

Tilt Sensors Induced by Liquid Metal Dynamic Motion in a Switchgrass-Molded Anisotropic Microcone: Materials, Sensors, and Equipment

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Cite This: *Langmuir* 2025, 41, 19845–19853



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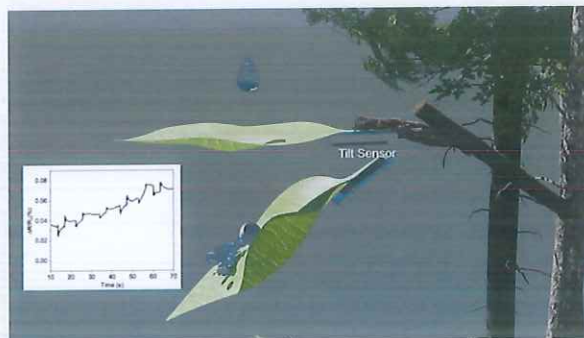


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ABSTRACT: Owing to the requirement for precise measurement of angular displacement across various industries, the development of tilt sensors has garnered significant attention in both academia and industry. Nevertheless, most current tilt sensors face challenges, such as mechanical friction and wear, complex structures, and high manufacturing costs. Here, a novel tilt sensor was designed by encapsulating based on Ga-based liquid metal in a nature-inspired capillary tube with an anisotropic microcone array. In the measurement range from -90° to 90° , the sensor exhibits a linear relationship with the inclination angle and features high resolution (0.1°) as well as ease of implementation. Leveraging these advantages, it can be employed to monitor changes in the leaves angle, stability of equipment, language programming, and surface topography of the scanning system, which is expected to have great potential applications in the agricultural and forestry industries as well as in mechanical manufacturing.



1. INTRODUCTION

The tilt sensor is a device designed to measure angular displacement or changes in angle, enabling the detection of rotational motion. It can be widely applied to accurately measure the angular change of an object relative to the horizontal or vertical plane and serves as a critical component for achieving equipment attitude monitoring, control, and stability.^{1–6} At the same time, it plays a positive role in various fields, such as drone flight attitude control, human body attitude monitoring, the automobile industry, the medical rehabilitation industry, robot technology, and so on, demonstrating significant research potential.^{7,8} Current angle sensors include traditional mechanical tilt sensors,^{9–18} optical tilt sensors, and magnetic tilt sensors.¹⁹ Notably, while these tilt sensors have made substantial contributions in their respective domains, they still encounter challenges such as mechanical friction and wear, complex structures, and high costs.^{20,21} To align with the trend of miniaturization, there is an urgent need to develop a new type of tilt sensor that is easy to manufacture and has low production costs, high resolution, low power consumption, strong stability, and fast response speed.²²

In recent years, owing to its excellent ductility, high conductivity, and recyclability, liquid metal (LM) has attracted researchers' attention for sensor development.^{23–33} Previously, mercury was employed as a replacement for the conductive

solution in traditional liquid pendulum inclinometers, which successfully reduced the overall size and enhanced the resolution. However, due to its toxicity, mercury-based designs have been phased out of the market.³⁴ In contrast, Ga-based LM, as a nontoxic alloy, demonstrates superior fluidity, low toxicity, and excellent conductive properties, making it highly promising for tilt sensor applications.³⁵ In this study, leveraging the wetting characteristics of the Ga-based LM, a tilt sensor with a new working mechanism was obtained. This design effectively suppresses hysteresis, achieves fast response and accurate tilt angle detection, exhibits good durability and a long service life, and possesses the advantages of low cost and ease of preparation.

2. EXPERIMENTAL SECTION

2.1. Tilt Sensor Sample Preparation. Switchgrass plants were obtained from the natural environment, and a small stem was selected and placed in polydimethylsiloxane (PDMS, DOW CORNING SYLGARD 184). PDMS and its cured agent was mixed with weight

Received: April 8, 2025
Revised: June 22, 2025
Accepted: July 22, 2025
Published: July 28, 2025

