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Towards robotically assisted electrical bio-impedance acquisitions for soft tissue characterization in surgical applications

Diego Dall'Alba*, Kim L. Schwaner†, Zhuoqi Cheng‡, Leonardo S. Mattos‡, Thiusius R. Savarimuthu† and Paolo Fiorini*
*Department of Computer Science – University of Verona, Verona, Italy
†The Mrsk Mc-Kinney Mller Institute – University of Southern Denmark, Odense, Denmark
‡Department of Advanced Robotics – Istituto Italiano di Tecnologia, Genova, Italy
Corresponding author: D. Dall'Alba (email: diego.dallalba@univr.it)

***Abstract*—Minimally invasive surgical (MIS) applications are among the most challenging scenarios where an intelligent and autonomous surgical robotics system (SRS) could operate. Current human-operated SRS integrates mainly endoscopic video feedback, but more advanced sensing modalities are required to support the execution of complex surgical actions, especially by an autonomous system. In this work, we present the application of an additional sensing modality based on a compact electric bio-impedance (EBI) measurement device that can be integrated into existing surgical instruments with minimum modifications. Reliable soft tissue EBI measurements are hard to be obtained due to the sensitivity of this sensing modality to acquisition parameters. Thus, we propose a robotically assisted EBI acquisition system (REAS) to obtain stable EBI measurements of soft tissue in a user-defined region. We demonstrate the feasibility of the REAS in an ex-vivo experiment using the da Vinci Research Kit (dVRK). The results confirm the capabilities of the proposed method in performing robust EBI data acquisition.**

***Index Terms*—robotic-assisted surgery, electric bio-impedance, advanced sensing**

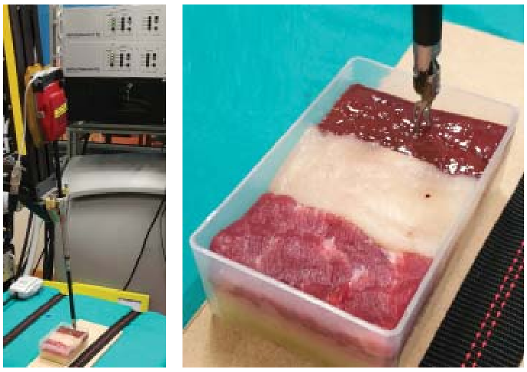

Fig. 1. Left: The bipolar forceps with integrated EBI sensor. Right: The phantom made of 3 different ex-vivo animal tissue samples, pork muscle (left), chicken breast (centre) and beef liver (right). The rough phantom dimensions are $88 \times 55 \times 25\,\mathrm{mm}$.

I. Introduction

Diffusion of SRSs has constantly increased over the last 15 years. The enhanced dexterity and 3D vision provided by this technology allows to translate a conventionally difficult MIS procedure into an easier work for surgeons and, ultimately, to better surgical outcomes for patients. The introduction of real-time sensing modalities (SMs) can bring further advantages to such systems, for example by supporting surgeons in tissue discrimination and manipulation. However, most of the sensing technologies available nowadays require the modification of the surgical tools or complex integration with the clinical robotic system [1]. In the future, these novel SMs could have a significant impact on autonomous SRS, enabling to correctly estimate the actual surgical conditions during the execution of complex procedures [2].

EBI measurements have been demonstrated to be a valuable supporting SM in a range of clinical applications, for example in the localization of pathological areas in breast [3]. This work is based on a compact electric bio-impedance (EBI) measurement device that can be integrated into standard surgical instruments with minimum hardware modification [4]. It is a challenging task, however, to obtain stable and robust measurements with a standard bipolar surgical instrument. In [4], Cheng et al. identify the two main parameters that impact these EBI measurements: the distance L between forceps jaws and tissue compression depth d. A graphical user interface is introduced to support the human operator in correctly controlling these critical acquisition parameters. Even with this interface, stable EBI acquisition between different measurements is difficult for a human operator to achieve.

In this work, we propose a robotically assisted EBI acquisition system (REAS) able to autonomously obtain stable EBI measurement over a regular sampling grid in a user-defined region of interest (ROI), with no knowledge about geometrical, anatomical and tissue properties. We demonstrate the feasibility of the REAS in an ex-vivo experiment based on the da Vinci Research Kit (dVRK) [5]. This could significantly improve the sensing capabilities of future autonomous SRS.

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II. Materials and methods

The EBI sensor used in this work is an embedded device based on an AD5933 (Analog Devices, Inc.) impedance converter IC. Please refer to [4] for a more detailed description of the sensor and its calibration. The sensor is mounted on the housing of an EndoWrist Maryland Bipolar Forceps (Intuitive Surgical, Inc.) and the bipolar leads of the instrument are used to connect the sensor circuit to the forceps grasper jaws. The jaws are placed in contact with the tissue sample under test (see Fig. 1) and the EBI sensor samples the complex impedance $|Z|\angle\theta$ with an excitation frequency of $100\,\mathrm{kHz}$, jaw opening $L = 6\,\mathrm{mm}$ and tissue pressing depth $d = 2\,\mathrm{mm}$. Impedance measurements are obtained at a rate of $50\,\mathrm{Hz}$.

We propose a measurement planning algorithm that requires only minimum input information. The algorithm is initialized with an orientation (vector n) and a bounding box representing the ROI to be analysed. The algorithm then generates a regular grid in a plane with normal n, above the tissue surface. The forceps is moved towards the surface, in correspondence to each grid point, keeping the wrist aligned with n. Surface contact is detected when the measured impedance magnitude $|Z|$ crosses a given threshold level. Once surface contact is detected the instrument is pushed against the surface along direction n to obtain the desired pressing depth d. Finally, the instrument is held steady for $0.4\,\mathrm{s}$ to collect 20 impedance measurements at that point.

An ex-vivo experiment is conducted with the dVRK platform to evaluate whether the sensor is indeed capable of autonomously detecting the tissue surface and map impedance measurements to the contact points. Fig. 1 shows the experimental setup in which a phantom made of three different animal tissues (beef liver and pork muscle and chicken breast) is used to test the proposed system. The measurement planning algorithm is initialized with acquisition orientation roughly aligned with the surface normal and a bounding box of $76 \times 40\,\mathrm{mm}$ centred with respect to the phantom. A grid of 21×12 evenly spaced measurements across the ROI is acquired.

III. Results

Fig. 2 shows the surface map generated using the impedance measurements collected at the contact points. Specifically, the axes show the Cartesian positions (relative to the robot kinematic frame) where instrument-tissue contact was detected. Surface triangle (x, y) coordinates were determined from the Delaunay triangulation between contact points and the z coordinates were found by linear interpolation. The surface colour was mapped to the mean of the magnitude of the impedance measurements $|\bar{Z}|$ taken at each point. The map shows a clear separation of impedance values between tissue types.

The fact that tissue-instrument contact detection was successful at each sample point demonstrates that contact detection is robust and reliable. Since we used a bipolar instrument, contact detection was limited to the moment when both grasper jaws are in contact with the tissue.

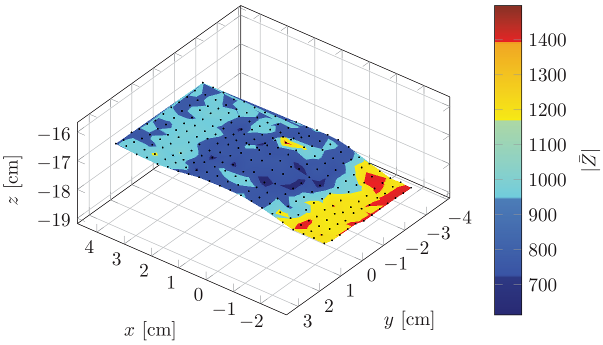

Fig. 2. Surface map showing the result of the phantom acquisition. Black surface points are extracted from robot kinematics and the surface colour is mapped to the mean of the corresponding impedance magnitude values $|\bar{Z}|$, measured in Ω.

A qualitative assessment of the resulting surface map confirms that the proposed REAS is able to distinguish between different tissue types. Autonomous REAS measurements enable accurate control of sample positions, pressing depth d and grasper jaw opening L. Although we can distinguish between different tissue types, further studies are required to evaluate how the method will perform in more realistic conditions, such as in-vivo animal trials.

IV. Conclusions

In this work, we demonstrated the feasibility of an autonomous REAS and experimentally evaluated its performance in ex-vivo conditions. The preliminary results are encouraging but also affected by many limitations. The results motivate future research to improve the actual acquisition performance and push the system closer to clinical applicability.

Future work will improve the scanning pattern by substituting the evenly-spaced grid with an adaptive grid to sample more densely in regions with significant EBI measurement difference. Another improvement will be related to the integration with stereo endoscopic images to obtain information about surface properties for optimizing acquisition parameters, e.g. by adapting instrument tip orientation to surface normal estimation.

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