a steeper learning curve and requires a deeper understanding of material science. The ability to manipulate materials at the nanoscale opens up new possibilities for sensor functionality and performance but demands significant expertise and precision in the fabrication process.

C. 3D Printing

Advances in multi-material 3D printing technology allow researchers to create compliant, versatile, adaptable beard sensors. Only the actual whiskers are 3D printed in the research presented in [83], which implements active whisking by using commercially available actuation and sensor devices.

3D printing technology is also used to print new sensitive materials, such as carbon nanocomposite and nanotubes. A single whisker sensor contains two strain gauges made of a flexible non-conductive material called Ninjaflex and a conductive thermoplastic poly-urethane respectively for force sensing, in which all the materials can be 3D printed [62]. Distinct from the 3D printing is used to create whisker directly, it is also possible to produce different whiskers by first making a mould and then filling this with different materials. A novel 3D air assembly technique was used to construct the re-configurable, multi-modal E-Whiskers by using shape memory polymer [27]. Through this material and process, this e-whisker could sense various external stimuli such as the force, material stiffness, and surface profile just using a single strain gauge. Similarly, screen printing was also employed to make a multi-modal whisker array [26].

The development of new materials has further facilitated the development of fully 3D printable flexible whisker sensors that can be applied to a wider range of soft robotics applications. However, the fragility of the new 3D printed materials will pose new challenges compared to the previous methods using traditional steel beams, springs, etc. How to improve their robustness and reduce their fragility will be a new challenge. In general, the emergence of new materials and new fabrication processes has opened up the possibility of making miniaturized, multi-functional, multi-modal whisker sensors.

V. Whisker sensor application

Biologically inspired whisker sensors can be used in a variety of applications where they can sense information about their surroundings and help robots perform complex tasks, and most of the sensors reviewed in this section are designed for this purpose. The advantage of lightweight and low-power whisker tactile sensing is that it can compensate for other sensors in extreme situations, such as fog, smoke, underground and in the dark, or in high brightness and high temperatures, where the accuracy of visual assessment of objects or infrared assessment is severely disturbed by reflections and glare. Therefore, for some nocturnal or subterranean creatures, the whiskers are more important than the eyes.

Whisker sensors can provide important information to help robots with target location detection, shape determination, and identification classification, as well as mobile robot navigation. Such sensing can even be used or even unmanned underwater vehicles or unmanned aircraft for current and airflow detection, respectively. In addition, miniature whisker sensors are also used in medical robots to detect physiological motion and force levels [59]. Although robots are still not able to match animals in terms of tactile perception, whiskers have an indispensable function in this field. Table IV lists the different types of whisker sensors and their applications and gives a short description of the functions of these sensors.

A. Objective Detection and Location

Artificial whiskers have been shown to be a particularly efficient method in several studies for animals such as rats and sea lions, which can use whiskers for object detection and localization in dark and extreme environmental information and features, without the need for vision. In 1989, Brooks installed a whisker detector on a hexapod robot as a simple binary proximity detector to assist navigation and obstacle avoidance [17]. After that, Russell *et al*. proposed an idea that to use a tactile whisker to measure an object's surface contours based on the vibration information [93]. Zurek *et al*. demonstrated that static whiskers can be used as navigation sensors to compensate for the limitations of visual motion during fast movements [94]. The method of target detection and localization based on vibrations generated by contact between whisker sensors and objects has been inherited by many subsequent researchers. However, a novel bio-mimetic whisker based on the fiber Bragg grating is constructed by Zhao *et al*. to determine the location and distance of obstacles [23]. Therefore, one possible promising research direction is how to use a single whisker sensor to collect enough

TABLE IV
A SUMMARY OF WHISKER SENSOR APPLICATIONS

Applications	Functions and Remarks
Objective detection and localisation	Whisker sensors were used to recognize the environment surrounding objects [23] and detect the obstacles [84]
Objective shape recognition	2D and 3D objects shapes were measured by the sensitive whiskers combined with location and distance information [85] [86]
Objective texture perception	Different whisker systems were designed to collect vibration signals to recognize and classify different objects' textures with high success, combining with the naive Bayes or template method [52] [87]
Mobile robots navigation	Whisker sensors are used on mobile robots for obstacle position detection [88], distance detection [89], terrain recognition [72], and navigation [90]
Unmanned underwater vehicles waterflow detection	Whisker sensors can detect the speed and direction of underwater vortex flow as well as the pressure they cause [39] [30]
Airflow detection	Unmanned aerial vehicle (UAV): Detect the airflow pressure and velocities for the safe flight of UAV [29] [91] Sensors for robotics: Whisker sensors were used to detect the airflow in two and three dimensions [48] [15]
Medical robots surgeries	Miniature whisker sensors are also used in medical robots to detect physiological motion [59]

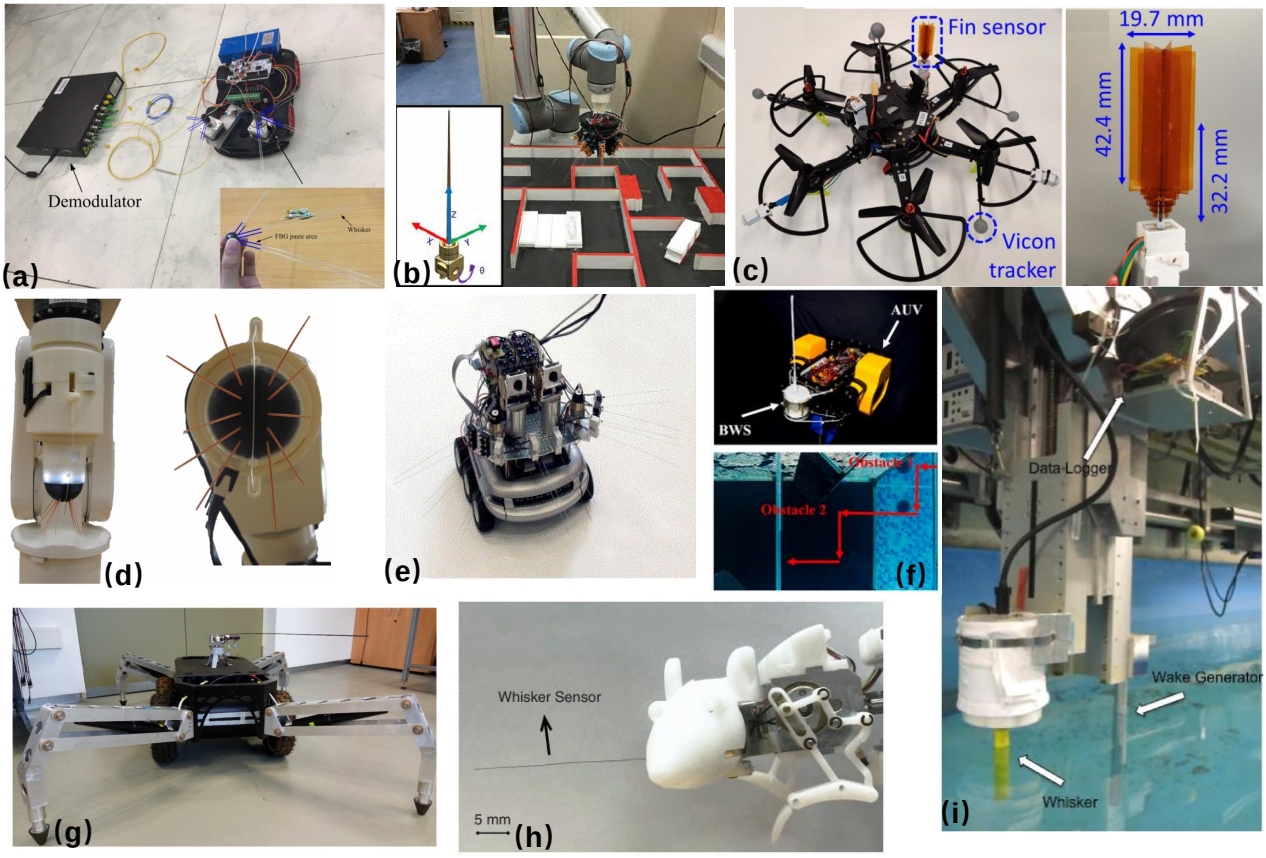


Fig. 9. Application of whisker sensors in different scenarios. (a) Target position detection [23]; (b) Whisker-RatSLAM for robot arm navigation [84]; (c) Whisker sensor for UAV multi-directional airflow sensing [29] ; (d) Optical-based whisker array for active object localization [28]; (e) Mobile robot target shape recognition [74]; (f) Unmanned underwater vehicles obstacle detection and avoidance [92]; (g) Object detection for legged robot [10]; (h) Whisker sensor mounted on Rat robot for texture discrimination [77]; (i) Water flow direction and velocity detection [45].

information about the position, distance, and angle of an obstacle.

However, in the previously mentioned studies, the bionic whisker could only act as a passive detector rather than actively detecting the size and distance of the obstacle. In [84], an active whiskered head tactile array has been successfully designed and mounted on UR-10 arm by Salman *et al*. for robot localisation and mapping. Batlle *et al*. designed and built a flexible whisker sensor with two degrees of freedom mounted on a legged-wheeled mobile robot, which can actively detect nearby objects by the sensing whisker beam and realize simple robot navigation [10], as shown in Fig.9 (g). Literature research has revealed how the design of active stiffness-controllable multi-degree-of-freedom whisker sensors will drive their wider application in object recognition.

B. Object shape recognition

Vision-based methods have been the most popular approach to recognize and classify object material property because it is o one of the most important properties of an object's surface especially when a robot requires effectively interacting with its surrounding environment. However, vision alone cannot

estimate the object's physical parameters such as friction coefficients, roughness, and stiffness by itself. In this respect, artificial whiskers have been generally used as tactile (contact detection) sensors to recognize and classify the object's shape and texture properties in extreme precision [20].

An active whisker was constructed to recognize the object's shape and determine the contact location by combining distance information and force directions based on force-moment sensors Kaneko [18]. By rotating vibration-based whiskers on a series of contact points of an object and collecting torque information, Solomon *et al*. proposed a method to obtain 2D and 3D information about the object [85]. To enhance the efficiency of object recognition, Pearson developed a new pose control strategy for tactile whisker array which reduces the pose dependence of object recall when the whisker slides the object surface [86]. However, the whisker cannot provide efficient information to recognize the objects' shapes and the whisker sensor was easily damaged. Therefore, inspired by the biology of rodent whiskers in Section.II, we need to further enhance the acquisition of target shape information by designing new whisker structures and by controlling the movement of the whiskers when they come in contact with the target. In addition, new manufacturing materials as well as structural designs can be considered to enhance its robustness.

C. Object texture perception

Object texture information is one of the most important properties and can be extracted by using a tactile sensor sweeping on the object's surface. Artificial whisker sensors have been validated that it can work as an efficient tool to discriminate surface textures of target objects for robots. A bio-inspired whisker system was developed to collect the vibration power spectrum and use it as a spectral classifier to classify object textures [95]. This principle was also used by Evans *et al*. to discriminate the raw floor texture vibration signal through a template matching algorithm, which is based on a whisker sensor system [87]. By pushing an active whisker sensor against different object surfaces, Lepora *et al*. developed a biomimetic optical tactile whiskered robot for comparing the difference between fingertips and whiskers in [88] [28]. N'Guyen *et al*. developed an artificial whisker system on both static and mobile platforms with a novel object texture discrimination algorithm, the results of their experiments have shown that this system is efficient and robust [96]. Furthermore, Steigenberger *et al*. theoretically analyzed the connection between the object's surface texture properties and mechanical reactions of the vibration signals based on the theory of static bending rod problems [97]. Therefore, taking our analysis of the biological behaviour of rodent whiskers in Section.II, one possible direction to enhance the acquisition of texture information is to have controllable stiffness of the whisker follicle or whisker beam to obtain information in different frequency ranges, and in addition to controlling the contact force and speed of the whisker with the target.

D. Fluid detection

Animals, such as rats and seals, have been shown to rely on whiskers to efficiently and accurately sense fluid information. Inspired by this, researchers have developed a variety of whisker sensors that can detect air information for drones and water information for underwater unmanned robots, respectively.

1) Unmanned underwater vehicles water flow detection: Water flowing from different directions will produce different drag forces on whiskers of different sizes. Since there is no nerve inside the whisker, the drag force will be transferred to the stress at the bottom of the whisker and generate an inductive signal to the seal [20]. As shown in Fig. 9 (i), a seal-inspired whisker sensor was developed and tested in the tank and sea to measure the water flow direction and velocity [45]. Based on a similar principle, Zhang *et. al.* invented a piezoelectric sensor-based self-driven seal whisker sensor, which can detect water velocity with an accuracy of up to $1.445\ V/(m/s)$. Besides, a whisker-like sensor was constructed by Zhu for amphibious mobile robots to detect the nearby object's information both on land and underwater environments, as well as it can measure external flow information [30]. These studies show that whisker-based sensors can help underwater drones perform better in complex underwater environments. Considering our biomechanical analysis of the shape of seal whiskers in Section.II, future scientists can also try to design whisker sensors of this shape of elliptical cross-sections with an undulating diameter to achieve accurate sensing of water flow speed and direction.

2) Airflow perception: Inspired by the abilities of mice and cats to use whiskers to sense airflow in confined spaces, they invented a soft whisker array to sense the speed of airflow in a two-dimensional surface [98]. Subsequently, a lightweight whisker array was fabricated to measure the airflow pressure force and the velocities at the same time, which could reach about 3.3 mN and 7.5 m/s [91]. This research opens the door to the application of whisker sensors for UAV flight status detection. Therefore, Kim *et al*. proposed a whisker-inspired fin sensor for UAV multi-directional airflow perception shown in Fig.9 (c). Experiments demonstrate the ability to capture the speed of a UAV by sensing the relative airflow during flight, which could further increase UAV flight safety [29]. Compared to the detection of obstacles by mobile robots on land, the detection of fluids, such as air and water, is relatively less investigated but has a wide range of applications.

E. Robots Navigation

Whisker tactile sensing can help robots better understand their surroundings, especially dusty and low-visibility environments, and thus navigate better. It can make up for the lack of vision sensors in extreme situations, as it can work in fog, smoke, underground and darkness, or in high brightness and high temperatures, where the accuracy of visual assessment of objects is severely disturbed by reflections and glare. As a result, whisker sensors have been widely used in unmanned ground vehicles [99] [100], unmanned aerial vehicles [29] [101], and even underwater unmanned robots [92]. For robot navigation, whisker sensors are typically used for obstacle detection and avoidance, fluid information detection, target recognition and so on. To our best knowledge, Jung *et al*.

firstly built a Yamabico Whisker robot to determine obstacle information and execute a simple wall-following navigation strategy by using the bending information of the whisker beam [99]. Based on the same principle, different whisker sensors are mounted on unmanned ground robots to perform obstacle detection and navigation tasks. In addition, whisker sensors are also used in underwater unmanned robots, where Liu *et al*. used whisker sensors to be used to detect and avoid obstacles underwater [92].

Although whisker sensors have been widely used in robotic environment sensing and navigation to compensate for other sensors' limitations in extreme situations, there is still a big gap between how animals use their whiskers skillfully and efficiently to survive in nature, as we discussed and analyzed in Section II. To identify future whisker design opportunities and to provide useful design guidelines, we will list some promising directions for future research in the whisker sensor design and applications in the next section.

VI. Discussion and Future research direction

The rapid development of whisker tactile sensors in the last few years has opened up new opportunities for their use in various robotic applications. Not only the type of whisker tactile sensor has to be considered in the application, but also the appropriate computational method to decipher the tactile encoded information is very important. At the same time, this poses many challenges to the effective use of haptic data. Through the comprehensive and critical literature review of the biological mechanisms of animal whiskers in Section.II and the sensor developments in previous Sections, Table.V demonstrates the research gap between whisker sensors and animal whiskers and future directions. Based on the review of the multidisciplinary literature in previous sections, we have identified the following as promising directions for future research in this area.

A. Whiskers sensor arrays

As shown in the Table.V, especially the multi-sensor array configuration, currently presents significant challenges. Although a single whisker sensor can capture a large amount of information and is widely used, the capability of a single device is nevertheless limited. Given that nature's whiskers all have their own complex, multidimensional sensing mechanisms, the first challenge is to increase the number of whiskers in the middle, especially while retaining detailed information about the bending of individual whiskers. Because of the engineering computational and hardware complexity this entails, the largest currently engineered whisker array has 20 whiskers, each with a transducer [102]. Although these arrays achieve amazing functionality, their excessive number of whiskers leads to a complex structure making them costly. This requires that we expand the number of whisker sensor arrays as much as possible to increase their functionality, but at the same time reduce their engineering complexity, simplify assembly procedures, and reduce costs. In addition, when designing the whisker array, it is important to take into account the rodent's biological inspiration, so that different whisker beams have different lengths and stiffnesses as much as possible, thus allowing information to be collected over a larger frequency range. Moreover, inspired by the array of animal whiskers, mounting multiple whiskers on various mobile robots or UAV formations could create a distributed whisker sensor network, offering navigation information to the host entity control, which may also be an intriguing direction.

B. Neuromorphic computing for whisked tactile perception

Deep learning, especially CNN, has been widely applied in the computer vision field. For example, it has been applied in the robotic tactile field for environment perception which includes object shape recognition, material properties estimation, and vision-tactile features fusion. However, to our best understanding, combining deep learning with robotic whisked tactile perception also requires in-depth research and several issues need to be carefully investigated when using deep learning for object shape and texture classification. Firstly, deep learning requires massive data to train the AI model, but it is relatively complicated for the whiskered tactile sensor to collect vibration signal data for training compared to vision datasets, especially for simple whisker tactile tasks. Moreover, there are still no universal whisker tactile sensing datasets for training deep learning models because the same algorithm may obtain distinct results if the data is collected from different whiskered tactile sensors. Therefore, as shown in Table.V, exploring animal-like neuro morphological methods for processing tactile information would be a promising direction, which could greatly reduce the arithmetic requirements for signal processing and improve the real-time performance of tactile information for robot navigation. This requires us to mimic the whiskers of rodents as much as possible in terms of structural design, signal conversion, and processing of the whisker sensors.

C. Whiskered tactile sensing in sensor fusion

Tactile sensors have been applied to compensate for vision limitation when in darkness, or occluded spaces such as voids or underground. Applications include obstacle detection, object recognition, object classification, and manipulation. For the whiskered tactile sensor, it can also be applied to extract objects' features to assist vision perception, as well as provide more accurate local and detailed environment information. For example, it is hard to obtain terrain truth for the robots only using vision perception [103] [29]. By combining the whiskered tactile sensor with the vision to determine and classify terrain surface texture, the robot navigation systems can avoid sinking into soft sand, cement, or soft soil.

Another direction of signal fusion is to fuse with the motion characteristics of the robot. As we analyzed in Section.II of the biological mechanisms of animal whiskers, the whisking behaviour of the animal is coupled with the motion behaviour, and the adjustment of the robot motion state to explicitly enhance the accuracy as well as the frequency breadth of the whisker sensor signal acquisition is a direction worth exploring.

TABLE V
RESEARCH GAP BETWEEN ENGINEERED WHISKER SENSORS AND ANIMAL WHISKERS

Functions	Gaps Between Biological Whiskers and Engineered Whisker Sensors	Representative Reference Papers
Structure	Most of the current research focuses on the design of a single whisker sensor, which limits the efficiency of whisker sensor information collection and versatility compared to animal whisker arrays.	[22], [45], [10], [59] [12]
	Artificial whisker arrays should have different lengths and adjustable stiffness as much as possible to mimic the whiskers of rodents to collect efficient information simultaneously.	[40], [28], [74]
	Fewer publications have focused on the design of whisker follicles, especially the active stiffness control of the whisker follicles, which is crucial for animals to acquire information in a wide frequency range.	[76], [38], [37]
Size	Most current engineered whisker sensors fabricated using traditional sensors are relatively large in size compared to animal whiskers, limiting their application in narrow spaces and mini robots.	[23], [62], [74], [71]
	Nanomaterials as well as 3D printing technology can contribute to the miniaturization and multifunctionality of whisker sensors, but they are relatively fragile and have poor robustness compared to biological whiskers.	[26], [27], [70], [69], [81]
Functions	The whisker sensors proposed in most of the publications are relatively single in function (e.g., force, distance, angle) and still have a gap in versatility compared to rodent whiskers, especially the simultaneous collection of different information.	[38], [22], [30], [92], [84]
	The whisker sensors proposed in most publications can only passively collect or differentiate particular tactile information but cannot actively differentiate between different stimuli applied simultaneously.	[62], [29], [60], [16]
Information Processing	Most of the current research uses traditional mathematical methods to process whisker tactile signals, which are quite different from how animals process whisker information, but neuromorphological computation may be another direction worth investigating.	[40], [72], [73], [31], [72],
	Most of the current research focuses on the design of whisker sensors and their functional implementation. It is promising to explore the integration of signals with other features, such as vision and movement, as rodents do.	[33], [42], [28]

D. Simultaneous detection of variable stimuli information

Another challenge is to use whiskers to sense complex and variable fluid information such as water and airflow, whose amplitude can vary over several orders of magnitude. Current laboratory tests have focused on the interaction of a single whisker (or whisker-like structure) with a steady stream of water or air. However, this may not be the same as in real life. A similar challenge is to distinguish between the different types of external stimuli that are incident on the whisker sensor. This is because both direct contact, fluid and motion stimuli at the base of the whisker can be sensed by the whisker. Therefore, it is still an unsolved challenge to differentiate between these different stimuli [104] [92]. Accurate recognition of external stimuli would represent a major advance in the field of whisker sensors as well as bionic robotics applications. Innovation in the structure of the whisker sensor would also be a very promising research direction. The first point is a reusable and structurally reconfigurable whisker sensor, because the material and size of the artificial whiskers in the above design are relatively fixed and not easily replaceable, without taking into account the different needs for different tasks.

E. Whisker Sensor Modeling and Miniaturization

Even though there have been a large number of different types of whisker sensors that have been developed for contact sensing, a common structural feature of all these methods is that they limit the deflection of the whiskers to very small strains (thus reducing sensitivity) and are usually either very large, thus making them challenging to construct and scale. Most are fixed on a fixed platform, considering the size of the transducer, the actuator they require, and the need for an external power supply, which also limits their application scenarios. Therefore, these conventional whisker sensors are not a suitable solution in environments with limited space or limited computing power. A possible alternative is to use sensors made of manufactured MEMS, which are small in size, low power consumption, and highly sensitive [105].

While future developments in whisker sensors, such as designing whisker sensor arrays, miniaturizing whisker sensors, and achieving multifunctionality, especially in the context of simultaneous detection of variable stimuli information, are of paramount importance, it is equally crucial to emphasize the role of modeling and simulation in whisker sensor research. This is because modeling and simulation can assist us in optimizing the design of whisker sensors, and predicting the performance of whisker sensors, thereby reducing the risk of experimental failures and enhancing performance. As demonstrated in [106], it is essential to establish a beam model of whisker sensors and conduct frequency response analysis before implementing whiskers-based reservoir computing experiments.Therefore, in the future, attempting to establish a generalized mathematical model for whisker sensors would be a highly intriguing research direction

VII. CONCLUSION

This paper presents a comprehensive and critical literature review of the biological mechanisms, engineered transducers, materials, design and fabrication approaches, and applications of whisker sensors. The review demonstrates the importance of adapting the physical morphology of a whisker to suit interactions dynamics in an environment. We show that engineered whiskers still fall short of biological counterparts in several aspects such as size, function, structure, and information processing efficiency. We show that a key to bridge this gap is to pay more attention to design the surface morphology and mechanical properties of the whisker beams, and to design whisker follicles with the ability to tune whisker parameters to serve targeted information acquisition in an ecological niche. New materials and fabrication techniques, especially

nanomaterials, multimaterial 3D printing, neuro morphological computing, and multi-modal sensor integration hold potential to fill this gap.

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