摘 要

基于鲑鱼微弱磁感知机理的仿生磁传感器研究

随着磁场应用的不断拓展，微弱磁场的检测与应用越发深入人们的生活。例如，地下 500m 的铁矿石探寻，地磁测量的辅助导航以及生物医疗的磁成像应用等等。微弱磁场检测对磁传感器性能提出了新的需求，市面上现有的磁传感器种类繁多，但都在弱磁检测方面存在一定的弊端，譬如高灵敏度与小体积无法兼顾、工作功率较大以及需要外接电源等等。这时，鲑鱼对微弱磁场的高敏感知能力给予研究者们新的灵感，探索鲑鱼微弱磁感知机理并设计制备出一款仿生磁传感器，拥有巨大的应用价值。因此，本文以鲑鱼为仿生模版，分析鲑鱼磁感知生物结构，建立鲑鱼磁感知机理模型，并以此为基础设计制备了仿生磁传感器。最后，对磁传感器进行性能指标测试，结合磁传感器各项优异性能，对其展开工程应用，主要研究工作如下：

（1）归纳鲑鱼微弱磁感知生物实验，分析鲑鱼微弱磁感知生物结构，总结出完整的鲑鱼磁感知生物过程。通过对生物机理进行简化与抽象，建立多层异质材料耦合结构的磁感知机理模型，分别模拟磁畴、中间介质与细胞膜。对模型进行有限元仿真，分析模型中重要参数对模型整体应力传导的影响，发现中间介质层的存在会降低应力传导效果，揭示了鲑鱼鼻腔处磁畴颗粒与细胞膜的直接耦合结构是鲑鱼拥有超高磁灵敏度的原因所在。在此基础上，对模型受力情况进行理论建模分析，并将理论计算值与有限元仿真进行趋势对比，进一步验证了模型的正确性，为仿生磁传感器的设计奠定了基础。

（2）以机理模型为基础，结合生物结构特征，设计了由 Terfenol-D 与 Ni 双层耦合构成的传感器磁敏部分，选取压电陶瓷（PZT）材料作为信号读出层，完成仿生磁传感器的制备。最后，对制备完成的磁传感器进行性能测试，实验结果显示，传感器灵敏度高达 10^{-9}T，输出线性度为 0.98，在连续 8 个小时的工作中保持平稳输出，具有良好的耐久性。仿生磁传感器还具有极佳的自偏置性，可以在零偏置处输出最大电压，完全摒弃了外部直流偏置磁场。

（3）结合仿生磁传感器无外接电源，平稳耐久且自偏置能力强等各项性能

优势，本文发现其在自供电领域拥有巨大的应用可能。又因为仿生磁传感器兼顾小体积与高灵敏度，再结合磁场本身的优异性能，本文将其应用于人体植入设备无线充电背景下，设计以仿生磁传感器为供能源的自供电储能系统。在系统中，为了及时知晓电池电量以便为电池充能，本文增添了以 CC2530 和 AT2401C 为核心的超低功耗 ZIGBEE 电压无线传输模块。最后，搭建磁场测试环境，对传感器及模块进行测试，验证其可行性。

综上所述，本文通过分析鲑鱼微弱磁感知生物结构，建立了多层异质材料耦合的磁感知机理模型，揭示了鲑鱼鼻腔处磁畴颗粒与细胞膜的直接耦合结构是鲑鱼拥有超高磁灵敏度的原因所在，并以此为基础完成仿生磁传感器的设计与制备。通过对磁传感器进行性能指标测试，验证了模型及传感器设计的正确性，并将传感器予以工程应用，为仿生磁传感器设计及磁传感器应用方面提供了新的思路。

关键词：

仿生学，鲑鱼，微弱磁感知，磁传感器，自供电

Abstract

Research on bionic magnetic sensor based on salmon weak magnetic sensing mechanism

With the continuous extension of the application of magnetic field, the detection and application of weak magnetic field are more and more deeply in people's life. Examples include the search for iron ore 500m underground, aided navigation for geomagnetic surveys, and magnetic imaging applications for biomedicine. Weak magnetic field detection has put forward new requirements for magnetic sensor performance. There are many kinds of magnetic sensors on the market, but they all have certain disadvantages in weak magnetic detection. For example, high sensitivity and small volume cannot be taken into account, large working power and the need for external power supply and so on. At this time, salmon's highly sensitive ability of weak magnetic field gives researchers new inspiration. To explore the mechanism of salmon's weak magnetic perception and design a bionic magnetic sensor, which has great application value. Therefore, this thesis takes salmon as a biomimetic template, analyzes the biological structure of salmon magnetic perception, establishes the mechanism model of salmon magnetic perception, and designs and prepares biomimetic magnetic sensor based on it. Finally, the performance index of the magnetic sensor is tested. Combined with the excellent performance of the magnetic sensor, the engineering application is carried out. The main research work is as follows:

(1) The biological experiment of salmon weak magnetic perception was concluded, the biological structure of salmon weak magnetic perception was analyzed, and the complete biological process of salmon magnetic perception was elaborated. By simplifying and abstracting the biological mechanism, the magnetic sensing mechanism model of multi-layer heterogeneous material coupling structure is established, and the magnetic domain, intermediate medium and cell membrane are simulated respectively. The finite element simulation was carried out to analyze the influence of important

parameters on the overall stress conduction of the model, and it was found that the presence of the medium layer would reduce the stress conduction effect, which revealed that the direct coupling structure between the magnetic domain particles and the cell membrane in the nasal cavity of salmon is the reason for the ultra-high magnetic sensitivity of salmon. On this basis, theoretical modeling analysis was carried out on the force of the model, and the theoretical calculation value was compared with the trend of the finite element simulation, which further verified the correctness of the model and laid the foundation for the design of the bionic magnetic sensor.

(2) Based on the mechanism model and combined with the characteristics of biological structure, the magnetic sensitive part of the sensor composed of Terfenol-D and Ni was designed. The Piezoelectric ceramics (PZT) material was selected as the signal reading layer to complete the preparation of the bionic magnetic sensor. Finally, the performance of the prepared magnetic sensor is tested. The experimental results show that the sensor sensitivity is as high as 10^{-9}T, and the output linearity is 0.98. The sensor can maintain a stable output in continuous 8 hours of work, and has good durability. Bionic magnetic sensor also has excellent self-bias, can output the maximum voltage at zero bias, completely abandon the external DC bias magnetic field.

(3) Combined with the performance advantages of bionic magnetic sensor, such as no external power supply, stable, durability and strong self-bias ability, this thesis finds that it has a huge application possibility in the field of self-power supply. Because the bionic magnetic sensor combines small size with high sensitivity, combined with the excellent performance of magnetic field itself, this thesis applies it in the background of wireless charging of human implant devices, and designs a self-powered charging system with bionic magnetic sensor as energy supply. In the system, in order to know the battery power in time so as to charge the battery, this thesis adds an ultra-low power ZIGBEE voltage wireless transmission module with CC2530 and AT2401C as the core. Finally, the magnetic field environment is built to test the sensor and module to verify its feasibility.

In summary, by analyzing the magnetic sensing biological structure of salmon, a magnetic sensing mechanism model of multi-layer heterogeneous material coupling was established in this thesis, and the direct coupling structure between the magnetic domain particles and the cell membrane in the nasal cavity of salmon was revealed to be the reason why salmon has ultra-high magnetic sensitivity. Based on this, the bionic magnetic sensor was designed and prepared. The correctness of the model and sensor design is verified by testing the performance index of the magnetic sensor, and the sensor is applied in engineering, which provides a new idea for the design and application of the bionic magnetic sensor.

Keywords:

Bionics, salmon, weak magnetic sensing, magnetic sensor, self-power

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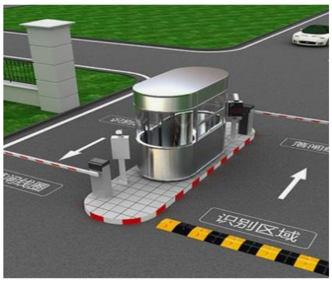
第1章 绪论

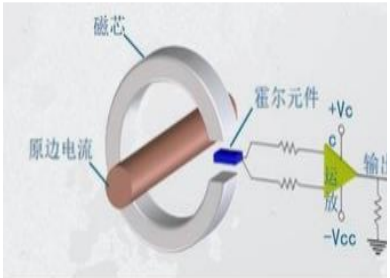
1.1 研究背景及意义

随着磁场应用的不断拓展，在人类科技与生活中的许多领域都涉及到磁场的测量与检测[1]。其中，磁感应强度作为磁场中最重要的物理量之一，磁场强度的感知测量在磁场应用中扮演着越发重要的角色。如图 1.1 所示，在中、强磁场测量领域，磁强度感知可用于智能停车场的车辆状态检测[2]、家电的开关门检测以及电机的电流转矩检测[3]等等。由于科技发展的需求加深，微弱磁场检测在许多应用层面发挥着更为重要的作用。在地底矿物检测方面，我国早已提出“立足国内，找矿增储”的战略意见，人们需要在地下 500m 处探寻铁矿石的所在[4]；在地磁检测方面，需要精准测量微弱的地磁场，构建地磁图用于船只在远海端的辅助导航[5]；在生物医疗方面，往往也需要检测极弱磁场，用于脑磁图和心磁图的成像应用[6,7]。目前弱磁检测技术主要是伴随着磁传感器的发展而发展的[8]，但现有的磁传感器在体积、灵敏度与使用条件等方面都具有一定的短板。因此，设计制备一款性能更为优越的新式磁传感器将进一步推动微弱磁场应用领域的发展。



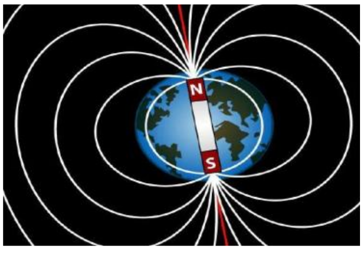
(a)智能停车场

(b)家电磁吸门

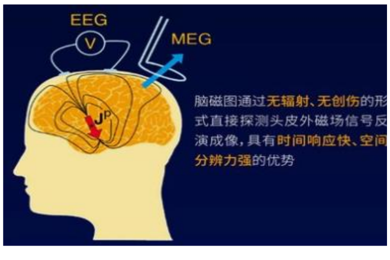


(c)电流转矩检测

(d)地底铁矿检测



(e)地磁检测



(f)生物医疗成像

图 1.1 磁场检测与应用

自然界中的生物在微弱磁场检测方面给予新的灵感与思考，许多生物都可以感知微弱的地磁强度变化，如图 1.2 所示。例如，鸟类中的北极燕鸥[9]与海鸟[10]，可以依靠感知地磁强度变化，飞行数百公里找到其繁殖地所在；昆虫中的黑脉金斑蝶[11]与博宫蛾[12]，通过感知不同地点地磁场强度的微弱差异，以此找到某一处特定的树林或洞穴；海洋鱼类中的珊瑚鱼[13,14]与鲑鱼[15]亦是如此，它们可以不受海洋洋流的影响，依靠感知地磁强度找到自己的出生地点。在这些磁感生物中，鲑鱼为其中最具代表性的生物。鲑鱼有着极其精确的地磁感知能力，它们通过感知入河口与海峡口之间微弱的地磁强度差异（10^{-7}T），可以从数十个入河口中找到唯一的出生地入河口[16]，整个过程的精确性与稳定性令人叹为观止。若能揭示鲑鱼弱磁感知机理并设计制备出一款仿生磁传感器，将会产生巨大的应用价值。

(a) 北极燕鸥

(b) 海鸟

(c) 黑脉金斑蝶

(d) 博宫蛾

(e) 鲑鱼

(f) 珊瑚鱼

图 1.2 拥有磁感能力的生物