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Surgical Audio Guidance: Feasibility Check for Robotic Surgery Procedures

Abstract: In robot-assisted procedures, the surgeon controls the surgical instruments from a remote console, while visually monitoring the procedure through the endoscope. There is no haptic feedback available to the surgeon, which impedes the assessment of diseased tissue and the detection of hidden structures beneath the tissue, such as vessels. Only visual clues are available to the surgeon to control the force applied to the tissue by the instruments, which poses a risk for iatrogenic injuries. Additional information on haptic interactions of the employed instruments and the treated tissue that is provided to the surgeon during robotic surgery could compensate for this deficit.

Acoustic emissions (AE) from the instrument/tissue interactions, transmitted by the instrument are a potential source of this information. AE can be recorded by audio sensors that do not have to be integrated into the instruments, but that can be modularly attached to the outside of the instruments shaft or enclosure. The location of the sensor on a robotic system is essential for the applicability of the concept in real situations. While the signal strength of the acoustic emissions decreases with distance from the point of interaction, an installation close to the patient would require sterilization measures. The aim of this work is to investigate whether it is feasible to install the audio sensor in non-sterile areas far away from the patient and still be able to receive useful AE signals. To determine whether signals can be recorded at different potential mounting locations, instrument/tissue interactions with different textures were simulated in an experimental setup. The results showed that meaningful and valuable AE can be recorded in the non-sterile area of a robotic surgical system despite the expected signal losses.

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1 Introduction

Robot-assisted interventions gain importance in surgical practice. The da Vinci Surgical System (Intuitive Surgical; California, USA) is the most widely used robotic system for minimally invasive procedures and has become particularly popular for laparoscopic applications. Up to four robotic arms of the da Vinci, equipped with special EndoWrist® instruments, can be controlled from a separate console. Compared to classical laparoscopy, the da Vinci offers increased precision and depth perception through 3-dimensional imaging. These advantages are reflected in lower complication rates and shorter hospital stays [1, 2]. This is contrasted by the absence of haptic feedback during the intervention. Without haptic sensation, essential processes such as the palpation of tissue or the controlled application of force by the instrument are difficult or impossible.

Several approaches have been proposed to enhance haptic feedback in robotic surgery. Kim et al [3] and Hong et al [4] presented surgical forceps with force measuring sensor elements integrated into the forceps jaws at the tip of the instrument to measure pulling and pushing forces. Forceps jaws equipped with sensor arrays are proposed to provide spatial force distribution feedback [5, 6]. Furthermore, the attachment of strain gauges to the instrument shaft for recording grasping and pulling forces was presented [7, 8]. The integration of measurement technology by modifying instruments is always associated with complex manufacturing processes and a high degree of miniaturization, resulting in high instrument costs. Also, many sensor-based approaches cannot withstand the sterilization process and would not meet the clinical requirements. And, any new device needs to undergo regulatory approval.

A modular solution for the da Vinci is presented by the concept of VerroTouch where a sensing unit is attached to the robotic arm [9]. The integrated accelerometer allows the measurement of vibrations caused by tool contact with tissue. These vibrations are then transmitted to the master handles of the console where they are perceived through the surgeon's hands. The main drawback of this technology is that the sensor dynamical range is lower than what an audio sensor can acquire, allowing audio to have access to more information from the process. Additionally, vibration reacts slower than audio in cases of an imminent adverse outcome.

The approach presented in this work is based on the recording of acoustic emissions. Structural sound is generated by interactions between tissue and instrument and travels through the instrument and all connected structures. It is radiated from surfaces to the surroundings as acoustic emissions which can be recorded using an audio sensor. This concept makes it possible to obtain information about intracorporal events extracorporeally and can be used in conjunction with conventionally used robotic surgical instruments. The information potential of the signals received with this method has already been demonstrated for guidewires, needles, and laparoscopic tools. Here, audio has proved to be a tool with a high potential for providing guidance information such as tissue-tissue passage, puncture and perforation events, and palpation information. [10, 11].

The first proof of concept for the applicability of this approach to robot-assisted surgery with the da Vinci system was already provided [12]. In an experimental setup, the tip of the forceps was moved over different textures. A MEMS microphone attached to the housing of the control unit of the instrument, located proximal to the shaft of the forceps, measured the emitted audio emissions that resulted from the tool texture contact. The transmission of information about tip/tissue interaction in the form of structural sound from the distal tip to the proximal end of the instrument was demonstrated in the experiments. The signals obtained showed different time and frequency domain characteristics for different textures, which are promising with respect to the classification of structures and surfaces.

The location of the microphone in this previous work was selected for optimum transmission and radiation characteristics for AE. However, the instrument, including its control unit, was in this case situated in the sterile zone. The application of this concept to a real case scenario is therefore not feasible since the electrical components for the recording of AE would not withstand sterilization.

To ensure the applicability of audio guidance in real robotic operations, the audio recording equipment must be placed at a location in the non-sterile area. A potentially suitable location is provided by the sterile drape that is pulled over the da Vinci arms during interventions. System components beneath the drape need not be sterile. The drape incorporates a build-in adapter that acts as a connector between the non-sterile robotic arms and the sterile interventional instruments. Because of direct contact, AE from the instrument are coupled into the adapter. This adapter offers the possibility to record AE without the need for sterilization of the recording equipment. However, it must be considered that the additional distance to the point of interaction point and the interface between instrument and adapter will result in damping effects that attenuate the signal.

The purpose of this work is to determine whether an acquisition of AE, which is realistic in the clinical environment, can be achieved. To this end, it is examined whether AE signals recorded at the sterile sheet adapter provide potential guidance information despite expected losses due to damping.

2 Materials and Methods

An experimental setup based on [12] was prepared to capture audio emissions during the interactions of a da Vinci Prograsp Forceps (Intuitive Surgical, California, USA) tip with different structures. A stable stand with an attached rotatable bracket (Fig. 1a)) served as a fixture for the adapter. A da Vinci Si sterile drape was pulled over the stand so that the adapter could be fixed by the bracket with the instrument inserted into the adapter (Fig. 1b)). Signals caused by interactions with three different tissue textures were generated for the experiments. The structures were placed under the instrument tip so that the normal force acting on the structures was determined by the weight of the instrument and was constant for all setups. Two synthetic test structures, felt cloth and denim cloth, were used. For this purpose, the textiles were fixed on a texture board (Fig. 1b)). In addition, a pig's liver was used as a third biological test structure.

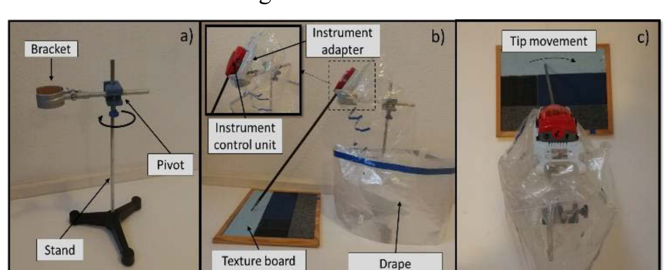

Figure 1: Experimental setup a) stable stand, b) fixed drape adapter with attached da Vinci instrument, c) Top view of the setup and indicated instrument movement

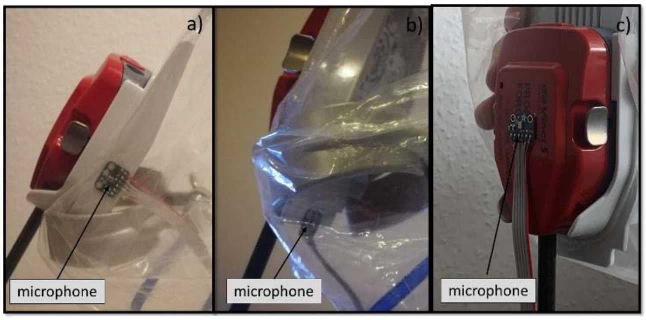

Figure 2: Experimental setup a) stable stand, b) fixed drape adapter with attached da Vinci instrument, c) Top view of the setup and indicated instrument movement

Each acoustic emission signal was generated by manipulation of the bracket, which resulted in a horizontal movement of the instrument tip over the structure surface from left to right over a length of 10 cm and over a period of two seconds (average speed of 5cm/s) (Fig. 1c)). The audio signals were recorded with a MEMS microphone (Adafruit I2S MEMS microphone SPH0645LM4H-B, Knowles, Illinois, USA) at 44100 Hz. The recordings were made at three different locations. For the first location (Fig. 2a)) the lateral frame of the adapter was selected. The second location (Fig. 2b)) was the bottom edge of the adapter. These locations have been selected to provide sufficient space for the attachment of an audio measuring unit during an intervention when the adapter is attached to the da Vinci arm. This has been taken into account to ensure applicability in a realistic scenario. The third location (Fig. 2c)) corresponds to the location already tested in [12]. The recordings made at this site are intended to serve as a reference to show the loss of information caused by the damping of acoustic emissions during the transition to the non-sterile area. The microphone was attached to the locations with double-sided tape.

For each location and tissue texture, 15 signals were generated and recorded for a total of 135 measured signals.

3 Results

Fig. 3 gives a time-domain impression of the obtained audio signals from the tested locations. Three signals are shown, which were recorded at the locations a) adapter lateral frame, b) lower edge of the adapter, and c) instrument control unit (as explained in the previous section and shown in Fig. 3). The Figure shows the concatenation of 1-second segments extracted from the signals obtained at different locations. Using this visualization, it is possible to better observe the time-domain signal differences between the different structures. Denim is relatively stiff compared to the other tissues and has a rough surface which leads to high friction and consequently a high energy in the excited audio emissions. At both alternative locations it was possible to pick up a clear signal during the instrument interaction with denim cloth, with location b) achieving higher amplitude values.

The interaction with the felt material resulted in weaker signal amplitudes than with denim. This can be explained by the fact that the felt surface is softer and dampens the interaction forces between the surface material and the instrument tip. The sliding movement over the liver surface displays the weakest audio signal intensity from all signals. The moist and smooth liver surface causes comparatively little friction and associated smoother interaction forces between tip and tissue. The courses are characterized by transient changes in the signal caused by irregularities in the bio-tissue as well as stick and slip events.

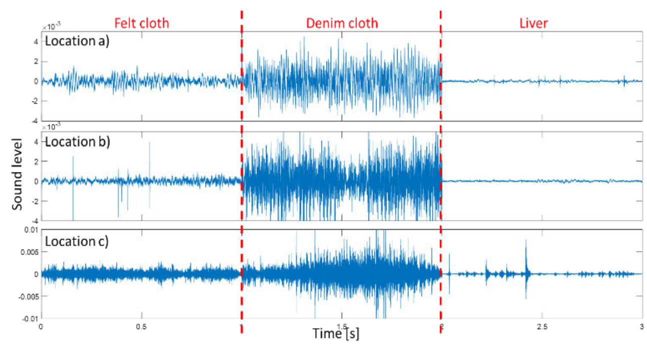

Figure 3: Signals concatenated from three 1-second segments recorded during interaction with felt cloth (left), denim cloth (middle), liver (right). Recorded at adapter frame (top), lower edge (middle), instrument control unit (bottom).

Figure 4 shows the time-varying spectrum of the concatenated signals obtained with a continuous wavelet transform (CWT) with the frequencies represented on a logarithmic scale. The three types of tissue cause different signal behaviour in terms of time-frequency characteristics in the three tested locations. The spectral energy of the signal obtained at location a) concentrates under 100 Hz for the three tested textures. In location b), the spectral energy concentrates under 100 Hz for interactions with felt cloth. During interactions with denim, the spectral energy of the signal recorded at location b) is mainly distributed in frequencies above 30 Hz, and during interactions with liver the energy is concentrated under 70 Hz. In location c) the interaction with felt causes a concentration of energy in high frequencies over 800 Hz. For location c) and denim, the energy appears in the whole spectrum while it tends to concentrate above 800 Hz. For location c) and liver, energy appearance can also be observed in the whole spectrum with the tendency to concentrate at lower frequencies between 20 Hz and 70 Hz.

With regard to the identifiability of tissues in the time-frequency trace, location b) offers the greatest potential from the three tested locations.

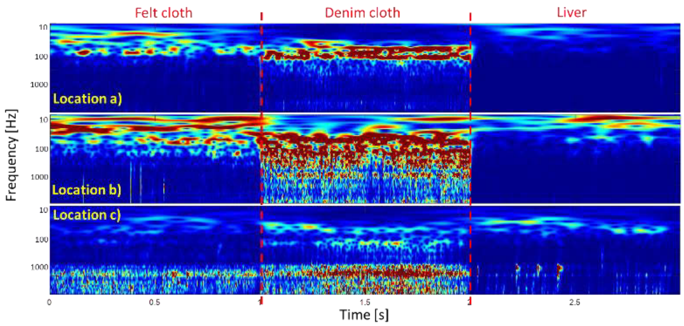

Figure 4: Time varying CWT spectrum. Top: measurement location a) adapter frame, middle: measurement location b) adapter edge, bottom: measurement location c) control unit

4 Discussion and Conclusion

The presented results demonstrated that AE caused by interactions of the da Vinci instrument with different structures can be recorded using an audio sensor and are useful for characterization even in the non-sterile zone. To ensure that the signals obtained are due to instrument/tissue interaction, the experiment was designed to eliminate all potential interfering signals. During a real operation, many factors are influencing the recordings, such as machine and personal noise as well as AE induced by friction between the instrument and its surroundings. To determine this influence further experiments in a clinical environment are needed.

As expected, the signal intensity of the recordings at the adapter is reduced by damping effects compared to recordings at the instrument control unit. However, the distinctive signal characteristics in the time domain demonstrate that AE contain interaction-specific information, which results from the underlying tissue. This is the prerequisite for signal-based characterization of tissue properties. Even small structural irregularities, such as the inhomogeneous liver tissue, lead to detectable signals. This suggests the potential for detecting hidden structures by palpation of tissue with the instrument. These assumptions are also supported by the distinguishable frequency composition of the signals.

This investigation examines a significant factor for the feasibility of the audio guidance concept for da Vinci procedures. The ability to obtain relevant acoustic signals in the non-sterile area is an essential aspect to meet the clinical requirements. The signal observations indicate a high information content for the characterization of haptic events. Considering the results obtained with this methodology [10,11] on other surgical instruments, classification of tissue properties, and relevant events such as unintended injuries is conceivable. Audio guidance stands out from other approaches because it can be easily integrated into clinical operations and used with existing instruments. It is a promising, safe, and cost-effective alternative to sensor-based solutions.

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