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Design of a Cuff Electrode - Inspired Wearable Bioimpedance Plant Sensor

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***Abstract*—In this study, we introduce a novel tomato plant "wearable" bioimpedance sensor design inspired by neuroprostheses. The design involves a robustly closing asymmetric tetrapolar cuff electrode to monitor hydration related bioimpedance. The aim of the design is to achieve optimal performance, ease of installation, durability, and cost-effectiveness. In the initial stages of this research, we elucidate our design methodology, utilizing COMSOL FEM simulations to define the optimal cuff geometry with an emphasis on the significance of tight closure. Additionally, we present the fabrication of initial dummy electrodes using a standard flexible PCB process, introducing a novel "serrated cable-tie" design feature to achieve tight closure around the plant stem or branch.**

***Index Terms*—plant sensor, plant wearable, bioimpedance, impedance, tetrapolar, cuff electrode, cable-tie cuff, flexible PCB.**

I. INTRODUCTION

In recent years, the development of on-plant sensors has attracted significant attention in agricultural technology research due to their potential to revolutionise crop management practices. These sensors offer real-time monitoring capabilities directly from the plant itself, providing invaluable insights into various physiological parameters crucial for optimizing crop growth and yield. Unlike traditional soil-based monitoring systems, on-plant sensors offer a more comprehensive understanding of plant health and performance by directly assessing the plant's physiological responses [1]–[3]. Plant bioimpedance "needle" electrodes (Fig. 1) have been shown to be effective for monitoring plant hydration levels [1], [2] through tetrapolar impedance measurements. Tetrapolar (four electrode) measurements offer advantages in relation to the more widely used bipolar approach, minimising the detrimental effect the electrode contact impedance [4]. However, the use of penetrating electrodes presents several potential challenges, including difficulty in installation, lack of repeatability in results, and damage to plant tissue, leading to physiological variations. These limitations highlight the need for alternative electrode designs that can provide mechanical stability and longevity, without damaging the plant. An attractive solution would feature a methodology transfer from neuroprostheses to plant sensing through the adaptation of cuff electrodes (Fig. 1), which have demonstrated successful long-term implantation in various biomedical applications [5]–[7]. The cuff electrode has become a commonly utilised technology for monitoring neural signals and/or delivering electrical stimuli in peripheral neuromodulation applications. Their advantages include biocompatibility, ease of installation, longevity and mechanical stability, without damage to the tissue. Ensuring a secure closure of cuff electrodes around nerves is essential to ensure reliable measurements [8]. Cuff electrode closure often relies on experts, e.g. surgeons, when sutures are required, while self-closing cuffs require specialised fabrication steps and can prove costly. Thus, it would be desirable to offer a robust and cost-effective solution, while minimising the need for a specialist operator for installation. In the work presented here, we propose a novel biomedical-inspired approach for developing plant wearable bioimpedance sensors to meet the aforementioned specifications. Our objective is to develop a robustly closing cuff electrode design for herbaceous plants

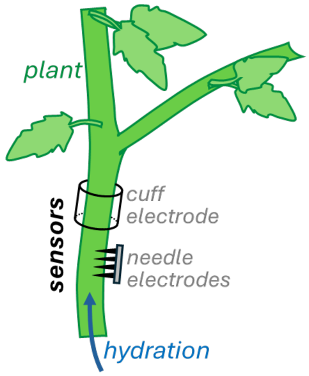

Fig. 1: Conceptual representation of wearable bioimpedance sensors.

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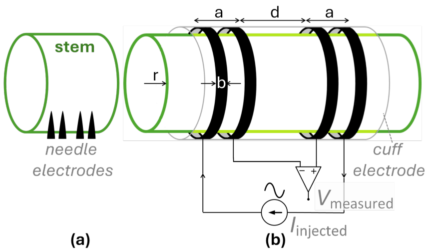


Fig. 2: Electrode configurations: (a) Tetrapolar needle electrode. (b) Tetrapolar cuff electrode with the tetrapolar impedimetric connectivity used in the COMSOL simulations.

- specifically for tomato plants (Solanum lycopersicum) - that will provide optimum performance, whilst allowing for ease of installation, longevity and cost-effectiveness. In these very initial steps of this work we present our design process, through the use of COMSOL FEM simulations to specify the optimum sensor geometry and assess the importance of tight closure. The paper also presents a novel asymmetric tetrapolar electrode topology fabricated using standard flexible PCB process. Tetrapolar cuffs have been proposed previously, only for directional selectivity in neuroprostheses [9]. Our approach also presents novelty in the concept of a cable-tie closure mechanism tested with two different edge shapes.

II. MATERIALS AND METHODS

A. FEM simulations

To specify the cuff's geometrical features and to compare its performance with that of an invasive electrode, an idealised digital twin of the plant stem in the form of a cylinder was modelled using the AC/DC module of COMSOL 5.5 (Fig. 2). It was assigned conductivity of 0.2 S/m and permittivity of 80 based on [10]. The cylinder length was 40 mm, with diameter ranging from $2-5$ mm. Silver (Ag) was chosen as the material for ring electrodes encircling the cylinder (Fig. 2). Different values of electrode thickness (t), width (b), CC and PU inter-edge distance (a), stem radius (r), and PU electrode inter-edge distance (d) were simulated to determine optimal parameters. For the needle electrodes, parameters a, b, and d mirrored those of the cuff electrodes. The diameter of the needles at the broader side measured 0.25 mm, with a length of 2 mm, where 1 mm penetrated the stem. In this in-line tetrapolar configuration, the two outer electrodes function as CC (current-carrying), for current injection, while the inner pair of electrodes serve as the PU (pick-up) electrodes, utilized for voltage measurement. The injection current was $100\mu A$ with an insulation boundary condition. An extremely fine mesh was employed for the simulation. In the Frequency Domain study, we utilised Sensitivity distribution, S, a commonly employed parameter for tetrapolar impedance measurement systems, which is,

$$S = \frac{\overline{J}_{CC} \cdot \overline{J}_{PU}}{I^2} \tag{1}$$

where, $\overline{J}_{CC}$ is the current density (A/m^2) due the injected current through the CC electrodes, and $\overline{J}_{PU}$ is the current density if the currents were injected using the PU electrodes, and I is the applied current magnitude. The transfer impedance was calculated by,

$$Z_t = \frac{V_{PU}}{I}\ \Omega \tag{2}$$

Here, V_{PU} is the measured potential between the PU electrodes for an injection current of I through the CC electrodes.

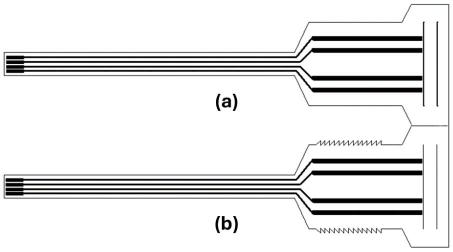


Fig. 3: Schematics of the flexible PCB cable-tie cuff electrode strips with a) smooth edges, and b) serrated edges (teeth) for tightly closed configuration.

B. Cuff fabrication

A "cable-tie" concept was coined and literature searches indicated a similar approach previously proposed for neural interfacing, with a limited number of golden serrations [11], thus increasing fabrication complexity and cost. Both versions of the design conceptualised here (Fig. 3) comprised a standard flexible PCB 95mm long strip with a thickness of 0.11mm, featuring four tracks along its length. The overall length was separated into two segments, a 28mm long, 18mm wide segment featuring the electrode tracks and a narrower insulated segment extending out to a connector, to be connected to a ZIF (zero-insertion force) socket and appropriate front-end circuitry. The silver electrode tracks were 24mm long and 1mm wide, grouped into two 2mm inter-edge spaced pairs. The distance between the two pairs was 5mm, as featured in the COMSOL simulation, with greater lengths avoided as tomato stems feature frequent bifurcations and irregularities that could affect the cuff geometry. The wide segment ending featured two 0.08mm slots to be used for the cuff closure following its wrapping around the 3mm-4mm diameter tomato stem. The cable-tie concept included the flexible-PCB strip looped twice around the stem, with one loop passing through the first slot and the other around the first layer and through the second slot for tighter fastening. One of the designs featured smooth edges while the other one featured serrated edges to ensure a better fit and more stable closure. Fig. 3 displays the diagram for the designed electrodes on the flexible PCB substrate.

III. RESULTS

Electrode size and spacing affect transfer impedance measurement in volume conductors by influencing contact area, electric field distribution, and sampling volume. After extensive simulations, the optimum parameters were chosen to be 1 mm electrode width (b), 2 mm inter-edge electrode pair distance (a), and 3-8 mm distance between PU electrodes.

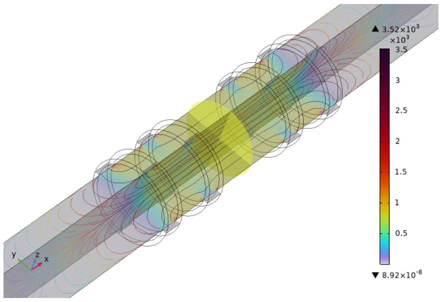


Fig. 4: Electric field distribution of fully closed tetrapolar cuff electrodes

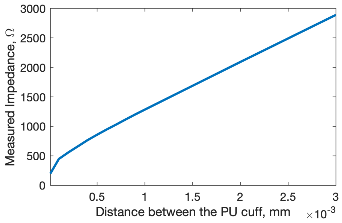


Fig. 5: Transfer impedance of a fully closed tetrapolar cuff

The electric field distribution for a cylinder with a radius of 2 mm with optimal electrode spacing is shown in Fig. 4 for a fully closed configuration of a tetrapolar cuff. The field is intensified in the volume between the PU electrodes, and field lines are mostly parallel in this region. The measured transfer impedance (Z_t) between the PU electrodes (Fig. 5), exhibits a linear relationship with the PU inter-electrode distance (d) when greater than 0.25 mm.

The sensitivity of Z_t along the central axis of the cylinder is depicted in Fig. 6 that shows that the sensitivity remains fairly constant in the central 5 mm region, which is the region between the PU electrodes.

The simulated sensitivity (S) distribution on the yz plane (perpendicular to the cylinder axis) is illustrated in Fig. 7. In panel (a), the cross-section for the needle electrode configuration is depicted, while panel (b) presents the corresponding sensitivity distribution (S). Panels (c) and (d) showcase the configurations and sensitivity (S) for the loosely closed cuff electrodes, whereas panels (e) and (f) exhibit the configuration and sensitivity (S) for the tightly closed cuff electrodes, respectively. In the needle electrode configuration, heightened sensitivity is observed in the immediate vicinity of the needle, resulting in the measured Z_t primarily reflecting localised material information proximate to the electrodes. The partially closed cuff structure demonstrates elevated S values at points of electrode-stem contact, while sensitivity diminishes significantly in open regions, potentially leading to skewed measurements. Conversely, the fully closed cuff configuration yields a relatively uniform distribution of S across the entire cross-section. Consequently, the fully closed cuff electrode offers nearly uniform S, electric field (E, and current density (J throughout the volume between the PU electrodes.

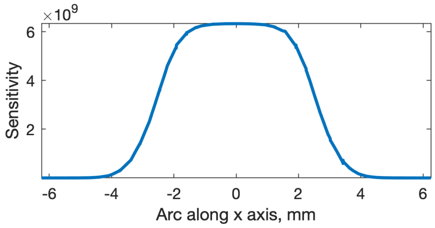
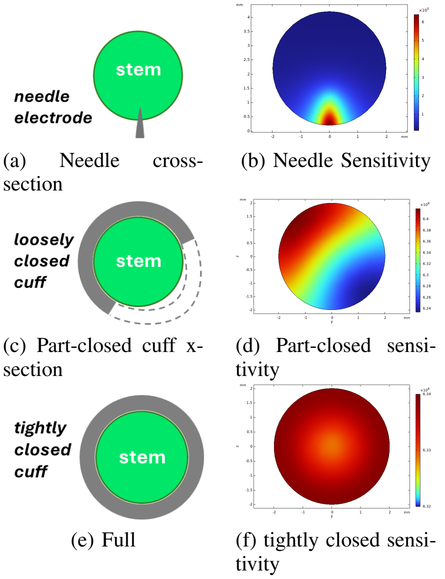


Fig. 6: Sensitivity distribution of the 1D line along the axis of fully closed tetrapolar cuff electrodes

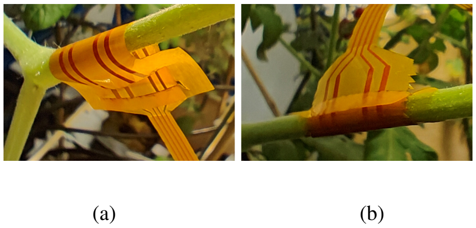


(a) Needle cross-section (b) Needle Sensitivity

(c) Part-closed cuff x-section (d) Part-closed sensitivity

(e) Full (f) tightly closed sensitivity

Fig. 7: Sensitivity distribution cross section



(a) (b)

Fig. 8: Electrodes setup on tomato stem a) partially closed configuration, smooth edge b) tightly closed configuration, serrated edge

Fig. 8(a) illustrates the smooth-edge placed on the tomato stem, revealing a loose fit with one side failing to make contact. Fig. 8(b) portrays the cuff with the serrated edge tightly enveloping the stem and thus maximizing stem-electrode contact.

IV. CONCLUSIONS

This study presents a novel biomedical-inspired methodology for tailoring a robustly closing cuff electrode plant wearable for herbaceous plants (here: tomato plants), aiming for optimal performance, ease of installation, durability, and cost-effectiveness. We utilised COMSOL FEM simulations to refine the geometry of a novel plant wearable cuff sensor and emphasised the importance of tight closure. The COMSOL simulation compared the previously reported needle electrode design and the proposed tetrapolar cuff electrode in terms of the stem cross-sectional sensitivity area that would contribute to bioimpedance hydration measurements. The cuff was shown to interrogate a greater proportion of the stem volume than the penetrating electrodes. As in its implantable counterparts, tight cuff closure provided a more uniform sensitivity distribution of the transfer impedance. The tightly closed configuration also exhibited a linear relationship between the transfer impedance and voltage measuring inter-electrode distance. Following simulations, we presented the fabrication of first prototype dummy electrodes using a standard flexible PCB process. Our proposed cuff electrode design featured an innovative asymmetric tetrapolar topology and a novel cable-tie closure mechanism. Our approach stands out because we use a single flexible polymer substrate with either smooth or serrated edges. This study is a proof-of-concept derived from extensive simulations to optimise electrode parameters for on-plant sensors. The next steps of our work will involve gathering experimental data from actual tomato stems. We also aim to introduce further features to deal with parameters like changing stem diameter with growth as well as stem sequential swelling following watering events. Our motivation is to be able to propose plant sensors for precision agriculture applications.

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