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Surface and Event Characterization - Proximal Audio Sensing to improve Manual and Robotic Device Interventions

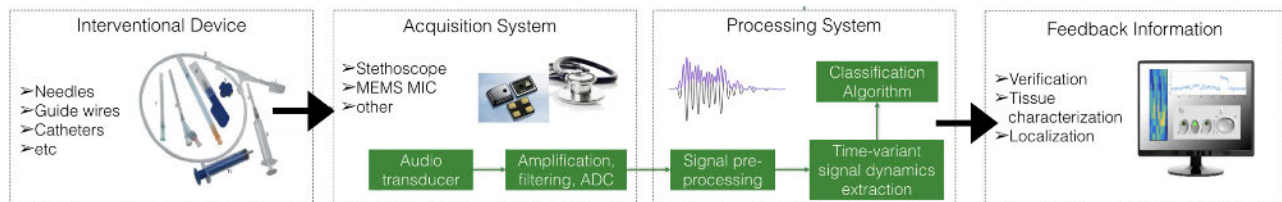


Fig. 1 An audio sensor is attached to the proximal end of an interventional device (e.g., guidewire / catheter / robotic instruments / aspiration needle / biopsy device) outside the body and without the need for a dedicated device, wires, and with greatly reduced sterilization efforts. The acquisition system preprocesses and filters the signal that is then sent to the processing unit. The user interface depends on the application and can range from a visual „traffic light“ feedback to an amplification and magnification of specific sounds.

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Abstract: Minimal-invasive procedures come with significant advantages for the patient. They also come with problems as the navigation/guidance of the devices to a target location is either based on pre-operatively acquired images and then performed free-hand or is accompanied by intra-operative imaging such as MRI or CT that is expensive, complicated and produces artifacts. Using robotic systems for moving and guiding these interventional and therapeutic devices adds additional issues like lack of palpation sensation and missing tissue feedback. While it is possible to add sensors to the distal tip, this creates other obstacles concerning reduced functionality, cables, sterility issues and added complexity and cost. We propose to use a proximally attached audio sensor to record the tissue tool interaction and provide real-time feedback to the clinician. This paper reports

on initial attempts to use this technology with robotic arms for surface characterization and interventional vascular procedures that gain increased attention in combination with robotic devices. In summary, Proximal Audio Sensing could be a versatile, cost-effective and powerful tool to guide minimally invasive needle interventions and enable (semi-) autonomous robot-assisted surgery.

Keywords: audio sensing, proximal sensor, audio feature extraction, signal processing, device guidance

1. Introduction

The device tip is often in an echogenic shadow when using ultrasound as an external guidance device for interventional procedures. Computed Tomography produces reconstruction - and MRI has extensive susceptibility - artifacts. Integrating robotic systems into the clinical process - current examples use telemanipulated robots to move diagnostic and therapeutic devices - adds issues like lack of palpation sensation and missing tissue feedback. Moving towards semi-autonomous or even fully autonomous robot-assisted surgery will require additional sensory input that works in combination with predictive machine-learning-based event segmentation and characterization tools.

Several sensor-based approaches have been proposed for tissue interaction assessment for haptic feedback in needle and guide wires [1,2]. The main drawback of these

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approaches is that the sensors are usually located at the distal end of the instrument, i.e., invasively in the part of the device that is inserted inside the body. Moreover, due to this distal placement characteristic, they come with a degradation of the device's clinical efficiency due to the size of the sensors and the placement of required cables or wires.

An alternative would be a clip-on device attached to the proximal end of an existing and technically not altered device that requires no or very little change to the current clinical workflow and setup.

We have proposed in the past to use audio signals created by the tissue tool interactions on needles and other devices and believe that this could be a viable approach to solve some of the mentioned drawbacks [3].

In this paper, we want to report on the initial attempts to add this technology to robotic arms for surface characterization [4] and for interventional vascular procedures that gain increased attention in combination with robotic devices [5,6].

We will also discuss additional application opportunities of this technology and the following research steps that would require inter-disciplinary and multi-center collaborative research approaches.

2. Materials and Methods

The technical principle is based on picking up a vibroacoustic signal generated through the movement of devices in human tissue (tissue-tool interaction) or of devices that are in contact with human tissue. The signal propagates over the device shaft and can be picked up on the proximal end using a dedicated clip-on microphone (see Fig. 1 and Fig. 4).

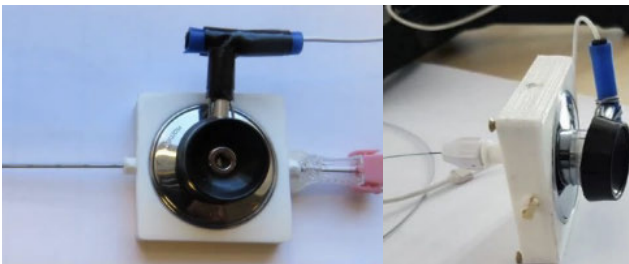


Fig. 2 Initial audio receive setup using a 3D printed adapter for needles (left) and for connection to the proximal end of a guide wire (right).

Initially, we used a 3D printed adaptor and a conventional stethoscope attached to a needle or a guide wire [4] (see Fig. 2). In the meantime, this was replaced with a dedicated and lightweight MEMS clip-on microphone that

integrates pre-processing, signal filtering and amplification, and the conversion to digital data. The information is then sent to a processing system performing advanced signal processing and feature extraction.

The results can subsequently be displayed and/or converted into other signals that are meaningful and valuable to the surgeon. This could be a visual signal indicating certain audible events, like crossing a tissue layer, or it could be used to select and amplify the audio information in human audible signals. The actual user interface and the data translation into human-perceptible information are still a work in progress. The setup on needles was tested in-vitro in a laboratory environment with different layers of animal tissue and comparison of audio signals with Ultrasound video information as well as correlation with a force measurement system.

Additionally, we performed several hundred interventions using pig hearts and vessels with a guide wire simulating a cardiac intervention to verify whether we could detect relevant events (vessel touching, bumping, and penetration) [5,6]. The proximally obtained audio information was processed using Time-Variant Autoregressive Modelling (TV AR), and the results in 2D and 3D together with a calculation of the maximum pole energy (see Fig. 3).

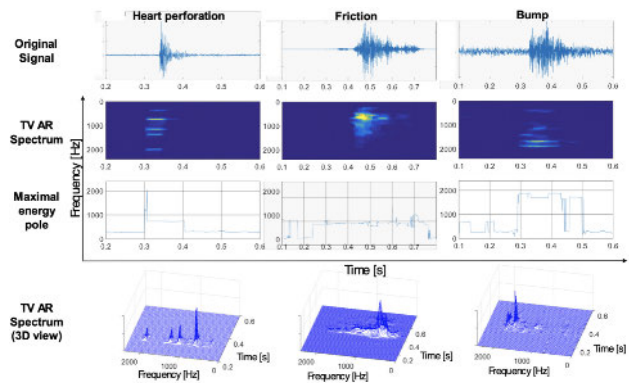


Fig. 3 Audio signals for different events during a guide wire / catheter procedure with an audio sensor attached to the proximal end of the guide wire. All examined events produced distinctively different results that allow event clustering with high accuracy [6]

Subsequently, we added the setup to a robotic arm of a Da Vinci system (see Figure 4) to measure the audio characteristics when moving the forceps over different materials. During the experiments, the robotic instrument was moved with equal speed and pressure. Please note that the connection is indirect via the housing.

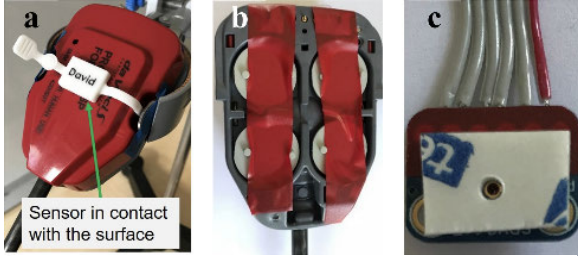


Fig. 4 Audio device attached to the control unit of the Forceps. The forceps wheels were fixed to limit the tip movement (b), sensor attached using double sided tape (c).

3. Results

Guidewire / Vascular Procedure

The experiments for detecting events (vessel touching, bumping, and penetration) during a guide wire/catheter procedure with an audio sensor attached to the proximal end of the guide wire have shown that all events produced distinctively different signals that allow event clustering with high accuracy. The different events could be clustered with high accuracy (98%) using various machine learning methods.

Robotic Grasper on Surfaces

With a novel and advanced device setup, we analyzed the characteristics of moving a grasper (robotic forceps) over different non-animal and animal tissues to see whether these produce distinctive audio responses. We could show that each of the four different surfaces/tissues (Fig. 5) that we examined produces a distinct time/frequency response and, therefore, could enable tissue differentiation.

Other Potential Applications

To verify the validity of the process and method for needle-based applications (e.g., biopsies, aspirations), we

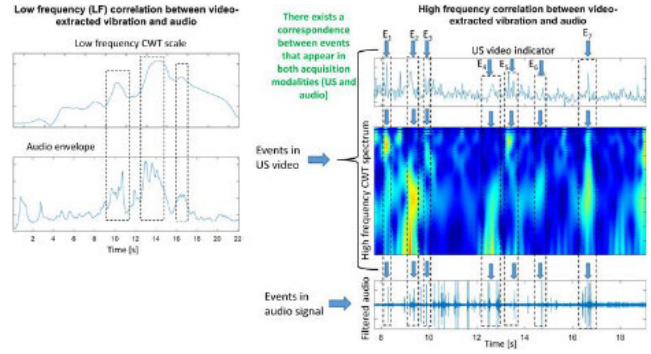


Fig. 5 The left graph shows the excellent correlation between extracted low-frequency-based vibrations in a needle insertion experiment from using the audio signal and an ultrasound video image and on the right the ones for the high-frequency components

also compared the low- and high-frequency components of the audio signal with a corresponding video analysis of an ultrasound (see Fig. 6).

We found excellent event correlation in both frequency bands (see Fig. 5).

In the meantime, we have created a device that can be added to needle and endoscopic instruments integrating the sensing and processing part (see Fig. 6 left). This setup was used for kidney punctures and to classify relevant events using a Veress needle for creating the endoscopic procedure access. All with very encouraging results (publications are work in progress).

3. Discussion and Conclusion

We also have conducted and completed several experiments to identify the effects of certain external procedural variations that could occur. An example is shown in Figure 7, where we examined the impact of different insertion velocities of a needle and different users into the tissue.



Fig. 6 Experimental setup including a synchronous US and audio data acquisition for manual needle insertions in porcine. Kidney placed in gelatine phantom — AGH, 2020.

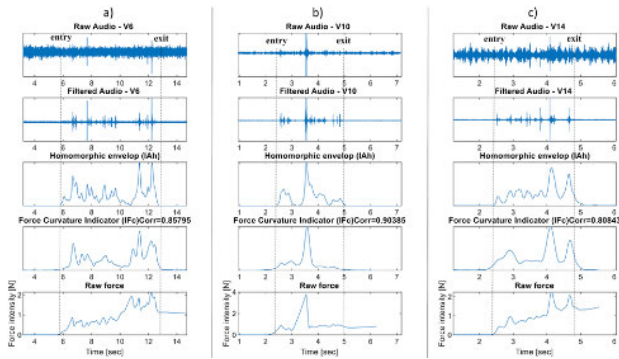


Fig. 7 Study of needle insertions at different velocities.

Vibroacoustic events are only observable when the device is in motion concerning the tissue. Audio provides real-time information, but certain significant events (e.g., crossing a tissue layer) can only be presented after they happen.

This can, however, also be used to predict upcoming adverse events. An example is the Veress needle procedure that must cross a known number of layers before it enters the abdominal cavity. By adding Proximal Audio Sensing, the clinician can be alerted about the progress. Abdominal organ injuries could be prevented.

Another application would be to guide interventional needles during vascular access or to provide information on harmful events during Cardiac Catheterization. If the clinician is informed about penetrating an artery, it is easily possible to retract the device before hurting internal structures.

Our past research has demonstrated that it is possible to identify events during minimally invasive procedures and even for robot-assisted interventions. We also envision more predictive and event characterization applications such as automatic tissue identification after generating more data and applying more machine-learning-based clustering and characterization.

We further believe that Proximal Audio Sensing and subsequent signal processing have many more clinical applications and believe that it should be added as an additional sense to minimally invasive procedures.

Author Statement

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Conflict of interest: NE, MS, and TS are Ph.D. students and employees at SURAG Medical with AI as the CEO. SURAG is a spin-off company of the INKA Innolab at the

Otto-von-Guericke-University, Magdeburg, Germany, trying to commercialize the technology presented.

Ethical approval: The research did not involve any humans. Animal trials followed all the relevant national regulations, and institutional policies and were performed in accordance with the tenets of the Helsinki Declaration and were approved by the authors' institutional review board or equivalent committee.

References

- [1] Trejos, A., Patel, R. & Naish, M. Force sensing and its application in minimally invasive surgery and therapy: a survey. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 224, 1435–1454 (2010).
- [2] Ferrari, M., Werner, G. S., Bahrmann, P., Richartz, B. M. & Figulla, H. R. Turbulent flow as a cause for underestimating coronary flow reserve measured by doppler guide wire. *Cardiovascular ultrasound* 4, 14 (2006).
- [3] Illanes A, Boese A, Maldonado I, Pashazadeh A, Schaffler A, Navab N, and Friebe M (2018). Novel Clinical Device Tracking and Tissue Characterization Using Proximally Placed Audio Signal Acquisition and Processing. *Scientific Reports*, 2018. DOI: 10.1038/s41598-018-30641-0
- [4] Chen C, Sühn T, Kalmar M, Maldonado I, Wex C, Croner R, Boese A, Friebe M and A. Illanes (2019). Texture differentiation using audio signal analysis with robotic interventional instruments. *Computers in biology and medicine* (2019): 103370. doi: 10.1016/j.combiomed.2019.103370
- [5] Illanes A, Schaffler A, Maldonado I, Boese A, and Friebe M (2017). Time-varying Acoustic Emission Characterization for Guidewire Coronary Artery Perforation Identification. *Computing in Cardiology* 44 (2017): 1. doi: 10.22489/CinC.2017.135-113
- [6] Mahmoodian N, Schaffler A, Pashazadeh A, Boese A, Friebe M, and Illanes A (2019). Proximal detection of guide wire perforation using feature extraction from bispectral audio signal analysis combined with machine learning. *Computers in biology and medicine* 107 (2019): 10-17. doi: 10.1016/j.combiomed.2019.02.001