Potential Applications of Whisker Sensors in Marine Engineering

Subjects: Engineering, Marine
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Perception plays a pivotal role in both biological and technological interactions with the environment. Recent advancements in whisker sensors, drawing inspiration from nature's tactile systems, have ushered in a new era of versatile and highly sensitive sensing technology. Whisker sensors, which mimic the tactile hairs of mammals, offer both high sensitivity and multifunctionality. They excel in capturing fine-grained environmental data, detecting various stimuli with precision, and finding applications in diverse domains.

Keywords: whisker sensors ; tactile perception ; marine science and engineering

1. Introduction

Perception forms the bedrock of both biological and machine interaction with the surrounding environment [1][2][3][4][5][6]. In the technological realm, the ability to perceive and respond to external stimuli remains a driving force behind ongoing innovations in sensor technology [7][8][9][10]. Optical and acoustic sensing technologies have consistently stood at the vanguard of this field, furnishing invaluable insights for our comprehension of the world surrounding us [11][12][13][14]. Nevertheless, there is a growing recognition of the need for more versatile and adaptable sensing solutions to meet the increasing demands of the modern world. Tactile sensing technology, serving as a pivotal complement to conventional optical and acoustic sensing technologies, has equipped machines and devices with broader sensing and responsive capabilities. Research and applications in this sphere have achieved significant breakthroughs across multiple domains [15][16][17][18][19][20]. A current trend in tactile sensing technology involves a growing inclination towards biomimicry, where researchers draw inspiration from nature's own sensory systems to create sensors capable of emulating the complexity and adaptability found in living organisms. This bio-inspired approach to tactile sensing has given rise to a gamut of biomimetic tactile sensors, each replete with unique advantages and applications [21][22][23][24].

Among the myriad biomimetic tactile sensors that have attracted considerable attention, whisker sensors stand out as a distinctive and promising category due to their exceptional ability to discern critical environmental cues [25][26][27][28]. They derive inspiration from the tactile sensing capabilities displayed by various animals, particularly mammals. Whiskers are highly sensitive elongated tactile hairs, and these remarkable appendages play an indispensable role in detecting and interpreting the surrounding environment, endowing animals with vital information about objects, surfaces, and even fluid dynamics [29][30][31][32][33][34]. Since the conceptualization of whisker sensors in 1987 [35], researchers worldwide have conducted extensive investigations into whisker sensors based on various sensing principles, yielding numerous exciting research outcomes. Compared to conventional tactile sensors, whisker sensors offer several advantages, with their most prominent attribute being high sensitivity, an inherent characteristic of their biomimetic design. Whisker sensors excel in capturing fine-grained environmental data, providing a more comprehensive understanding of the surroundings than traditional tactile sensors [36][37]. Traditional tactile sensors often struggle to discern subtle changes in touch, pressure, or texture, while whisker sensors, with their flexible and responsive whisker-like structures, can minutely discriminate variations in the environment [38][39][40][41]. This heightened sensitivity renders them exceptionally valuable in applications where precision and accuracy stand as paramount requisites. Additionally, whisker sensors exhibit significant versatility and are capable of detecting various stimuli, including static and dynamic touches [42][43][44], airflow [45][46], vibrations [47][48], and even fluid flow [49][50]. The multifunctionality of whisker sensors expands their applicability across various fields, including robotics, automation, environmental monitoring, and scientific research.

2. Typical Categories of Whisker Sensors

2.1. Optical Whisker Sensors

Optical sensing technology, as one of the most widely employed sensing methodologies in contemporary applications, has witnessed significant advancements in the maturity of its sensing components [51][52][53]. The construction of whisker sensors utilizing optical sensing elements presents a direct and viable approach. Depending on the optical sensing mechanism employed, optical whisker sensors can assume diverse configurations. For instance, in the research conducted by Wang et al., whisker sensors were meticulously designed and produced using optical polymer-formed whiskers [54]. These whiskers, emerging from the central core of a seven-core optical fiber (SCF), connect to solid pendulums, thereby forming six parallel Fabry–Pérot interferometers between the SCFs.

2.2. Magnetic Whisker Sensors

Magnetic whisker sensors represent one of the predominant categories of whisker sensors currently employed, primarily relying on the incorporation of Hall sensors in their design [55][56][57][58]. Owing to the compact dimensions, multi-dimensional capabilities, and robust environmental adaptability inherent in Hall sensors, magnetic whisker sensors can be developed with enhanced miniaturization and integration. Variations in the position of the whisker’s base are registered by an underlying Hall effect sensor. This mechanical configuration can be simplified to a fundamental torsion spring model, allowing for the modulation of the whisker’s sensitivity to external stimuli through adjustments to the spring's elasticity coefficient.

2.3. Resistive Whisker Sensors

Resistive whisker sensors constitute a category of sensors that employ resistive materials to enable sensory functions. Their sensing principle is rooted in the resistive effect, wherein the detection of whisker deformation relies on measuring changes in the resistance of the resistive material in response to external stimuli. These sensors are known for their structural simplicity, low energy consumption, and wide detection range. This design approach provides a plethora of material choices, including silicon [59][60], carbon [61][62], graphene [63][64], and more [65].

2.4. Capacitive Whisker Sensors

Capacitive whisker sensors employ various types of capacitors as sensing elements [66][67][68]. External stimuli cause strain on the whisker, resulting in a change in the relative position between the two plates of the capacitor, leading to a modification in capacitance. Detecting this change in capacitance provides strain information. These sensors offer several advantages, including high sensitivity, low energy consumption, and insensitivity to temperature variations.

2.5. Piezoelectric Whisker Sensors

Piezoelectric whisker sensors are a specialized category of sensors designed to detect whisker strain by harnessing the piezoelectric effect inherent in certain materials when subjected to external stimuli. In essence, these sensors leverage the piezoelectric effect. This effect entails the polarization of internal charges within the piezoelectric material, resulting in the generation of charges on the material’s surface. A distinctive feature of piezoelectric whisker sensors is their self-driving capability, allowing them to function effectively without the need for an external energy supply. This characteristic proves particularly advantageous in energy-constrained scenarios, such as robotics [69][70][71].

2.6. Triboelectric Whisker Sensors

Triboelectric whisker sensors utilize the triboelectric effect and electrostatic induction to convert the minute mechanical energy generated by whisker strain into electrical signals, facilitating the analysis of strain information in whiskers. In comparison to piezoelectric sensors, triboelectric sensors possess the advantages of self-driving capabilities, higher output voltage, and lower cost, rendering them more advantageous in the development of sensing systems [72][73][74].

Another advantageous feature of TENG is its high flexibility, enabling the design of diverse structures employing various materials. One such example is a follicle-inspired triboelectric whisker sensor closely mimicking the follicle structure of a mouse whisker [75].

3. Potential Applications of Whisker Sensors in Marine Science and Engineering

3.1. Marine Structure Monitoring

Marine structure monitoring encompasses the real-time or periodic assessment of diverse engineering structures, facilities, or natural phenomena situated in the ocean. These structures encompass offshore facilities, submarine cables, marine energy devices, marine bridges, marine platforms, ports, and offshore vessels, among others. Whisker sensors present many application prospects in monitoring marine structures [76][77][78][79][80]. They can establish contact with the structure's surface or its surrounding environment to capture the physical condition of the structure, thus enhancing the safety, reliability, and longevity of marine structures. Reeder et al. introduced a dense, highly sensitive, and multimodal electronic whisker sensing array constructed on a shape memory polymer substrate [81]. This array can detect proximity, microtexture, surface roughness, force, material rigidity, and temperature with a response time of less than 250 μs. Electronic whiskers are fabricated from resistive sensors using planar lithography and transformed into shape-adjustable, deterministic 3D components using directed airflow at temperatures above the substrate's transition temperature. This electronic whisker array can discern fingerprints and leather textures, with the texture mapping results aligning with those obtained using a profilometer. While this study did not delve deeply into its application in the field of marine structure monitoring, this versatile sensing array can be affixed to robotic arms or robots for surface damage detection on structures. Furthermore, its ability to sense force and temperature makes it suitable for extended monitoring of marine structures such as marine risers and ship pipelines.

3.2. Marine Measuring Instruments

Marine measurement instruments encompass a range of devices and equipment employed for data collection and measurement in the marine environment. Whisker sensors, as miniature, integrated, and intelligent sensors, hold the potential to significantly enhance the sensing capabilities of existing systems, offering insights into multiple parameters, including velocity [82][83], viscosity [84], vibration [85], underwater acoustics [86][87][88], and more. Liu et al. devised a deployable Kirigami whisker sensor by combining Kirigami skin pop-up functionality with flexible conductive layers [89]. This sensor transitions from a flat state to a sensing state, with adjustable whisker stiffness and initial pop-up angle achieved by tuning pre-stretch strain. It comprises Kirigami layers with printed conductive sensor layers. Kirigami, a 2D layer structure cut into specific patterns, transforms into 3D pop-up structures when subjected to strain. A trapezoidal pattern was chosen for its superior stretchability and larger pop-up angle.

Drawing inspiration from marine mammal tactile whiskers, Rooney et al. introduced a novel method for determining the relative viscosity density of fluids using driven flexible beams [90]. The sensor structure incorporates artificial whiskers based on the Hall effect sensor model, installed within follicle casings and connected to a PC for data sampling via a straightforward microcontroller interface. The whisker sensor generates two voltages proportional to the deflection degrees along two orthogonal axes of the whisker shafts. The voltage-to-deflection ratio is pre-programmed during assembly and calibrated using load sensors and micrometer displacement tools.

3.3. Marine Robot Tactile Perception

Tactile perception in marine robots encompasses the capacity to sense objects and surfaces within the environment through touch and pressure sensors, facilitating interactive engagement. Integration of whisker sensors with marine robots extends their functionality to address diverse application needs. For instance, whisker sensors enable distance and shape recognition, facilitating the development of tactile Simultaneous Localization and Mapping (SLAM) systems for cabin inspection robots [91][92][93][94]. This complements their limited optical perception capabilities in close proximity. Underwater robots, equipped with whisker sensors, gain tactile recognition capabilities, enabling the detection and identification of surrounding obstacles, thereby enhancing their operability. Wei et al. proposed a MEMS-based (MEMS, Micro-electromechanical Systems) biomimetic whisker sensor inspired by rodents, which integrates four sensing units on a square silicon wafer measuring 6.8 mm per side [95]. This design allows mounting on small robots similar in size to real rodents.

Autonomous guided vehicles (AGVs) serve as viable choices for cabin or offshore platform inspection robots. An et al. designed a flexible biomimetic whisker mechanoreceptor (BWMR) inspired by the way animals employ hair-based sensors to explore their environment [96]. The BWMR utilizes triboelectric nanogenerator technology, allowing it to convert external mechanical stimuli into electrical signals without the need for an external power source. This feature makes it suitable for widespread use in robots. The BWMR facilitates the identification of objects that conventional environmental detection methods like vision and ultrasonic radar cannot detect, substantially expanding a robot's ability to gather information about its surroundings

By ensuring the waterproofing and specialized design of whisker sensors, they can also be directly applied in underwater environments. Taking inspiration from sea otter whisker structures, Xu et al. designed a TENG-based biomimetic whisker sensor (BWS) to assist underwater robots in perceiving the underwater environment [75]. The sensing unit generates electrical signals through triboelectric effect and electrostatic induction between an FEP thin film and ink.

3.4. Marine Non-Contact Environmental Sensing

The utilization of whisker sensors for non-contact environmental sensing in the marine environment represents an innovative approach. These specialized sensors draw inspiration from marine mammals and other animals' whiskers to gather information about the underwater environment without the necessity for direct physical contact. In contemporary research, the development of sensors geared towards achieving non-contact environmental sensing in the ocean is predominantly influenced by seal whiskers [97][98][99][100]. Extensive studies on the fluid dynamics associated with seal whiskers provide a robust theoretical underpinning for the design and implementation of whisker sensors for marine non-contact environmental perception. Zheng et al. introduced a fully 3D-printed MEMS cantilever sensor designed to experimentally measure the responses to vortex-induced vibration (VIV) and flow-induced vibration (WIV) in individual 3D-printed seal whiskers and arrays [101].

In a similar vein to seal whiskers, Wang et al. introduced a flexible biomimetic whisker sensor, distinct from the previously mentioned whisker sensors, denoted as the Underwater Biomimetic Whisker Sensor (UBWS) [102]. The UBWS comprises an internally autonomous layered triboelectric nanogenerator sensing unit, flexible silicone gel follicles (Dragonskin 00-20), and artificial whiskers (polydimethylsiloxane, PDMS). The follicles envelop the upper portion of the sensing unit, while the artificial whiskers cover the lower portion. The variation in material elasticity between the upper and lower halves of the UBWS culminates in the primary deflection point along the sensing unit, generating strain at the material junction. The UBWS is integrated into a robotic fish for the purpose of underwater target tracking.

4. Challenges

(1) In-depth Research into Whisker Sensing Theory: The existing landscape of whisker sensors divides them into rigid and flexible categories based on the properties of artificial whisker materials. Rigid whisker sensors boast simpler structures, facilitating the establishment of sensing models; however, they often fall short in terms of performance. In contrast, flexible sensors exhibit superior sensitivity but frequently entail intricate strain processes, typically simplified into two-dimensional models for analytical purposes, rendering them theoretically less mature. Consequently, the ongoing pursuit revolves around the development of dependable mechanical models for artificial whiskers. The creation of robust theoretical models founded on well-established theory can underpin the design and fabrication of whisker sensors, curtailing trial-and-error costs. Simultaneously, the intricacies of the marine environment can be streamlined through further exploration of the fluid-structure coupling mechanism between whiskers and fluids.

(2) Enhancing Sensing Capabilities: The capabilities of whisker sensors pivot primarily on their design and materials. The sensing mechanism is heavily influenced by design configuration, making the optimization of design crucial to enhance sensing capabilities. Additionally, the material properties of the sensor not only impact the accuracy of artificial whiskers but also define the capacities of the sensing unit. For instance, in the case of triboelectric whisker sensors, improving the charging performance of both the dielectric layer and the electrodes within the sensing unit is a pivotal step towards enhancing sensing capabilities. The amelioration of artificial whisker materials can concurrently fortify their durability and stability, warranting intensified research efforts in the materials domain.

(3) Developing Long-Term Monitoring and Autonomous Operation: The marine milieu presents unique challenges concerning energy supply. Mitigating sensor energy consumption to enable protracted monitoring or autonomous data collection capabilities emerges as a critical imperative for sustained marine research. Current research endeavors have extended into the domain of self-powered sensing technologies, which include the utilization of piezoelectric or triboelectric nanogenerator technologies. These advancements enable sensors to function autonomously, without reliance on external power sources. The exploration of their integration with whisker sensors presents a promising avenue for addressing this challenge.

(4) Integration and Intelligence: Whisker sensors, classified as tactile sensing technologies, harmonize seamlessly with other sensory modalities like sonar, cameras, and LiDAR (Light Detection And Ranging), culminating in multi-sensor fusion systems that augment overall marine perception in terms of comprehensiveness and precision. For instance,

amalgamating whisker sensors with optical sensing apparatuses on underwater robots confers synchronous perception of the surrounding environment, encompassing far-field and near-field scenarios. This synergy enables superior detection and tracking of marine entities and structures.

(5) Multidisciplinary Cross-Integration: Whisker sensors inherently epitomize the product of interdisciplinary research. Their deeper exploration across various disciplines assumes pivotal significance in ameliorating their performance and broadening their horizons with regard to application areas. In the realm of materials science, the optimization or invention of new materials requisite for whisker sensors assumes centrality. Within the domain of mechanical design, inventive approaches can be pursued to ensure sensor robustness and stability. In the purview of biology, a deeper comprehension of the sensory mechanisms underpinning biological whiskers can serve as a fount of inspiration for whisker sensor designs. The field of data analysis and algorithm development requires the creation of intelligent algorithms designed to process and analyze sensor output data. In the realm of physics, the formulation of effective models and analyses relevant to whisker sensors can contribute to the refinement of theoretical models.

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