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„Concept and Design for an Intraoral Ultrasonic Micro-Scanner“

Thorsten Vollborn, Fabrice Chuembou Pekam, Daniel Habor, Klaus Radermacher, Stefan Heger
Lehrstuhl für Medizintechnik, Helmholtz-Institut für Biomedizinische Technik, RWTH Aachen, Aachen, Deutschland
E-Mail: vollborn@hia.rwth-aachen.de

Joachim Tinschert, Stefan Wolfart
Klinik für Zahnärztliche Prothetik und Biomaterialien, Zentrum für Implantologie, Universitätsklinikum Aachen, Aachen, Deutschland

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Concept and Design for an Intraoral Ultrasonic Micro-Scanner

Thorsten Vollborn[1], Fabrice Chuembou Pekam[1], Daniel Habor[1], Joachim Tinschert[2], Stefan Wolfart[2], Klaus Radermacher[1], Stefan Heger[1]

[1]Chair of Medical Engineering, Helmholtz-Institute for Biomedical Engineering, Aachen, Germany
[2]Department of Prosthodontics and Dental Materials, University Hospital, Aachen, Germany

Contact: vollborn@hia.rwth-aachen.de

Introduction

Traditional impression taking in restorative dentistry based on elastomer casts, gypsum models, handmade scaffolds and veneers is time consuming and error prone. Over the last decade, extra- and intraoral optical scanners combined with CAD/CAM technology became the centre of attention for manufacturing of highly durable and aesthetically satisfying restorations. Although intraoral optical scanners are getting more and more accurate, digitizing the subgingival preparation borders without using retraction cords or electro surgery is an infeasible task due to the fact that optical waves can hardly penetrate gingival tissue. Most of the available optical systems need a thin powder layer to cope with different translucency and reflectivity of the target materials such as teeth, gums, preparations, resins, etc. [1]. This powder, made of titanium dioxide, tends to agglutination, which causes surface errors in the CAD model after digital reconstruction. Hence, the dentist has to perform a challenging task: Cleaning and drying the impression region in the oral cavity of saliva and blood prior to and during the scan procedure.

High frequency ultrasound (HFUS) could be an alternative to produce digital imprints of hard tissue surfaces such as teeth with high resolution. Furthermore, ultrasonic waves can penetrate soft tissue and fluids without using ionizing radiation. Hence, the influence of blood and saliva is marginal and subgingival preparation borders may be detected in a patient-friendly way. Within the framework of the IDA (Intraoral Data Acquisition) project, a miniaturized ultrasound scanner for dental use is developed. This paper presents one of the developed concepts including the mechanical design, a signal processing method and first investigations on calibration procedures.

Material and Methods

Mechanical Design

The mechatronic concept mainly consists of a mechanically driven ultrasound transceiver and a reflector for beam steering and forming. Since the scanner has to be a cost effective alternative to other optical systems, a HFUS single element transducer is used. Therefore the mechanical part of the system needs at most five degrees of freedom (DOF). The fixed focus of the single element transducer has to be adjusted along the sound beam axis by one DOF. Two additional translational DOF are required for shifting the sound beam axis in the lateral direction. Since scattered echoes from lateral tooth surfaces are expected to be weak and diffuse due to the flat beam angle, the sound beam has to be tilted around two axes meaning other two DOF. Obviously, designing a 5 DOF robotic system in the size of a tooth brush is a highly complex task, considering requirements on dynamics and accuracy. Hence, a first important step is to find a design which reduces the number of DOF without affecting the scan quality. Integration of a synthetic aperture focusing technique (SAFT) into the digital tooth reconstruction process decreases the number of mechanical axes by one. The geometry of a prepared tooth let us choose a fixed rotation trajectory of the transceiver in front of the reflector, whose geometry also can influence the focusing and tilt of the beam. This leads to a scanner concept with two controllable mechanical DOF.

The use of ultrasonic waves for rigid surface reconstruction requires a coupling medium with low damping and low impedance to receive maximum echo amplitudes for every reflecting surface point. Furthermore, relative movement between the scanner coordinate system and target surface has to be suppressed. We could face these problems with the design of a fixation bar filled with the coupling medium. The bar is a removable part of the scanner and can be designed for individual intraoral scanning situations, e.g. canines, incisors or molars (Abb. 1).

In this paper, a combination of the trajectory of the moving point of measurement and the applied signal processing method is called scan-strategy. In order to evaluate and optimize different scan-strategies and calibration procedures, we have developed an extraoral ultrasound scanner with four DOF as an up-scaled reference system.

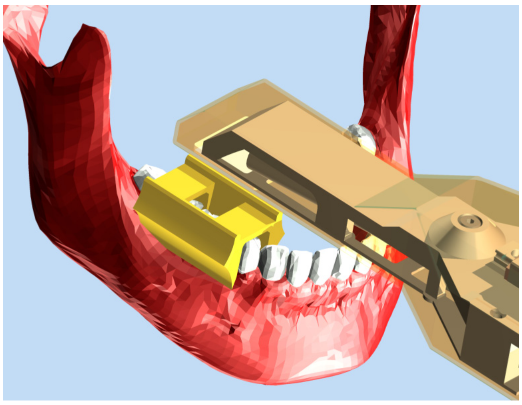

Abb. 1: IDA Scanner and fixation bar on lower jaw

Calibration

Due to the scan trajectory (rotation and translation) and the accuracy specification, a calibration method is required to determine the speed of sound as well as the exact position and orientation of the transceiver within the reference coordinate system of the scanner.

The implemented method uses a simple calibration geometry that can easily be integrated into the scanner. During the calibration procedure the distance between the US emission point and the surface of the calibration geometry is recorded based on time of flight measurements for varying angles of the rotation axis. The angular scans are repeated for different distances between the rotation axis and the calibration geometry. An algebraic model describing the relation between the location and orientation of the rotational and translational axes, the measured distances, the speed of sound and the parameter vector describing the misalignment of the ultrasound is derived. Finally, a set of non-linear equations and the model is solved by using the Levenberg-Marquardt algorithm [2].

Signal Processing

Tooth micro-scanning without mechanically adjusting the focus reduces both the number of mechanical DOF and scanning time. However, the limited depth of field of the focused transducer causes poor resolution in regions out of the focus. To overcome this problem, a monostatic synthetic aperture focusing technique (MSAFT) can be applied [3]. The MSAFT approach considers the focus of a strongly focused single element transducer as a virtual source of approximately spherical waves which are mechanically shifted to entirely cover the volume of interest. For appropriate superimposition of the received RF-echoes, a time based delay and sum beamformer can be applied extending the depth of field and increasing the lateral resolution outside the focus. The method was experimentally evaluated using the extraoral reference scanner (10µm stepping), a wire phantom (tungsten, 60µm diameter) and a prepared human molar. All experiments have been carried out with a single element transducer (75 MHz, F/# = 2) and a HFUS pulser/receiver [4].

Results

The calibration method based on the Levenberg-Marquardt algorithm was tested with the reference ultrasound scanner. The set of equations could be solved with high accuracy. Differences between real length measurements and corresponding simulated length measurements yield a deviation of about 5µm. However, an angular dependency of the distance error was observed.

First evaluation of the MSAFT using clearly demonstrate an improvement of the resolution at the occlusal surface (4mm out of the focus) of the prepared molar and the extension of the penetration depth of the signal after applying the MSAFT method if compared to conventional B-mode imaging. Tab. 1 shows an improvement of 60% of the lateral resolution (6-dB beam-width) measured on the wire phantom approximately 3mm behind the focus.

Tab. 1: Lateral resolution (6dB) of 60 µm tungsten wires

Depth	RF	MSAFT
Focus	60 µm	60 µm
1.54 mm behind the focus	150 µm	90 µm
3.03 mm behind the focus	250 µm	100 µm

Discussion

The calibration is important to achieve a high resolution and accuracy. The use of MSAFT is a promising and cost efficient method to reduce the number of mechanical axes of the scanner, without a loss of the required resolution and depth of focus in the region of interest. Investigations about the use of a-priori knowledge about the tooth surface to improve the signal processing algorithms as well as the evaluation of the reflector influence on our calibration concept are part of our on-going work. Finally, the developed methods have to be evaluated and transferred into the miniaturized model of the IDA scanner.

Conclusion

The concept as well as the evaluation of parts of a high frequency ultrasound scanner for intraoral geometry digitization in restorative dentistry has been presented in this paper. The proposed system, based on a mechanically driven high frequency transceiver (2-DOF) and a reflector for beam steering, is a promising micro-scanning concept for intraoral use, which fulfils the requirements, in particular dynamics and size.

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