Tactile Sensing Technology Based on Magnetic Sensors

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Tactile perception is one of the most important ways for organisms to obtain environmental information, just like vision and hearing. How to make robots acquire tactile perception like human beings is one of the hot spots in scientific research. With the idea of bionics, a large number of tactile sensors have been designed based on the working principle of human skin. Biomimetic tactile sensors are important media for robots to perceive external environment, which help robots get information about pressure, vibration, roughness, and temperature. Tactile sensors have played an important role in medical treatment, artificial skin, robot tactile feedback, and human–machine interaction. With the discovery of new materials and the development of microelectronics, tactile sensors based on a variety of transducing mechanisms such as resistance, capacitance, piezoelectric, and optics have been developed.

Keywords: tactile sensing ; magnetic sensor ; sensor application

1. Classification and Development

1.1. Types of Magnetic Sensors

1.1.1. Hall Sensor

Hall sensors are based on the Hall effect, which refers to the physical phenomenon that a transverse potential difference is produced when the magnetic field acts on the carriers in metal conductors or semiconductors. The manufacturing process of Hall sensors is mature and compatible with the semiconductor manufacturing process. Hall sensors are the most common magnetic sensors because of their low cost and simple fabrication. They have a wide detection range and are often used to detect strong magnetic fields. Although the performance of Hall sensors is not as good as magnetoresistive sensors in weak magnetic detection, they have been widely used as magnetic switches and magnetometers in various applications [1][2].

Hall sensors are frequently used in tactile sensing. The most common usage method is to insert both permanent magnets and Hall sensors into flexible material. When the flexible material is deformed by force, the position of permanent magnets will change. So, the magnetic strength and direction of the magnetic field around the magnets are changed. By detecting the change with Hall sensors, the amplitude and direction of the tactile force can be obtained successfully. Based on this principle, Eduardo et al. developed a Hall tactile sensor as early as 2006 [3]. They made a hollow hemispherical structure with flexible silicone. A permanent magnet was placed on the top of the hemisphere, with four Hall sensors underneath. Hall sensors detect the position change of the magnet caused by the contact. Finally, the sensor achieved a resolution of 94 mN for normal force.

The commercialization of Hall sensors is very successful, and the enhancement of tactile sensor performance is also closely related to the development of commercial Hall sensors. In particular, the commercialization of three-dimensional magnetic sensors makes the perception of three-dimensional tactile force easier. Ledermann et al. combined a three-dimensional magnetic sensor chip AS54xx (Fraunhofer Institute for Integrated Circuits, Erlangen, Germany) with flexible silicone for tactile sensing [4], so they could measure three-dimensional force with only one sensor. Its minimum resolution is 150 mN with little hysteresis. A classic representative of commercial three-dimensional Hall sensors is MLX90393 (Melexis, Ieper, Belgium), which is widely used by researchers [5][6][7][8][9][10]. For example, Hongbo Wang has made a variety of tactile sensing devices with MLX90393 [5][6].

Benefiting from a large measuring range and low cost, Hall sensors will still be the main magnetic sensor used in tactile sensing in the future. Especially with the development of packaging technology, the ability of Hall sensors to realize three-dimensional perception in small volume has become increasingly prominent, which is of great significance for the development of three-dimensional tactile perception.

1.2. Anisotropic Magnetoresistive (AMR) Sensor

The AMR effect refers to the phenomenon that the resistance of anisotropic magnetic materials varies with the change of the angle between the magnetization and the current direction. The magnetic sensitivity of AMR sensors is improved compared with that of Hall sensors. AMR sensors have low 1/f noise and are more suitable for low-frequency magnetic detection. It is most commonly used for geomagnetic detection.

There are also a small number of reports on tactile sensing with AMR sensors. Ping Yu produced a tactile sensor with a commercial 3-axis AMR sensor (Honeywell HMC1053). A permanent magnet was embedded in the flexible hollow PDMS (polydimethylsiloxane) material, and the AMR sensor was below the magnet. Finally, this sensor could detect a minimum force of 10 mN, with a sensitivity of 58 mV/N and a working range of 0–20 N (Z-axis).

AMR sensors are one type of magnetoresistive sensors, which are easier to fabricate than GMR sensors and TMR sensors. Therefore, AMR sensors are easier to combine with other complex processes to achieve more powerful functions. In 2022, Christian Becker et al. combined the AMR manufacturing process with traditional three-dimensional origami technology, and made a three-dimensional device, which could realize three-dimensional perception of magnetic field [11]. By using the origami technology, they can bend the AMR film to a non-horizontal plane. Then, they combined the sensor array with a neodymium iron boron (NdFeB) permanent magnet attached to the end of cilia.

There are not many studies on tactile sensing with AMR sensors. On the one hand, the performance of mature Hall sensors has been able to meet the needs of general tactile sensing. On the other hand, for high-precision tactile sensing, the performance of AMR still lags behind that of other magnetoresistive sensors. In addition, due to the influence of working temperature and external magnetic field, AMR sensors with the Wheatstone bridge structure easily generate bridge bias after being used for a period of time. It is usually necessary to rearrange the internal magnetic domains with auxiliary devices such as set/reset coils. This increases the volume of the sensor and is not conducive to the long-term use of the device.

In the future, AMR sensors should give full play to the advantages of being easily manufactured. AMR sensors can be fully integrated with the existing manufacturing processes of flexible tactile structures to achieve more complex and powerful tactile capabilities.

1.3. Giant Magnetoresistive (GMR) Sensor

The giant magnetoresistance (GMR) effect is a quantum mechanical phenomenon which was first found in the structure of multilayer magnetic metal film [12][13]. Now, most GMR sensors are spin-valve structures [14]. The most classical structure of spin valve is two layers of ferromagnet sandwiched with a layer of conductive materials (such as Cu, Cr). When the magnetic moment directions of adjacent ferromagnetic layers are parallel or anti parallel under the action of external magnetic field, the resistance of multilayers will change. The resistance change of GMR sensors is one order of magnitude larger than that of AMR sensors, so a weaker magnetic strength can be detected. Soon after its discovery, the GMR effect played a great role in magnetic storage, and has great application value in sensors [15].

At the beginning of the 21st century, GMR sensors have been widely used as tactile sensing elements. For example, Goka and Nakamoto have successively designed tactile sensors with GMR elements [16][17][18][19]. Goka used flexible circular bulges embedded with permanent magnets as the sensitive structure. A commercial GMR sensor from the NVE company was used to obtain signals. The working range of this sensor is −40 to 40 N, and the minimum force that can be detected is 60 mN. Nakamoto et al. further optimized this design. They used a magnetic film embedded with two permanent magnets and multiple GMR sensors, and the large-area perception of contact force was successfully realized.

With the help of bionics, the realization of artificial skin is an important research target of tactile sensing technology. The requirement of artificial skin is achieving large-area, high-resolution perception while maintaining flexibility. There are also attempts in this field with magnetic sensors. Jin Ge et al. grew GMR multilayer films on flexible PI substrates as sensitive elements, and successfully produced a thin-film magnetic tactile skin. They used permanent magnetic particles as the source of the magnetic field and designed an air gap between the skin and the sensor. When contacting external objects, the magnetic skin is closer to the GMR sensor below, so the magnetic signal is stronger. This sensor realizes non-contact measurement, which has great application value in medical diagnosis. In addition, it is worth mentioning that this study made a pyramid convex structure under the magnetic skin. When the force is large, the top of the pyramid structure will contact the GMR sensor and deform with the increase of the force. This design greatly increases the detection range of applied force. Although this sensor is fully flexible, it has the problem of a reduction of durability. In addition to the fact that the electrode is prone to fracture after multiple bending, GMR multilayer films are also very fragile. Therefore, this sensor is not suitable for applications in complex scenes such as large angle bending and stretching.

In order to balance flexibility and complexity, Miguel Neto designed a flexible-rigid hybrid sensor on a robot finger in 2021 [20]. They produced GMR sensors on silicon wafer and flipped them on a flexible circuit board. The connection between the two was realized by a silver conductive epoxy resin. Since the silicon wafer is small enough (0.8 mm × 1.5 mm), the whole device is still flexible enough and is more adaptable to harsh environments.

1.4. Tunnel Magnetoresistive (TMR) Sensor

There are many similarities between TMR sensors and GMR sensors, and both of them are multilayer film structures. However, the middle layer in TMR multilayer films is not metal materials, but insulating materials (such as AlOx, MgO). The magnetic moment direction of the pinned layer is fixed as a single direction, and the direction of the free layer can follow the direction of the external magnetic field. When the two directions are the same, the resistance of the multilayers is large, and the resistance is small when they are different. The TMR effect is based on the tunneling effect of electrons in insulating materials, and the change in resistivity is one order of magnitude larger than the GMR effect. Therefore, TMR sensors have extremely high sensitivity, which are very suitable for weak magnetic field detection. At the same time, TMR sensors also have better temperature stability and lower power consumption.

At present, there are only a small amount of studies on tactile sensing with TMR sensors. In 2018, Dongfang Zhang proposed a new tactile sensor for detecting the hardness of objects [21].

Although TMR sensors can theoretically provide better resolution for tactile sensing, there are not many reports. This is mainly due to the influence of 1/f noise [22][23]. When the frequency of the magnetic field is low, the noise of the TMR sensors is very high. For tactile sensing, in addition to the detection of high-frequency vibration, most of the signals are low-frequency. Therefore, TMR is not applicable in this situation. In addition, compared with AMR and GMR sensors, the film thickness of TMR sensors has a significant impact on the performance of the sensor. Furthermore, the current in TMR sensors needs to flow vertically to the film plane, which has much higher requirements for the manufacturing process. The complexity of the process and lower consistency make it difficult for mass production, which is a major obstacle for the wide application of TMR sensors.

Thanks to the high sensitivity of TMR sensors to weak magnetic fields, the future application of TMR sensors in tactile sensing can focus more on the measurement of force on micro-Newton and nano-Newton scales. Additionally, it can be applied in special application areas such as minimally invasive surgery.

1.5. Giant Magnetoimpedance (GMI) Sensor

GMI sensors are designed based on the giant magneto-impedance effect. The giant magnetoimpedance effect refers to the phenomenon that the impedance of specific materials changes significantly with the change of magnetic field. GMI sensors are a kind of magnetic sensor that theoretically integrates many advantages such as high sensitivity, fast response, low hysteresis, wide temperature range, good stability, and low cost. It has the advantages that other magnetic sensors do not have or cannot have at the same time [24].

GMI sensors have also been applied in tactile sensing in recent years. For example, Yuanzhao Wu proposed a tactile sensor based on a GMI sensor [25]. They used the Co-based amorphous wire as the sensitive material and wrapped a copper coil outside the wire to provide a biased magnetic field. When there is a force, the flexible layer mixed with magnetic particles deforms. The change of the magnetic field leads to the change of the impedance of the Co-based amorphous wire. Because the signal is AC, this sensor outputs digital (frequency) signals directly, which is beneficial for subsequent signal processing. This sensor is very sensitive, with a minimum detectable force of 10 µN and a minimum detectable pressure of 0.3 Pa.

However, GMI sensors require an extremely high frequency (100 MHz to GHz) drive signal. The circuit that generates high-frequency signals is also complex. This brings difficulties to the miniaturization and low power consumption of devices. Moreover, GMI sensors need a biased magnetic field when working, so coils or permanent magnets are needed outside GMI materials. In addition, GMI sensors have other drawbacks, such as large residual magnetism, magnetic characteristics susceptible to environmental conditions, and high noise of detection circuit, which limit their future development in tactile sensing technology.

1.6. Other Magnetic Sensors

In addition to the above sensors, magnetic sensors also include fluxgate meter, atomic magnetometer, superconducting quantum interference devices (SQUID) and so on. Fluxgate meter has high sensitivity and stable performance, which is very suitable for low-frequency weak magnetic field detection. However, the sensitivity of fluxgate meter is proportional to the measurement area of coil, so the volume of high-resolution fluxgate is large, and it is difficult to miniaturize and does not facilitate easy electronic integration [26]. The resolution of the atomic magnetometer can reach several fT without a low-temperature environment. It is widely used in large-scale equipment for outer space exploration, anti-submarine, and anti-mine. However, its volume is even larger than that of fluxgate sensor. Although it can be miniaturized with the help of MEMS technology, it is often difficult to achieve both miniaturization and sensitivity [27][28]. SQUID is the most sensitive magnetic sensor at present, which can detect the magnetic strength on a fT scale or even lower, with wide measurement range and high response frequency. SQUID is also the most mature sensor in biological magnetic field detection, which has important application value in disease testing. However, SQUID can only work at extremely low temperatures, requiring complex devices such as liquid helium or liquid nitrogen cooling. SQUID also needs an excellent magnetic shielding environment when working. Therefore, SQUID is very large in size, high in power consumption, and high in cost [29]. At present, it can only be used in specific application areas, which is not suitable at all in tactile sensing. At present, there are also some studies on hydrogel magnetic sensors and actuators [30][31][32][33]. The hydrogel has excellent biocompatibility when it is used in electronic skin and medical sensors. However, reports of its application in tactile sensors have not appeared. This is also a possible research direction of magnetic tactile sensors in the future.

2. Source of Magnetic Field

A magnetic sensor itself has no ability of force sensing. It can only sense magnetic field. Therefore, as a medium, the source of magnetic field is necessary for tactile sensing. For example, as mentioned above, there are a large number of studies using permanent magnets as the source of magnetic field. In addition to permanent magnets, magnetic field sources also include permanent magnetic particles, inverse magnetostrictive materials, and coils. They have different characteristics when applied to tactile sensing technology. Next, them will be introduced respectively.

2.1. Permanent Magnet

Permanent magnets are the most common source of magnetic fields. There are many kinds of permanent magnet materials, some of which come from nature, such as magnetite. Nowadays, artificial magnets are more widely used, such as ferroalloys doped with Al and Ni elements. Among all kinds of permanent magnets, rare-earth magnets (such as NdFeB and samarium cobalt magnets) have high remanence, large coercivity, and are not easy to demagnetize. They are the most common permanent magnets in tactile sensing.

Permanent magnets are simple to use, and the size and direction of the magnetic field can be flexibly adjusted through the placement of the permanent magnet. In 2019, Muhammad Rosle et al. studied the influence of the number and placement angle of cylindrical permanent magnets on a magnetic angle sensor [34]. They designed eight placement methods.

There are lots of designs that use permanent magnets to provide magnetic field [11][16][35][36][37][38][39]. Although permanent magnets are easy to use, they are generally large in size, which is not conducive to the miniaturization of devices. Furthermore, permanent magnets will change the elastic properties of materials, which is not friendly for the flexibility and wearability of devices. In addition, after repeated deformation, the connection position between the permanent magnet and the flexible material is easy to change irreversibly, resulting in the change of initial magnetic field and reducing the durability.

Because of simplicity and high magnetic strength, permanent magnets are the most common magnetic sources in magnetic tactile sensors. In the future, permanent magnets will still be the best choice for tactile sensors without high performance and volume requirements.

2.2. Permanent Magnetic Particle

In addition to permanent magnets, permanent magnetic particles can also be the source of magnetic field. Generally, the addition of permanent magnet blocks will reduce the flexibility of devices. Permanent magnetic particles can avoid this problem. The diameter of permanent magnetic particles can be as low as several microns or even several tens of nanometers [40][41]. As long as the volume ratio of flexible body and magnetic particles is well-controlled, the flexibility and magnetism of the sensitive structure can be well-combined. Magnetic particles are also very conducive to the miniaturization of devices, because the number of particles can be configured flexibly according to the size requirements of devices.

There are also many studies on tactile sensing with permanent magnet particles [25][42][43][44][45][46]. Especially in recent years, magnetic skin has been widely studied [47][48]. For instance, Tess Hellebrekers created a magnetic skin with a mixture of silicone and magnetic particles.

There are also a few problems in the application of magnetic particles. After mixing magnetic particles with elastomer, the magnetic field direction of magnetic particles is disordered. Therefore, it is necessary to magnetize the magnetic particles with a strong magnetic field. The magnetization process needs to be completed before the flexible structure is combined with the magnetic sensor, otherwise the strong magnetic field will damage the magnetic sensor. In addition, magnetic particles are prone to aggregation when mixed in the flexible body, resulting in an uneven distribution of the magnetic field. These problems introduce more complexity in the manufacturing of sensors. Despite all this, with the rapid development of flexible electronics, the advantages of easy combination with flexible materials and easy miniaturization means that magnetic particles have great potential in artificial skin and other related applications in the future.

2.3. Inverse Magnetostrictive Material

In addition to permanent magnetic materials, inverse magnetostrictive materials can also be applied to provide magnetic fields. For example, when a Fe-Ga alloy (Galfenol) deforms due to external force, the magnetic strength around the material will change. The magnitude of the external force can be converted by detecting this change with a magnetic sensor.

Michael Marana designed a flow and tactile sensor with Galfenol as the magnetic field source [49]. The change of magnetic field was detected by a GMR sensor placed around the Galfenol beam.

However, the inverse magnetostriction effect requires a permanent magnet to provide a bias magnetic field. Furthermore, for magnetostrictive elements, the length of the cantilevers needs to be large enough to provide sufficient sensitivity. In the future, the miniaturization of reverse magnetostrictive devices is the most important problem to be solved when they are used in tactile sensing technology.

2.4. Coil

Coil is one of the most primitive and simplest magnetic field generating devices. Its principle is Faraday's law of electromagnetic induction. Wattanasarn et al. proposed a three-dimensional magnetic tactile sensor with coils embedded in a flexible body.

The method of providing the magnetic field with coils is very simple, and the strength of the magnetic field can be flexibly adjusted. This is advantageous to improve the sensing range of the tactile sensor. However, there are also some problems of coils in tactile sensing. Firstly, to improve the performance, the size of the coils is often large, and an iron core is often needed. Therefore, the volume of the device is generally large. Secondly, compared with the permanent magnet, the coil needs continuous power supply when providing the magnetic field, so the power consumption of the device is very large. These problems hinder the application of coils in tactile sensing. Recently, micro-excitation coils have also been studied [50][51]. The application of micro-excitation coils to the magnetic tactile sensors can greatly reduce the size of tactile devices, which is worth further study in the future.

3. Structure of Sensitive Body

The structures of flexible sensitive bodies also play a great role in magnetic tactile sensors. The common structures are convex structure, film structure, and ciliary structure. Their characteristics are introduced respectively below.

3.1. Convex Structure

As previously mentioned, the convex structure is the most common tactile sensing structure. As shown in [5][6][10][35], the shapes of convex structures include hemispherical, pyramid, cylindrical and so on. Compared with the film structure, the convex structure has better detection ability for the tangential force in addition to the normal force. Therefore, it is more suitable for the detection of multi-dimensional tactile force. In addition, because a part of the convex structure is higher than the plane, it can detect more complex and diverse surfaces, including bulges, planes, and even depressions.

Some studies added air gaps in convex structures. Air gaps are very effective to reduce the Young's modulus of the sensitive structure, and help sensors get higher sensitivities. However, air gaps also make sensors easier to be saturated, resulting in a reduction in detection ranges. In practical applications, whether to use air gaps or not should be judged according to needs.

There are some problems in the application of convex structures. When many convex structures are combined to form a large area array, the surface of the array will be uneven, which cannot meet the high requirements for surface continuity and consistency of tactile skin. For example, for the same normal force, the signal output at gaps and vertices of convex structures is different. This makes it difficult to characterize objects with sharp or other complex structures.

3.2. Film Structure

Film structures are more suitable for large-area tactile sensing when combined with a sensor array. For example, Tito Tomo et al. proposed a tactile sensor with a simple film structure in 2016. There is a permanent magnet in the center of the film. This sensor can distinguish a minimum force of 10 mN. Later, they miniaturized the sensing structure and made it into an array. Then, they put the array on the finger muscle belly of a robot [52]. In 2017, they further applied this sensor array to robot fingertips, which brought the spatial integration of magnetic tactile sensors to a new level [8]. In addition to adding permanent magnets to the films, more studies used the method of adding magnet particles into the films,. This is advantageous for improving the flexibility and magnetic consistency of the device.

Decoupling the signals of normal force and tangential force is one of the difficulties in tactile sensing technology. At present, it is necessary to design complex sensing structures or use complex mathematical models to realize decoupling. In addition, decoupling and super-resolution detection cannot be achieved at the same time. To solve these problems, professor Shen Yajing cooperated with professor Pan Jia and proposed a new tactile sensor based on magnetic films [42].

Film structure is very suitable for large-area tactile sensing. Based on this, magnetic skin is a promising research direction of artificial skin. Large-area tactile sensing requires a large number of magnetic sensors to form an array, which has high requirements for the consistency and miniaturization of magnetic sensors. The fabrication of fully flexible magnetic sensors is also a problem that must be solved. Moreover, the increase in the number of sensors also means that the signal reading and anti-interference circuits become more complex, which reduces the portability and wearability of the tactile sensor.

3.3. Ciliary Structure

The ciliary structure is one of the most sensitive structures known in nature. It is often seen in the bodies of natural creatures, such as the side lines of fish, the hairs on spider feet, and the antennae of mosquitoes. The biological ciliary structure is mainly composed of two parts. One is a hairy structure that will deform under force, and the other is nerve cells that can feel this deformation. With the bionics of these ciliary structures, the application of ciliary structure is of great help to improve the detection ability of tactile sensors [53][54][55][56]. In recent years, researchers have combined ciliary structures with various sensors, including magnetic sensors.

Based on the same principle, Pedro Ribeiro conducted similar research [44]. PDMS was also used as the flexible material, but the source of the magnetic field was replaced by NdFeB magnetic particles. The magnetic strength of NdFeB particles is greater than that of Fe nanowires, so the sensitivity of the sensor is greater. The performance of this sensor is more excellent, and the minimum force of 333 μN can be distinguished. Furthermore, with a GMR sensor, in order to further improve the resolution of the device, Alfadhel Ahmed tested the performance of a single cilium [41]. The single cilium is able to distinguish a smaller force, which is as low as 31 μN.

Although ciliary structures have high sensitivity and are able to detect much smaller forces, there are still many problems to be solved. Firstly, the detection range is small, which is limited by the small Young's modulus of cilia. Secondly, the content of magnetic particles in cilia is very low, so the magnetic strength around cilia is similar or even smaller than that of the geomagnetic field. Therefore, the geomagnetic field cannot be simply treated as environmental noise. Generally, additional shielding devices or complex circuit processing are required. Thirdly, after long-term use, the cilia will be irreversibly tilted or damaged, which brings great challenges to the durability of the sensor. In addition, compared with normal force, cilia are more suitable for measuring tangential force. When the normal force acts on the cilia, the direction of cilia bending is random, and the linearity of the signal is poor. This leads to the complexity of signal extraction and processing.

4. Application

Magnetic tactile sensing technology is still immature, but it has been applied in some specific application areas. There are a number of studies that have tried various cutting-edge applications, mainly including robot precision grasping, texture characterization, flow velocity measurement, and medical treatment. These applications are summarized below.

4.1. Robot Precision Grasping

Tactile sensors can provide feedback signals for robots, and help robots realize precision operations such as grabbing fragile objects. In recent years, there have been many manipulators using magnetic sensors as tactile feedback elements [8][9][10][20][52][57]. For example, Alireza Mohammadi integrated multiple magnetic sensors with convex structures into a manipulator. When the manipulator grabs objects, the convex structures will squeeze. The permanent magnets in the convex structure are closer to the Hall sensor, thus generating the output signal. Such sensors can be installed in different positions of the manipulator according to requirements, such as fingertips, finger pulps, and palms. Different positions have different requirements for sensor structures. The fingertip generally requires a sensor with convex structures, while the finger pulps and palms generally require a sensor with film structures.

There are three main problems when integrating magnetic tactile sensors into manipulators. Firstly, magnetic sensors do not have the ability to sense force directly. They must be combined with magnetic materials to work. Therefore, the volume of magnetic tactile sensors is difficult to reduce, resulting in low sensing spatial resolution of manipulators. Secondly, for tactile manipulators, the magnetic sensors and actuators are all needed, and a large number of connecting wires are required, which make the manipulators very cumbersome. Thirdly, the mechanical structures and actuators of manipulators often contain ferromagnetic materials. The magnetic field produced by these devices is often difficult to shield and eliminate. When manipulators grab objects with ferromagnetic materials, there will also be interference signals.

4.2. Texture Characterization

Texture characterization can be applied in object state recognition, safety human–machine interaction, food safety, and other application areas. Current methods of texture characterization are mainly based on two principles: optics [58] and acoustics [59]. However, these methods often have low portability and high power consumption, so they are difficult to be integrated on robot platforms. The method based on the piezoelectric principle has also been studied, which is very promising. Topographical scanning capable of resolving features with 25 µm thickness have been reported [60].

In recent years, magnetic sensors have also been applied in texture characterization. Texture characterization has high requirements for the resolution of sensors, so the ciliary structure is often used.

4.3. Flow Velocity Measurement

In nature, a lot of organisms can sense the changes of external flow with the help of ciliary structures. For example, spiders can perceive changes in air flow by the ciliary structures on their legs, and fish can perceive the speed of water flow by their side lines. Similar to force, the flow of air or water will also lead to the bending of magnetic cilia. The flow velocity can be obtained by detecting the change of stray magnetic field with magnetic sensors.

For the detection of water flow velocity, the waterproofing of the device is very important. For piezoresistive or piezoelectric sensors, because current flows in the sensitive structure exposed to water, it can be easily damaged. Magnetic sensors can solve this problem. There is no current in the magnetic cilia, which is completely independent and separated from the magnetic sensor. In contrast, the magnetic sensor only needs to be completely sealed to be waterproof. In other words, the non-contact measurement ability of the magnetic sensor makes the waterproofing of the device very simple.

4.4. Medical Treatment

In medical treatments, several experimental explorations with magnetic tactile sensors have been carried out [61]. The most common way is to extract physiological signals with the sensors.

High-performance tactile sensors will play an important role in medical treatment in the future. The ciliary structure greatly improves the sensitivity of magnetic tactile sensors, which makes these sensors suitable for application in specific areas such as minimally invasive surgery. However, medical treatment has extremely high requirements for the reliability of devices.

References

1. Wei, R.; Guo, S.; Yang, S. Low-power CMOS integrated Hall switch sensor. Act. Passiv. Electron. Compon. 2017, 2017, 5375619.
2. Boero, G.; Demierre, M.; Popovic, R. Micro-Hall devices: Performance, technologies and applications. Sens. Actuators A Phys. 2003, 106, 314–320.
3. Torres-Jara, E.; Vasilescu, I.; Coral, R. A Soft Touch: Compliant Tactile Sensors for Sensitive Manipulation; Massachusetts Institude of Technology: Cambridge, MA, USA, 2006.
4. Ledermann, C.; Wirges, S.; Oertel, D.; Mende, M.; Woern, H. Tactile Sensor on a Magnetic Basis using novel 3D Hall sensor-First prototypes and results. In Proceedings of the 2013 IEEE 17th International Conference on Intelligent Engineering Systems (INES), San Jose, Costa Rica, 19–21 June 2013; pp. 55–60.
5. Wang, H.; De Boer, G.; Kow, J.; Alazmani, A.; Ghajari, M.; Hewson, R.; Culmer, P. Design methodology for magnetic field-based soft tri-axis tactile sensors. Sensors 2016, 16, 1356.
6. Wang, H.; De Boer, G.; Kow, J.; Ghajari, M.; Alazmani, A.; Hewson, R.; Culmer, P. A low-cost soft tactile sensing array using 3D Hall sensors. Procedia Eng. 2016, 168, 650–653.
7. Tomo, T.P.; Somlor, S.; Schmitz, A.; Jamone, L.; Huang, W.; Kristanto, H.; Sugano, S. Design and characterization of a three-axis hall effect-based soft skin sensor. Sensors 2016, 16, 491.
8. Tomo, T.P.; Schmitz, A.; Wong, W.K.; Kristanto, H.; Somlor, S.; Hwang, J.; Jamone, L.; Sugano, S. Covering a robot fingertip with uSkin: A soft electronic skin with distributed 3-axis force sensitive elements for robot hands. IEEE Robot. Autom. Lett. 2017, 3, 124–131.
9. Dwivedi, A.; Ramakrishnan, A.; Reddy, A.; Patel, K.; Ozel, S.; Onal, C. Design, modeling, and validation of a soft magnetic 3-D force sensor. IEEE Sens. J. 2018, 18, 3852–3863.
10. Mohammadi, A.; Xu, Y.; Tan, Y.; Choong, P.; Oetomo, D. Magnetic-based Soft Tactile Sensors with Deformable Continuous Force Transfer Medium for Resolving Contact Locations in Robotic Grasping and Manipulation. Sensors 2019, 19, 4925.
11. Becker, C.; Bao, B.; Karnaushenko, D.D.; Bandari, V.K.; Rivkin, B.; Li, Z.; Faghih, M.; Karnaushenko, D.; Schmidt, O.G. A new dimension for magnetosensitive e-skins: Active matrix integrated micro-origami sensor arrays. Nat. Commun. 2022, 13, 2121.
12. Baibich, M.N.; Broto, J.M.; Fert, A.F.; Nguyen, V.; Chazelas, J. Giant Magnetoresistance of (001)Fe/(001)Cr Magnetic Superlattices. Phys. Rev. Lett. 1988, 61, 2472–2475.
13. Binasch, G.; Grünberg, P.; Saurenbach, F.; Zinn, W. Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange. Phys. Rev. B 1989, 39, 4828.
14. Freitas, P.P.; Silva, F.; Oliveira, N.J.; Melo, L.V.; Costa, L.; Almeida, N. Spin valve sensors. Sens. Actuators A 2000, 81, 2–8.
15. Hirohata, A.; Yamada, K.; Nakatani, Y.; Prejbeanu, I.-L.; Diény, B.; Pirro, P.; Hillebrands, B. Review on spintronics: Principles and device applications. J. Magn. Magn. Mater. 2020, 509, 166711.
16. Goka, M.; Nakamoto, H.; Takenawa, S. A magnetic type tactile sensor by GMR elements and inductors. In Proceedings of the 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, Taipei, Taiwan, 18–22 October 2010; pp. 885–890.
17. Nakamoto, H.; Takenawa, S.; Kida, Y. Structure and fundamental evaluation of magnetic type tactile sensor. Int. J. Appl. Electromagn. Mech. 2012, 39, 1021–1026.
18. Nakamoto, H.; Goka, M.; Takenawa, S.; Kida, Y. Development of tactile sensor using magnetic elements. In Proceedings of the 2011 IEEE Workshop on Robotic Intelligence In Informationally Structured Space, Paris, France, 12–13 April 2011; pp. 37–42.
19. Nakamoto, H.; Wakabayashi, T.; Kobayashi, F.; Kojima, F. Estimation of displacement and rotation by magnetic tactile sensor using stepwise regression analysis. J. Sens. 2014, 2014, 459059.
20. Neto, M.; Ribeiro, P.; Nunes, R.; Jamone, L.; Bernardino, A.; Cardoso, S. A Soft Tactile Sensor Based on Magnetics and Hybrid Flexible-Rigid Electronics. Sensors 2021, 21, 5098.
21. Xue, L.; Zhang, D.; Chen, Q.; Rao, H.; Xu, P. Tactile sensor of hardness recognition based on magnetic anomaly detection. In Proceedings of the Young Scientists Forum 2017, Shanghai, China, 24–26 November 2017; pp. 607–616.
22. Hooge, F.N. 1/f noise sources. IEEE Trans. Electron Devices 1994, 41, 1926–1935.

23. Jiang, L.; Nowak, E.R.; Scott, P.E.; Johnson, J.; Slaughter, J.M.; Sun, J.J.; Dave, R.W. Low-frequency magnetic and resistance noise in magnetic tunnel junctions. Phys. Rev. B Condens. Matter 2004, 69, 054407.

24. Mohri, K.; Uchiyama, T.; Panina, L.V.; Yamamoto, M.; Bushida, K. Recent advances of amorphous wire CMOS IC magneto-impedance sensors: Innovative high-performance micromagnetic sensor chip. J. Sens. 2015, 2015, 718069.

25. Wu, Y.; Liu, Y.; Zhou, Y.; Man, Q.; Hu, C.; Asghar, W.; Li, F.; Yu, Z.; Shang, J.; Liu, G. A skin-inspired tactile sensor for smart prosthetics. Sci. Robot. 2018, 3, eaat0429.

26. Lei, J.; Lei, C.; Zhou, Y. Micro fluxgate sensor using solenoid coils fabricated by MEMS technology. Meas. Sci. Rev. 2012, 12, 286.

27. Schwindt, P.D.; Knappe, S.; Shah, V.; Hollberg, L.; Kitching, J.; Liew, L.-A.; Moreland, J. Chip-scale atomic magnetometer. Appl. Phys. Lett. 2004, 85, 6409–6411.

28. Sheng, D.; Perry, A.R.; Krzyzewski, S.P.; Geller, S.; Kitching, J.; Knappe, S. A microfabricated optically-pumped magnetic gradiometer. Appl. Phys. Lett. 2017, 110, 031106.

29. Drung, D. Recent low temperature SQUID developments. IEEE Trans. Appl. Supercond. 1994, 4, 121–127.

30. Guo, Q.-Y.; Ren, S.-Y.; Wang, J.-Y.; Li, Y.; Yao, Z.-Y.; Huang, H.; Gao, Z.-X.; Yang, S.-P. Low field nuclear magnetic sensing technology based on hydrogel-coated superparamagnetic particles. Anal. Chim. Acta 2020, 1094, 151–159.

31. Banerjee, H.; Suhail, M.; Ren, H. Hydrogel actuators and sensors for biomedical soft robots: Brief overview with impending challenges. Biomimetics 2018, 3, 15.

32. Thoniyot, P.; Tan, M.J.; Karim, A.A.; Young, D.J.; Loh, X.J. Nanoparticle–hydrogel composites: Concept, design, and applications of these promising, multi-functional materials. Adv. Sci. 2015, 2, 1400010.

33. Zhou, H.; Jin, Z.; Gao, Y.; Wu, P.; Lai, J.; Li, S.; Jin, X.; Liu, H.; Chen, W.; Wu, Y. Thermoresponsive, magnetic, adhesive and conductive nanocomposite hydrogels for wireless and non-contact flexible sensors. Colloids Surf. A Physicochem. Eng. Asp. 2022, 636, 128113.

34. Rosle, M.H.; Wang, Z.; Hirai, S. Geometry optimisation of a Hall-effect-based soft fingertip for estimating orientation of thin rectangular objects. Sensors 2019, 19, 4056.

35. Yu, P.; Qi, X.; Liu, W.; Fu, X. Development of a compliant magnetic 3-D tactile sensor with AMR elements. In Proceedings of the International Conference on Intelligent Robotics and Applications, Guangzhou, China, 17–20 December 2014; pp. 484–491.

36. Kim, S.-H.; Oh, S.; Kim, K.B.; Jung, Y.; Lim, H.; Cho, K.-J. Design of a bioinspired robotic hand: Magnetic synapse sensor integration for a robust remote tactile sensing. IEEE Robot. Autom. Lett. 2018, 3, 3545–3552.

37. Nakamoto, H.; Matsumoto, T. Tactile texture classification using magnetic tactile sensor. Int. J. Appl. Electromagn. Mech. 2016, 52, 1673–1679.

38. Weerasinghe, L.; Chathuranga, D.S. Development and characterization of a soft tactile sensor array used for parallel grippers. In Proceedings of the 2018 Moratuwa Engineering Research Conference (MERCon), Sri Lanka, 30 May–1 June 2018; pp. 102–107.

39. Chathuranga, D.S.; Wang, Z.; Noh, Y.; Nanayakkara, T.; Hirai, S. Magnetic and mechanical modeling of a soft three-axis force sensor. IEEE Sens. J. 2016, 16, 5298–5307.

40. Alfadhel, A.; Khan, M.A.; Cardoso, S.; Leitao, D.; Kosel, J. A magnetoresistive tactile sensor for harsh environment applications. Sensors 2016, 16, 650.

41. Alfadhel, A.; Khan, M.A.; Cardoso, S.; Kosel, J. A single magnetic nanocomposite cilia force sensor. In Proceedings of the 2016 IEEE Sensors Applications Symposium (SAS), Catania, Italy, 20–22 April 2016; pp. 1–4.

42. Yan, Y.; Hu, Z.; Yang, Z.; Yuan, W.; Song, C.; Pan, J.; Shen, Y. Soft magnetic skin for super-resolution tactile sensing with force self-decoupling. Sci. Robot. 2021, 6, eabc8801.

43. Park, J.J.; Reddy, K.S.M.; Stadler, B.; Flatau, A. Magnetostrictive Fe–Ga/Cu nanowires array With GMR sensor for sensing applied pressure. IEEE Sens. J. 2017, 17, 2015–2020.

44. Ribeiro, P.; Khan, M.A.; Alfadhel, A.; Kosel, J.; Franco, F.; Cardoso, S.; Bernardino, A.; Santos-Victor, J.; Jamone, L. A miniaturized force sensor based on hair-like flexible magnetized cylinders deposited over a giant magnetoresistive sensor. IEEE Trans. Magn. 2017, 53, 4700205.

45. Ribeiro, P.; Khan, M.A.; Alfadhel, A.; Kosel, J.; Franco, F.; Cardoso, S.; Bernardino, A.; Schmitz, A.; Santos-Victor, J.; Jamone, L. Bioinspired ciliary force sensor for robotic platforms. IEEE Robot. Autom. Lett. 2017, 2, 971–976.

46. Ge, J.; Wang, X.; Drack, M.; Volkov, O.; Liang, M.; Canon Bermudez, G.S.; Illing, R.; Wang, C.; Zhou, S.; Fassbender, J.; et al. A bimodal soft electronic skin for tactile and touchless interaction in real time. Nat. Commun. 2019, 10, 4405.

47. Kondo, M.; Melzer, M.; Karnaushenko, D.; Uemura, T.; Yoshimoto, S.; Akiyama, M.; Noda, Y.; Araki, T.; Schmidt, O.; Sekitani, T. Imperceptible magnetic sensor matrix system integrated with organic driver and amplifier circuits. Sci. Adv. 2020, 6, eaay6094.

48. Dahiya, R.S.; Mittendorfer, P.; Valle, M.; Cheng, G. Directions Toward Effective Utilization of Tactile Skin: A Review. IEEE Sens. J. 2013, 13, 4121–4138.

49. Marana, M.A. Development of a Bio-Inspired Magnetostrictive Flow and Tactile Sensor; University of Maryland: College Park, MD, USA, 2012.

50. Khalifa, A.; Zaeimbashi, M.; Zhou, T.X.; Abrishami, S.M.; Sun, N.; Park, S.; Šumarac, T.; Qu, J.; Zohar, I.; Yacoby, A. The development of microfabricated solenoids with magnetic cores for micromagnetic neural stimulation. Microsyst. Nanoeng. 2021, 7, 91.

51. Lee, J.-I.; Seist, R.; McInturff, S.; Lee, D.J.; Brown, M.C.; Stankovic, K.M.; Fried, S. Magnetic stimulation allows focal activation of the mouse cochlea. Elife 2022, 11, e76682.

52. Tomo, T.P.; Wong, W.K.; Schmitz, A.; Kristanto, H.; Sugano, S. A modular, distributed, soft, 3-axis sensor system for robot hands. In Proceedings of the 2016 IEEE-RAS 16th International Conference on Humanoid Robots (Humanoids), Cancun, Mexico, 15–17 November 2016.

53. Liu, C. Micromachined biomimetic artificial haircell sensors. Bioinspiration Biomim. 2007, 2, S162.

54. Timonen, J.V.; Johans, C.; Kontturi, K.; Walther, A.; Ikkala, O.; Ras, R.H. A facile template-free approach to magnetodriven, multifunctional artificial cilia. ACS Appl. Mater. Interfaces 2010, 2, 2226–2230.

55. Patanè, L.; Hellbach, S.; Krause, A.F.; Arena, P.; Dürr, V. An insect-inspired bionic sensor for tactile localization and material classification with state-dependent modulation. Front. Neurorobotics 2012, 6, 8.

56. Virta, A.; Timonen, J.V.; Ras, R.H.; Zhou, Q. Force sensing using artificial magnetic cilia. In Proceedings of the 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, Algarve, Portugal, 7–12 October 2012; pp. 1–6.

57. Youssefian, S.; Rahbar, N.; Torres-Jara, E. Contact behavior of soft spherical tactile sensors. IEEE Sens. J. 2013, 14, 1435–1442.

58. Yuan, W.; Dong, S.; Edward, A. GelSight: High-Resolution Robot Tactile Sensors for Estimating Geometry and Force. Sensors 2017, 17, 2762.

59. Hughes, D.; Correll, N. Texture recognition and localization in amorphous robotic skin. Bioinspiration Biomim. 2015, 10, 055002.

60. Yi, Z.; Zhang, Y.; Peters, J. Bioinspired tactile sensor for surface roughness discrimination. Sens. Actuators A Phys. 2017, 255, 46–53.

61. Chathuranga, D.S.; Wang, Z.; Noh, Y.; Nanayakkara, T.; Hirai, S. Disposable soft 3 axis force sensor for biomedical applications. In Proceedings of the 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Milan, Italy, 25–29 August 2015; pp. 5521–5524.