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Designing, Fabricating, and Analyzing the Whisker Sensor for Autonomous Surface Defect Detection

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Abstract:

This paper presents a new bioinspired whisker sensor system tailored for surface defect detection. A rotational whisker sensor is designed and installed on a homemade wheeled robot, enabling active detection across a wide area. The sensor array is made of carbon fibers reinforced with polyepoxides and controlled by an ESP8266 microcontroller via Wi-Fi. The simulation investigation using Sim-Scape software indicates that adjusting dynamic parameters like frequency and response speed improves sensor performance. The study proposes that this approach proves effective in identifying surface anomaly, especially in noisy conditions.

Keywords: Whisker Sensor, Simulation, Autonomous Robot, Surface Defect, Frequency response.

Introduction

Drawing inspiration from nature's tactile systems has led to significant advancements in sensing technology and haptic feedback [1]. Whisker sensor technology, inspired by the tactile hairs of mammals, has emerged as a valuable addition to conventional optical and acoustic sensors [2]. These sensors are used in a variety of applications, ranging from obstacle avoidance to map reconstruction [2]. The Whisker sensor can be classified into different types based on their sensing principles, which include optical whisker sensors, magnetic whisker sensors, resistive whisker sensors, and piezoelectric whisker sensors [2-3]. Among these, magnetic whisker sensors, utilizing Hall sensors, stand out for their multidimensional capabilities, robust environmental adaptability, and high resolution [2]. In this context, a new whisker-based sensor system has been developed, integrated into an autonomous robot, enabling the detection of surface anomalies.

Material and Methods

In this section, the mechanical design and electronic configuration of the autonomous robot are initially described, followed by a discussion of sensor design and simulation procedure.

To accurately detect the shape of surface defects, a foundational robot capable of scanning in the XY plane is essential. In this context, a four-wheel robot was designed and fabricated inspired by the Geneva wheel concept. At the forefront, a rotor was intricately connected to a gear-like structure, enabling it to rotate smoothly via a DC stepper motor (Modelcraft RB350018). The integration of the L298N dual H-bridge motor driver ensured precise motor control, facilitating accurate positioning of the measurement unit. Speed regulation was achieved through an Arduino UNO controller in conjunction with a digital rotary encoder (KY04RE). The final design enables movement along both the X and Y axes, as well as angular movement around these axes, mimicking the behavior of active whiskers in animals. The whole system, including the sensor, was depicted in Fig. 1.

Various materials, including carbon fibers, spring steel, and polymers, were investigated in the literature for whisker sensor fabrication [2]. Carbon fibers reinforced with polyepoxides, with diameters of 0.28mm and 0.5mm, were selected for this study based on elasticity properties. As depicted in Fig. 1, a rotational sensor array was designed to provide convenient speed control compared to a linear array. This system included four whiskers attached to a holder 3D-printed adapter. Indirect whisker movement measurement was achieved using a digital three-axis IMU sensor (Melexis MLX90393 Triaxis), calibrated using Magneto software.

Simulation and modeling of the whisker array were conducted using Sim-Scape software. When the whisker makes contact with a surface, the resulting force is transmitted to a beam, which is excited until force equilibrium is achieved. The position of the whisker tip can then be calculated based on the position of the beam's end. Taking into account the deflection of the whisker, which is assumed to be small, Euler-Bernoulli beam theory for a cantilever beam with an end load can be applied.

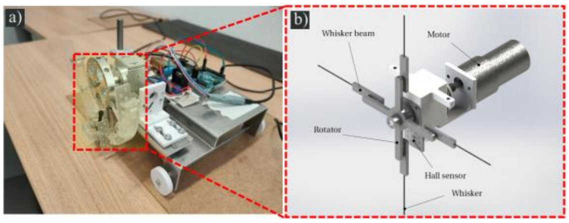

Fig. 1. a) Whisker-based surface monitoring robot, b) Schematic of sensor configuration.

Result and Discussion

Fig. 2 illustrates a spike in the whisker sensor signal occurring at 0.75S, when the surface is touched at low rotation speed. As the Whisker moves across the surface, it bends, storing energy in the spring as E = k * ϕ, with ϕ representing the angle. Upon leaving the surface, this stored energy is released, leading to oscillation and explaining the spikes observed in Fig. 2. Conversely, if the surface has a defect causing temporary loss of contact, this oscillation occurs earlier and can be detected via signal processing. Understanding dynamics behaviour is crucial for accurately detecting surface defect shape and dimensions, which can be facilitated by simulation studies.

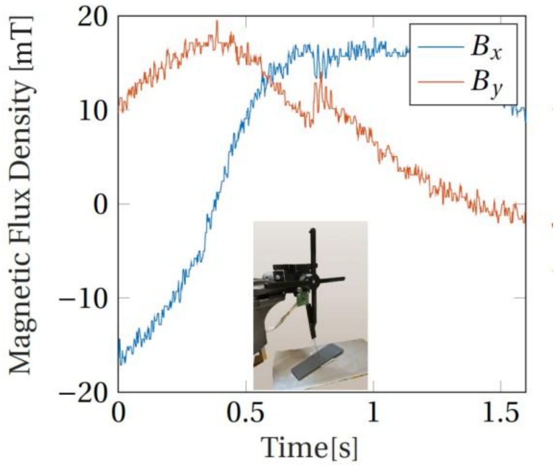

Fig. 2. a) Magnetic flux density of a moving whisker over the surface, with an inset showing the measurement apparatus.

The simulation has been conducted by moving the whisker across various surfaces. As illustrated in Fig. 3, surface irregularities cause vibrations in the whisker sensor, which can be reasonably approximated. However, as shown in the inset of Fig. 3, calibrating the frequency significantly impacts sensor performance. When the speed doesn't match properly, the whisker loses contact with the surface repeatedly, hindering the ability to gather information about the surface. One potential solution is to increase the natural frequency of the whisker system by optimizing sensor parameters such as elasticity, length, and diameter.

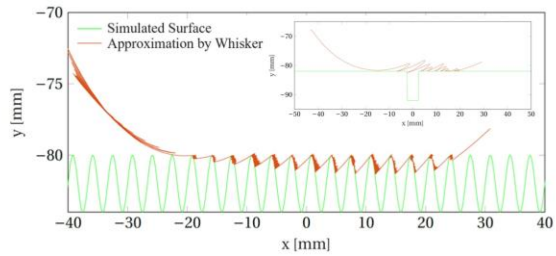

Fig. 3. Simulation results for detecting surface defects at low frequency (0.1 Hz), with an inset depicting sensor behavior at a higher frequency (1.6 Hz).

Conclusions

In this study, the capability of a whisker sensor for surface defect monitoring was investigated through simulation and experimental tests. A wheel explorer robot equipped with a custom hall-based whisker sensor was designed and fabricated for this purpose. The robot was operated through a Wi-Fi connection by an ESP8266 microcontroller. The rotational sensor array was constructed from carbon fibers reinforced with polyepoxides. Indirect measurement of whisker movement was accomplished using a digital three-axis IMU sensor (Melexis MLX90393), calibrated with Magneto software. Whisker array simulation was carried out using Sim-Scape software across various virtual surfaces. Results from both experimental tests and simulations suggest that the rotational whisker sensor shows promise for non-invasive surface monitoring applications, particularly in noisy open-air environments. Nevertheless, aspects such as whisker mechanical properties, resolution, and durability require further investigation, which can be pursued in future research.

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