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Plant Growth Monitoring Using Electromechanical Sensors

Benjamin Lehner[1], Alexander Stoiber[1], Florian Bauernfeind[1], Florian Stöger[1], and Gerda Buchberger[1]
[1] Institute of Biomedical Mechatronics, Johannes Kepler University (JKU) Linz, Altenberger Str. 69, 4040 Linz, Austria
gerda.buchberger@jku.at

Summary:
This work presents proofs-of-concept (POCs) of two types of electromechanical sensors that record changes in plant length. The first one consists of an extensible solenoid with a cast iron core and possesses a length-dependent inductance. The second one is a highly stretchable resistor made from an elastomer and compliant electrodes. Both sensor principles were applied successfully to pea plants. They have potential applications in agriculture, market gardening, forestry, and vertical farming.

Keywords: plant growth monitoring, wearable, electromechanical sensor, stretchable sensor, extensible solenoid

Background, Motivation, and Objective

Flexible plant-wearable sensors show great potential for precise and intelligent monitoring of real-time physical and chemical signals in forestry seedlings [1]. They are also an emerging data collection tool for plant phenotyping in general [2].

Description of the New Method or System

We present two types of electromechanical sensor proofs-of-concept (POCs) for plant growth monitoring in the millimeter range. The first one consists of a solenoid with a core of cast iron that changes its inductance when extended (Fig. 1a). The second type of POCs was manufactured from an elastomer and compliant electrodes of carbon black particles. The resistances of these POCs change with elongation (Fig. 1b).

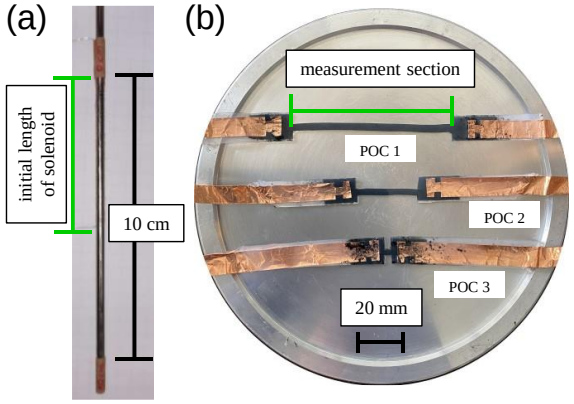

Fig. 1. Proofs-of-concept of electromechanical sensors. (a) Self-wound extensible solenoid. (b) Stretchable resistors made from silicone rubber with compliant carbon black particle electrodes.

The extensible solenoid was manufactured using a Ni/Fe 60/40 core with a diameter of 3.2 mm (VDB-Schweißtechnik NIFE 60/40 WIG Schweißstäbe Gußeisen) and enamelled copper wire with a diameter of 0.1 mm (Block-Trafo Dreifach isolierter Kupferdraht, FA-Nr.: 310863) by chucking the cylindrical core into a handheld drill and simultaneously guiding the wire by hand. It possessed approximately 80 windings. For the stretchable resistors, an Ecoflex/carbon black/Ecoflex sandwich structure was employed. To this end, parts A and B from the silicone rubber Ecoflex 0035/1 from Smooth-on were mixed in a 1:1 weight ratio. The entrapped air bubbles were removed using a vacuum chamber. The silicone mixture was cast onto an aluminium plate. Then carbon black particles (Carbon black ≥99%, metals basis, Super P® Conductive from Thermo Fisher Scientific) were applied using brushes and paper templates. At the ends, adhesive copper tape was placed on top of the carbon black. To protect the electrodes, a second layer of Ecoflex was poured onto the configuration. Last, the POCs were cut out using a scalpel, and the widths of the measurement sections were reduced during this processing step.

Results

The solenoid was characterized by measuring the root-mean-square voltage signals versus the length of the (extended) solenoid (Fig. 2); the measurement data were fitted with a 4th-degree polynomial function. The measurements were conducted using a peak-peak supply voltage of 5 V with a frequency of 5 MHz and a resistor of 38.3 Ω in a high-pass configuration.

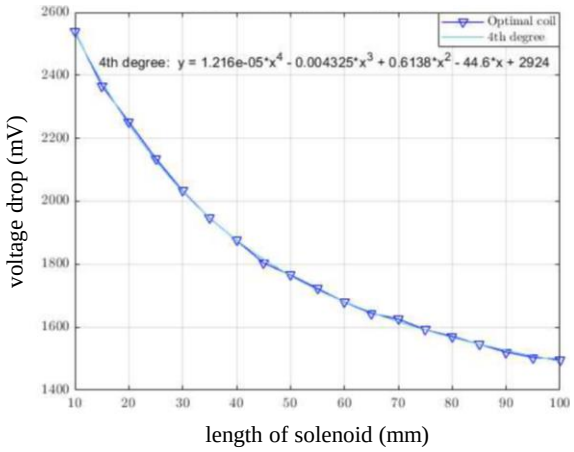

Fig. 2. Characterization of the extensible solenoid. The graph shows the voltage drop at the solenoid versus the length of the solenoid.

Furthermore, the resistances of the POCs made from silicone rubber and carbon black electrodes were recorded under elongation using a digital multimeter.

For growth monitoring of pea plants, the iron core was stuck into the earth next to the plant and the top of the extensible solenoid was wound around the top of the plant (Fig. 3a). The stretchable resistor was plugged through the holes at the bottom of the pot and clamped between the two bifurcating top twigs of the pea plant (Fig. 3b).

Using the manufactured POCs, the heights of pea plants were measured over a time period of one week (Fig. 4). For the extensible solenoid, the measured and calculated heights were in good agreement (Fig. 4a). The measurement section of the stretchable resistor (Fig. 1b) had an initial length of 50 mm, an initial width of 1 mm, and an initial thickness of 2 mm. The outer sections at the ends of the sensor were 10 mm wide.

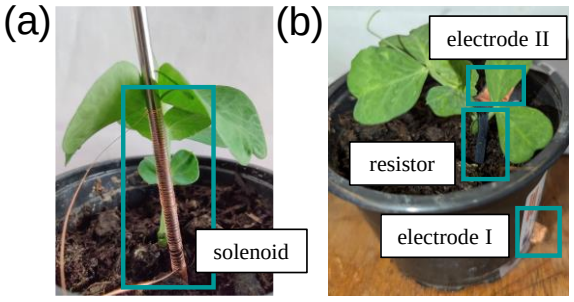

Fig. 3. Attachment of the POCs for plant growth monitoring. (a) Extensible solenoid with an iron core. (b) Stretchable resistor. The electromechanical sensor POCs are highlighted with green rectangles.

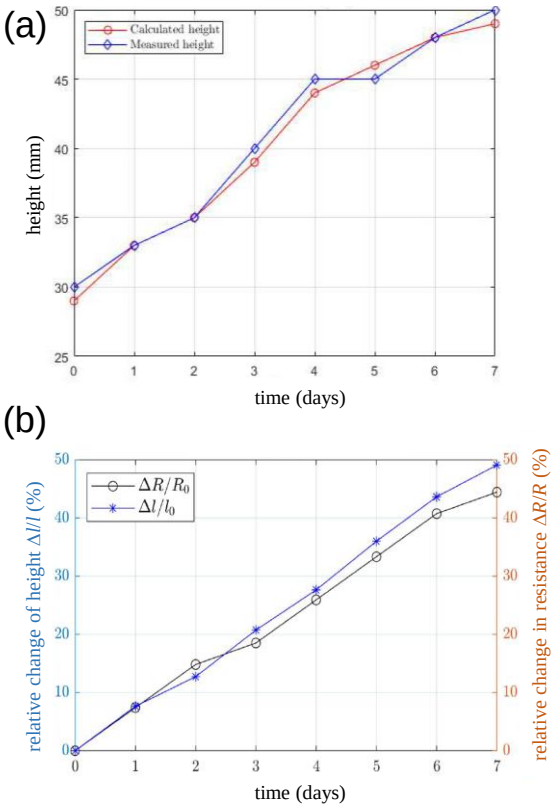

Fig. 4. The electromechanical sensors were applied to pea plants for growth monitoring. (a) The height calculated from the measured voltage drop at the solenoid is in good agreement with the measured height of the pea plant. (b) The relative change in resistance of the silicone rubber-carbon black sandwich sensor correlates well with the relative change in pea plant height.

The stretchable resistor had a resistance of 136 kΩ in the unmounted configuration. In the pre-stretched mounted configuration on a plant with an initial height of 27 mm, the resistance was 275 kΩ. The relative resistance changed approximately linearly with the relative change of plant height (Fig. 4b).

References

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