

Automatic Sensor Data Fusion for the Detection of Bone Layer Transitions and Channel Length Measurement in Axial Oscillation Bone Drilling

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Abstract

In surgery, bone drilling techniques depend largely on the surgeon's tactile perception, which can be subjective and unreliable. Indeed, accurate detection of bone layer transitions during drilling is critical in orthopedic surgery to avoid over-penetration, as well as thermal and mechanical damage to surrounding tissue. This study introduces automatic sensor data fusion approaches to improve the detection of transitions between cortical and cancellous bone during axial oscillation drilling. Here, multiple signals from a multisensory drive train are fused to enable automatic identification of layer boundaries and overall drill channel length. Experimental validation on pig rib bones shows that time-domain analysis achieves high accuracy, with a standard deviation of 0.22 mm and a mean systematic deviation of 0.26 mm relative to caliper references. The time-frequency approach exhibits larger deviations, with a mean systematic deviation of 1.05 mm and variability up to 1.52 mm. While drill breakthrough is consistently detected, internal layer transition detection reaches 60 % success. Overall, the results demonstrate reliable drill length estimation and highlight the need for improved algorithms for transition detection, supporting the potential of sensor fusion for precise, feedback-driven surgical drilling.

Keywords: Drilling, process monitoring, sensor-fusion, inhomogeneous materials, measurement uncertainty.

1. Introduction

Orthopedic procedures require accurate detection of bone layer transitions during drilling to prevent over-penetration, thermal and structural damage. Conventional bone drilling depends on the surgeon's tactile feedback, which is often subjective and unreliable in complex or minimally invasive interventions. Therefore, Sorg et al. [1] tested a method for estimating the drill channel length when drilling porcine bones by employing a multisensory drive system and an evaluation of the signal amplitudes in the time domain. The method employs a reflective photoelectric sensor, an optical distance sensor as well as a motor current sensor and was experimentally evaluated through drilling tests on pig rib bones. Although a promising measurement uncertainty of 0.3 mm ($k_p = 2$) was reported, validation of the determined bone layer transition using a well-referenced object is still pending.

Guan et al. [2] developed a method to identify the beginning and completion of drilling for spinal pedicle screws aiming at identifying different bone layers. By recording force and acoustic emission signals and analyzing them in the frequency range between 10 kHz and

15 kHz, the position of the transitional region between cortical and cancellous bone layers could be successfully determined.

Furthermore, a method for automatic drill breach identification during spinal pedicle drilling using vibroacoustic sensors was created by analyzing the signal spectrograms and applying a neural network [3]. Various vibroacoustic sensors (including a contact microphone, a free-field microphone, a tri-axial accelerometer, and a uni-axial accelerometer) along with an optical tracking system, were integrated into the experimental setup. By incorporating sensor data fusion and deep learning, the proposed method demonstrates potential to enhance the autonomy of robotic surgery.

Experimental results demonstrated that evaluating the measured force values enables the detection of different bone layers and the drill breakthrough as developed in 2012 by Aziz et al. [4]. The work introduced a method for real-time breakthrough detection during bone drilling using a CRS Catalyst-5 robot. It applies a breakthrough algorithm that analyzes signals from a six-degree-of-freedom force-torque sensor during the drilling process.

Zdero et al. [5] describe experimental methods for measuring force and torque during surgical drilling into whole bone, focusing on instrumentation, data acquisition, and parameter control (e.g., feed rate, spindle speed, drill geometry, and bone type). The study highlights how drilling conditions influence mechanical response and potential thermal damage affecting fixation quality. While force–torque signals may reflect structural variations, the work does not explicitly analyze bone layer transitions or drill channel length as independent variables.

Feldmann et al. [6] experimentally evaluate artificial cortical bone substitute materials for surgical tool development, training, and drill wear analysis. Through controlled drilling tests, thrust force and torque responses of various polymers and composites are compared with bovine cortical bone. Results indicate no material fully replicates bone behavior, revealing trade-offs in performance and durability. The study focuses on material response and does not explicitly analyze bone layer transitions or drill channel length as independent variables.

Torun and Öztürk [7] propose a novel breakthrough detection method for robotic orthopedic drilling based on closed-loop control signals and machine learning. Using features derived from control and force data, the approach achieves high detection accuracy ($\approx 97\% - 98\%$) and enables timely drill stopping within a small breakthrough margin, improving surgical safety. The study focuses on real-time breakthrough detection and drill state estimation, rather than explicitly analyzing bone layer transitions or drill channel length.

This study presents an automatic sensor data fusion method that integrates signals from a multisensory drive train to identify transitions between cortical and cancellous bone layers and the drill channel length during axial oscillation drilling and finally evaluating the respective measurement uncertainties.

Section 2 describes the measurement principle of the multisensory drilling system and the main components of the experimental setup. Section 3 outlines two realizations of a sensor data fusion. In Section 4, the experimental setup is presented and Section 5 shows and discusses the experimental results concerning the drill channel length measurements as well as the layer transition recognition into bone material. Finally, Section 6 concludes the article with closing remarks.

2. Principle of the solution approach

The measurement principle relies on a drilling system which comprises a sensory drive

train (originally introduced in [1]) equipped with various sensors (green), along with a sensory workpiece holder that includes an acoustic emission (AE) sensor, Fig. 1.

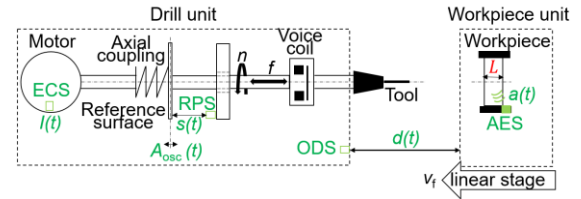


Fig. 1: Measurement principle of the multisensory drilling system, adapted from [1].

On the left-hand side of Fig. 1, the drill unit is schematically shown which remains fixed in a constant position during the drilling process. The electric motor drives the drill by rotating the connected shaft at a specified and controlled rotational speed n .

The motor current $I(t)$ is measured with an electric current sensor (ECS) from which the torque M can be determined via a calibrated constant k :

$$M = k I(t). \quad (1)$$

The rotational speed is measured by using a reflective photoelectric sensor (RPS), which detects a notch on a disk mounted to an axial coupling that rotates with the shaft.

The axial coupling, which links the motor-side input shaft to the tool-side output shaft, allows for small axial displacements of the output shaft relative to the input shaft. As a result, the drill rotates with an additional superimposed axial oscillation f , induced by an electrical voice coil mounted on the tool-side output shaft.

During the drilling process, the feed force F acting on the tool increases the measured distance $s(t)$ between the RPS and the disk, as the axial coupling behaves like a spring that compresses under load and returns to its original state when the load is removed. Consequently, the RPS provides an indirect measurement of the drilling feed force F . The mean feed force F is equal to the average spring force, which is derived from the low-pass-filtered displacement $s(t)$ and the spring constant D ,

$$F = D \cdot (\overline{s(t)} - s_0), \quad (2)$$

where s_0 is the initial distance between the RPS and the disk.

On the right-hand side of Fig. 1, the workpiece unit is schematically represented, which moves towards the drill by means of a linear stage with the set and controlled constant drilling infeed velocity v_f .

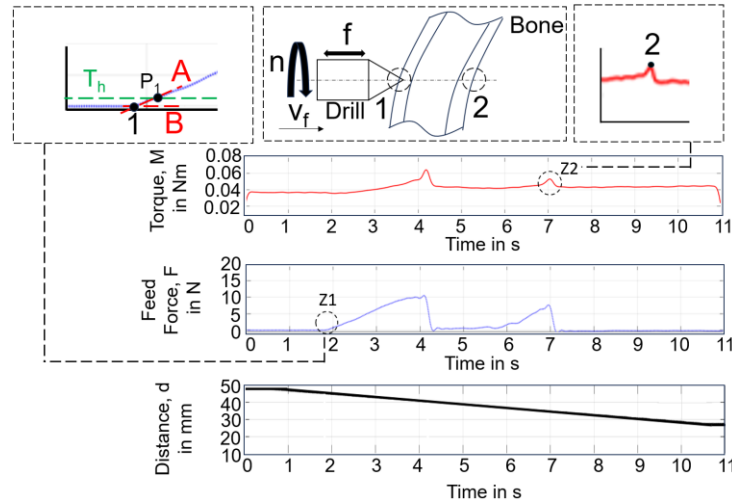


Fig. 2: Automatic sensor data fusion approach based on time domain features.
 Top left: Initial drill–bone contact. Top middle: Schematic diagram for the determined drill time instant points. Top right: Drill breakthrough determined by the maximum torque signal value. Bottom: Exemplary behavior of M , F and $d(t)$ during drilling.

The distance $d(t)$ between the drill unit and the workpiece unit is measured using an optical distance sensor (ODS) based on laser triangulation, which is used to indirectly measure v_f .

As the workpiece is subjected to F during drilling in addition to contact and friction occurring between the tool and the material, its lattice structure becomes locally distorted and rearranged. This deformation releases energy and produces elastic stress waves within the material, commonly referred to as acoustic emission (AE) waves with an amplitude $a(t)$ that can be captured by an AE sensor. To obtain these waves to derive additional information about the workpiece structural layers and tool breakthrough, an AE sensor (AES) is mounted on the mechanical vise to record the AE signals generated during the drilling process.

3. Sensor Data Fusion

The drill channel length L is automatically obtained through a developed signal processing analysis, which makes use of different sensors' outputs over time and frequency domain features. The time gap between two time instants - t_1 for the detected initial workpiece contact of the drill and t_2 for the drill breakthrough - defines the drilling duration. By using v_f as the average cutting tool infeed velocity, the drill channel length L is determined by calculating

$$L = v_f \cdot (t_2 - t_1) - \Delta L_{\text{spring}} \quad (3)$$

with ΔL_{spring} as the spring compression of the axial coupling at the time t_2 (indirectly determined via the RPS signal).

Two different approaches to determine the time instants t_1 and t_2 have been investigated, and the first one makes use of solely time domain features, whereas in the second approach, t_1 is defined through a time domain feature and t_2 is instead found based on a frequency domain feature. Both approaches are examined with regard to the quality of the channel length result in terms of the achieved systematic and random errors.

3.1 Sensor data fusion based on time domain features

Fig. 2 schematically shows the sensor data fusion algorithm based on time domain features.

The characteristic initial, almost linear rise observed in the feed force F corresponds to the period when the drill contacts the workpiece and the drill is increasingly pressed into the workpiece surface layer. The beginning of the force rise marks the time instant t_1 of the bone entrance. This feature is determined by using the algorithm shown in Fig. 2, in which a threshold T_h above the noise level (green dashed line) is applied, and the first point exceeding this threshold is identified as P_1 . Regression lines (red dashed lines A and B) are then approximated to the signal on both sides of P_1 using an evaluation window of 0.2 s centred

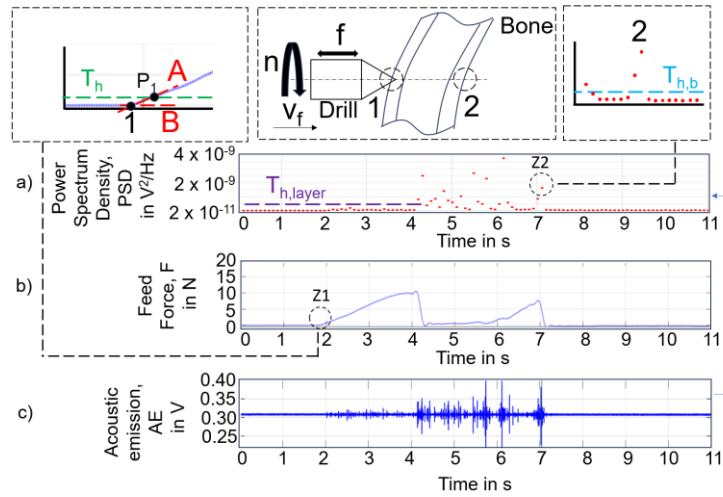


Fig. 3: Automatic sensor data fusion approach based on time and frequency domain features.
Top left: Initial drill–bone contact. Top middle: Schematic diagram for the determined drill time instant points. Top right: Drill breakthrough determined by Power Spectrum Density (PSD) function. Bottom: Measured behavior of PSD, F and AE during drilling.

at P_1 . The intersection of these regression lines defines t_1 , which marks the drill's initial contact with the workpiece.

The moment t_2 , corresponding to the breakthrough, is simply established from the peak value shown by the torque signal (Fig. 2, zoomed view Z2 of point 2).

3.2 Sensor data fusion based on time-frequency domain features

The sensor data fusion algorithm for the evaluation of L based on time-frequency domain features is schematically shown in Fig. 3. As the time instant t_1 cannot be determined from frequency domain features, it is derived in the time domain like in Section 3.1, as shown in Fig. 3b.

Only the time instant t_2 associated with the drill tool exit is obtained through the processing of the AE signal by evaluating its power spectrum density (PSD), see Fig. 3c. The automatic computation of the PSD is implemented in succeeding time intervals of 0.1 s for the complete digitized AE signal. It extracts the maximum value of the PSD, Fig. 3a. Based on the plot of the maximum PSD values over time, the drill breakthrough position t_2 is defined as the last maximum PSD value that oversteps the static limit $T_{h,b}$, as schematically shown in the upper right-hand side of Fig. 3. The definition of $T_{h,b}$ is

$$T_{h,b} = \mu_{\text{PSD_peak_end}} + C \cdot \sigma_{\text{PSD_peak_end}}, \quad (4)$$

where $T_{h,b}$ is the threshold for detecting the breakthrough instant t_2 , $\mu_{\text{PSD_peak_end}}$ refers to the peak mean value at time window Δt_{end} at the

last 1 s time duration of the PSD plot, C is a constant value and $\sigma_{\text{PSD_peak_end}}$ corresponds to the PSD peak standard deviation at time window Δt_{end} .

Although the AE signal is not suitable for detecting the drill entry into the bone, it can be used to identify the cortical-cancellous drill transition inside the bone.

This recognition works similar to the breakthrough detection. By identifying the first maximum PSD value that oversteps the static limit $T_{h,\text{layer}}$, as schematically shown by the pink dashed line of Fig. 3a, the time instant of the transition is defined. The necessary static limit is calculated based on statistical parameters,

$$T_{h,\text{layer}} = \mu_{\text{PSD_peak_initial}} + C \cdot \sigma_{\text{PSD_peak_initial}}. \quad (5)$$

Here $T_{h,\text{layer}}$ is the threshold for detecting the layer transition time instant $t_{\text{layer 1,end}}$ regarding the end of cortical layer, $\mu_{\text{PSD_peak_initial}}$ refers to the peak mean value at time window $\Delta t_{\text{initial}}$ at the first 1 s time duration of the PSD plot, C is a constant value and $\sigma_{\text{PSD_peak_initial}}$ corresponds to the PSD peak standard deviation at time window $\Delta t_{\text{initial}}$.

4. Experimental setup

The developed experimental setup of the multisensory drilling system is shown in Fig. 4. An AC motor from Nanotec (DB41M024030-A) with 24 V, 50 W, 0.5 Nm torque, and 3000 min^{-1} speed has been used for providing the cutting movement to the drill tool. The motor current is measured via the Hall-effect ECS from Allegro (ACS712), producing an AC voltage. Torque $M(t)$ is obtained by removing offset, computing

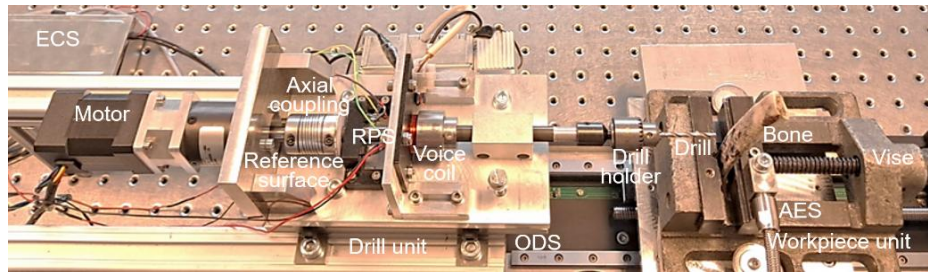


Fig. 4: Experimental setup and procedure.

RMS current, applying a Gaussian filter, and converting the signal using motor's data sheet.

The axial movement of the shaft is generated by a voice coil, driven by a sinusoidal signal with 80 Hz via an amplifier. The RPS to determine the shaft movements by distance measurements to the reference disk is from Vishay Semiconductors (CNY70, 950 nm). Feed force F is derived by applying a 5 Hz low-pass IIR filter to the raw data of the RPS, removing noise and isolating slow mechanical deflections.

The AES from Kistler Instruments GmbH (8152C0050500) measures acoustic emission during drilling and is clamped to the vise holding the pig rib bone. A constant 15 mm distance ensures consistent amplitude. Signals are sent to an AE coupler (5125C3) for amplification and low-pass filtering, by using an analog cut-off frequency of 100 kHz. The coupler outputs a voltage signal.

A linear stage from Physik Instrumente (M-414.2DG) moves the bone material toward the drilling unit at speeds up to 3 mm/s. An ODS from Micro-Epsilon (optoNCDT 1401) uses laser triangulation, offering a 50 mm range, 25 μm resolution, and 90 μm linearity.

The analog signals from ODS, ECS, RPS, AES, and voice coil oscillation are digitized using two devices from National Instruments. The NI-9234 samples ECS signals (3.4 kHz) at 51.2 kS/s, while the NI-9222 records ODS (1 kHz), RPS, voice coil oscillation and AES at up to 200 kS/s to prevent aliasing. Data acquisition is implemented in LabVIEW, with processing in MATLAB.

The machining procedure involves constant plunge drilling with axial oscillation. A standard twist drill (3.0 mm diameter, 135° tip angle) is used, and the process parameters are listed in Table 1.

The tool starts at a safe distance, positioned away from the workpiece. Drilling proceeds until a set position beyond the workpiece ensures full penetration. The tool then reverses its feed without rotation or oscillation, preventing further cutting.

Tab. 1: Drilling process parameters.

Drill type	Twist drill
Drill diameter	3 mm
Rotation speed n	600 min^{-1}
Infeed cutting velocity v_f	2 mm/s
Axial oscillation frequency f	80 Hz

The workpiece thickness is measured with a caliper gauge (0.05 mm resolution) for reference and a total of five experiments are carried out.

5. Experimental Results

Fig. 5 shows the results from five L measurements by using both sensor fusion approaches, when drilling through a pig rib bone. For comparison, also the reference values from caliper gauge measurements of the bone thickness are shown, which are equal to the drill channel length measurements.

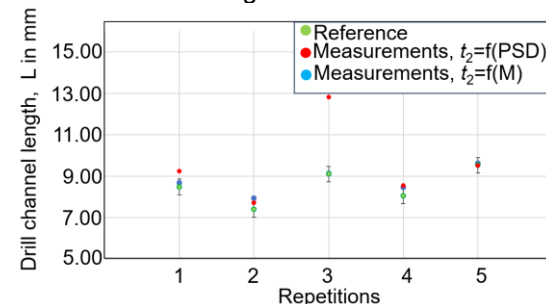


Fig. 5: Repeated drill channel length L measurements during drilling of bone material for both evaluation approaches (time domain and time-frequency domain features) including also caliper reference measurements.

The reference values for each borehole were obtained by averaging four subsequent thickness readings. The caliper gauge values serve as the baseline for evaluating measurement accuracy of the two presented approaches and their error bars show the standard deviation of the mean of the four thickness measurements. The thickness values

scatter over the five different boreholes due to the varying geometry of the bone.

When using the sensor fusion approach based on *time domain* features, a standard deviation of 0.22 mm for the differences between sensor and reference values results. In addition, a mean systematic deviation of 0.26 mm compared to the reference values is observed. These values indicate, that the time domain-based approach achieves good accuracy and precision.

For the sensor fusion approach based on *time-frequency* features the evaluated channel lengths also show that, with exception of repetition 3, the measurements follow the general trend of the caliper-based reference values, thus indicating good agreement across all repetitions. Both overestimation and underestimation are observed, as reflected in deviations ranging from -0.02 mm to 3.72 mm.

The mean systematic deviation between measurement and reference is 1.05 mm. This indicates a positive bias that needs to be corrected for the estimation of t_2 compared to the time domain approach, since t_1 is determined the same way in both approaches. The observed error deviations are generally moderate, (with exception of repetition 3) with most values lying within a standard deviation interval of the differences between measurement and reference values of 1.52 mm, highlighting a reasonable error that needs correction.

In summary, the L measurements found with the time-frequency domain sensor fusion approach also demonstrate overall good consistency with the caliper gauge reference values, characterized by a systematic overestimation of 1.05 mm and an spread measurement variability.

Regarding the detection of the bone-internal transition between the cortical and the cancellous layer, an accurate detection of the transition time instant could recently not be achieved. The detection was only successful for 60 % of the investigated boreholes, indicating that the evaluation algorithm has to be improved for the detection of internal bone layer transitions.

6. Conclusion and Outlook

This study demonstrates the feasibility and effectiveness of an automatic sensor data fusion approach for detecting bone layer transitions and measuring drill channel length during axial oscillation drilling. By integrating multisensory signals and alternative time-domain- and time-frequency-domain-based analyses, the proposed method provides a

reliable framework for real-time process monitoring.

When considering the time-domain analysis, the experimental results confirm that drill channel length can be estimated with sufficient quality for the application in surgical treatments, as indicated by low random measurement errors and acceptable systematic deviations relative to caliper-based references.

While drill breakthrough was consistently and accurately identified with the time-based analysis, corrections need to be implemented in the time-frequency domain approach, in which the detection of intermediate layer transitions showed moderate reliability, highlighting an area for further refinement. Nonetheless, the observed correlation between signal features and physical drilling events confirms the potential of the approach.

Overall, the proposed system enhances the objectivity and robustness of bone drilling procedures, reducing reliance on subjective tactile feedback. The proposed method establishes the foundation for intelligent, feedback-driven drilling systems capable of adapting to bone structure evaluation aiming at enhancing surgical precision and safety. Future research should focus on optimizing spectral feature extraction, reducing systematic errors, and validating the method under varying drilling conditions and bone properties to further strengthen its applicability.

Acknowledgement

The authors gratefully acknowledge the financial support of the current research project by the Volkswagen-Stiftung within the scientific project SMILE (Laboratory for sensitive machining of biological materials) – Funding ID: Momentum.

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