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A precise embedded curvature sensor module for soft-bodied robots

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ABSTRACT

As an emerging field, soft-bodied robots require profoundly different approaches to sensing and actuation compared to their rigid-bodied counterparts. Electro-mechanical design, fabrication, and operational challenges due to material elasticity significantly complicate embedded, modular and precise proprioceptive feedback. This work presents a novel curvature sensor module to address the unique soft robotic specifications. The proposed device utilizes a magnet and an electronic Hall effect sensing component to accurately measure curvatures on a soft-bodied bending segment on a flexible circuit board, ensuring contact-free sensing. We verify performance of sensor modules on static and dynamic bending deformations based on a single initial calibration step. To the best of our knowledge, the presented device is the first modular and integrated soft-bodied sensor design that is demonstrated to be accurate up to 7.5 Hz with a root mean square error of 0.023 cm^{-1} between measured and actual curvature without filtering out the intrinsic noise, and available for use with soft-bodied kinematic bending chains.

1. Introduction

Obtaining kinematic configuration information of soft bodied robots is one of the current challenges in the field. The traditional approach to determine the configuration of a rigid kinematic chain is to obtain discrete angle measurements from each joint. In contrast, soft bodied robots possess infinitely many passive degrees of freedom [1,2] as a result of continuously deformable segmented bodies [3,4], emphasizing the need for new sensing techniques. Our research problem in this paper is to explore the capabilities of a novel embedded soft curvature sensor designed to capture configuration information from soft robotic bending segments.

The emerging field of soft robotics suffers from a lack of modeling and control efforts for both kinematic configuration and dynamic properties. We believe soft manipulators and soft-bodied mobile robots [5–9] can expand their capabilities through accurate models, and corresponding feedback controllers. Our approach to modeling the configuration of a soft robot is based on defining the bending deformation of soft segments as curvatures [4,10,11] instead of discrete angles. Thus, the orientation and position of every point on a continuously deformable segment is uniquely defined with respect to its curvature. Robot configuration is then modeled as a kinematic chain of segments, where each segment is defined by a single curvature value. In prior work, we were able to model and reproduce lateral undulation for a soft robotic snake comprising four soft bidirectional bending segments [4,10]. This approach requires us to sensorize a soft body for implementation and this is the main motivation behind our curvature sensors.

This work details the design, fabrication, and experimental verification of a soft curvature sensor comprising a miniature magnet and a Hall effect measurement integrated circuit (IC). The magnet is positioned in a specific way with respect to the Hall element on a flexible circuit (see Fig. 1) to measure the curvature of bidirectional out-of-plane deformations in a standalone package, without the need for external electronics. This is a versatile approach, which can be adapted to measure other physical deformations in a soft body. For example, a setup consisting of a magnet mounted over a Hall effect sensing component can be used for measuring normal forces. In this work, we are limiting our attention to curvature sensing due to its practical applications on our soft robotic snake [4,10].

Hall elements are compact, accessible, and inexpensive. The quick response and accuracy of Hall elements for traditional robotic applications have previously been verified for joint angle proprioception [12,13] as well as tactile exteroception [14,15]. Contact-free sensing capabilities are highly desired for soft robotic research [16]. Thus, a unique advantage of our non-contact magnetic field measurement approach is its negligible effect on material stiffness.

Alternative solutions to curvature sensing include commercial resistive flex sensors, optical fiber Bragg gratings, and embedded liquid metals. Resistive flex sensors offer a simple and compact solution for embedded sensing in soft robotics. Nevertheless, we

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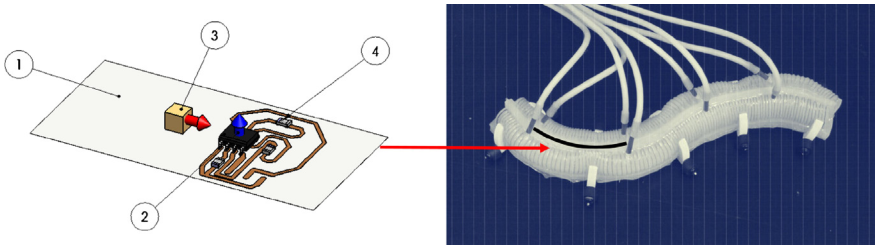

Fig. 1. Left: Computer aided design of the sensor assembly is shown. Number definitions: (1) flexible substrate, (2) Hall effect IC, (3) magnet, (4) circuit paths and components. Red and blue arrows indicate horizontal (x-axis) and vertical (y-axis) directions respectively. Right: The sensor is built to be integrated in the middle of the soft snake robot for proprioceptive curvature measurements. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

concluded in a preliminary study (reported elsewhere) that they suffer from dynamic artifacts, such as delayed response and drift.

Optical fiber Bragg grating is a powerful sensing solution for deformable bodies used successfully for force measurements on a soft finger [17], and shape reconstruction [18]. Although this technology facilitates highly accurate curvature measurements using a thin and flexible optical fiber, the required supporting hardware disables embedded operation, especially for tetherless mobile robots with many degrees of freedom.

A novel and specialized sensor technology for soft robots is the use of liquid metals embedded in rubbers, a technology stemming from mercury-in-rubber strain gauges from 1960s [19]. Thus, dimensional changes due to deformations in the substrate are reflected as resistance changes by the liquid metal. Recent work incorporates fluidic channels inside silicone rubber filled with eutectic Gallium–Indium (eGaIn) to measure joint angles of a finger [20] and for a tactile sensing array [21]. A short survey on sensors built with eGaIn is given in [22]. An interesting work that applies eGaIn sensors to a suit for gait detection is presented in [23]. Main limitation of eGaIn sensor is a relatively complicated fabrication phase. They require a 3D mold with channels. Afterwards eGaIn is injected from one side of the mold while air inside the channels is vacuumed from the other side. Thus, repeatability and complexity in manufacturing these sensors may be a challenge.

To address the fundamental challenge of providing accurate and dynamic proprioceptive feedback for soft-bodied robots, this work proposes a novel soft curvature sensor, based on the state of the art in flexible sensing technologies. Specific contributions of this work are as follows:

- Robust and precise curvature feedback with rapid response for soft-bodied robots.
- Integrated measurement of kinematic configuration for soft-bodied arms and mobile robots composed of soft bending segments.
- A custom test platform for soft-bodied curvature sensors.

The following section explains the fundamentals of design, modeling, and fabrication. We provide detailed information on positioning of the magnet-sensor pair, design specifications, and manufacturing steps. We present results of numerically simulating the sensor response to different curvatures. Simulation results inform the positioning of discrete elements, gain and offset adjustment.

We also present a test platform to repeatably characterize and verify our soft curvature sensors under static and dynamic loading conditions. Section 3 displays and discusses results obtained from the proposed curvature sensor using the custom test platform, reporting experimental results on calibration, repeatability, as well as static and dynamic verification of the proposed soft curvature sensors.

2. Methods

2.1. Curvature sensor design

The main requirements for a curvature sensor for soft robotics are flexibility and minimal effect to material stiffness. Along with structural specifications, accurate, precise and fast responses are also required for feedback control applications based on proprioceptive curvature sensing.

We adopt locomotion parameters of a soft-bodied snake robot [4] as another set of design specifications to achieve an embedded curvature sensing module that is consistent and compatible with the literature. The soft robotic snake deforms between 0.2 cm^{-1} and 0.4 cm^{-1} and the frequency of traveling curvature waves to achieve undulatory locomotion is between around 2 Hz. Thus, a curvature sensor working at frequencies above around 3 Hz without dynamic attenuation is expected to provide accurate reconstruction of the robot configuration.

An accurate mapping is required to convert measurements to curvature values. Two desired properties of the calibration function are linearity and injectivity. To show that such a mapping exists, we developed a simulation platform that considers both finite element analysis of a magnet and its theoretical model. Once the sensor is calibrated and a mapping is obtained, curvature measurements are absolute (i.e. not subject to initial conditions or temporal variations).

Theoretical modeling of magnetic flux density vectors around a magnet provides intuition on the curvature sensor response. A simple dipole model of magnetism approximates these vectors, but it does not include volumetric constraints. A more accurate 2D analytical model of a rectangular magnet is derived in [24]. According to this model, the Cartesian magnetic field vector components in the magnet frame can be written as:

$$B_x(x,y) = \frac{\mu_0 M_s}{2\pi}\left(\arctan\frac{2h(x+w)}{(x+w)^2+y^2-h^2} - \arctan\frac{2h(x-w)}{(x-w)^2+y^2-h^2}\right), \tag{1}$$

$$B_y(x,y) = \frac{\mu_0 M_s}{4\pi}\left(\ln\frac{(x+w)^2+(y-h)^2}{(x+w)^2+(y+h)^2} - \ln\frac{(x-w)^2+(y-h)^2}{(x-w)^2+(y+h)^2}\right). \tag{2}$$

In the equations above, B_x and B_y are magnetic flux density vector components in different (x, y) positions with respect to the magnet. The coordinates and the origin of the frame, in which equations are defined, can be seen in Fig. 2. X-axis and Y-axis are parallel to horizontal and vertical lines respectively, and origin of the magnet frame is attached to the middle of the cube magnet. μ_0 is the relative magnetic permeability of the medium. M_x is the surface