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Original scientific paper

An Innovative Photogrammetric System for 3D Digitization of Dental Models

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Abstract: This paper presents an innovative system for 3D reconstruction of a physical dental model. The innovative system is based on close-range photogrammetry and enables the projection of digital light texture on the objects surface. It is based on the application of mirrors that direct the digital light texture to the vertical surfaces of the physical model. In this way, high coverage of the object is achieved, and 3D reconstruction from one set of photographs is possible. 3D digitization, verification and comparison of the proposed methodology was performed on dental models that are characterized by extremely complex surfaces. It was performed by comparing the proposed approach with active stereovision, and the efficiency was evaluated in relation to the reference 3D model obtained by the structured light 3D scanner. The comparison of the results was performed on the basis of the mean deviation and standard deviation for the 3D model with combined teeth and for the 3D model with metal caps. The absolute mean deviations for the 3D model with combined teeth are 0.004-0.021 mm, with a standard deviation of 0.055-0.058 mm, and for the 3D model with metal caps absolute mean deviations are 0.015-0.033 mm, with a standard deviation of 0.095-0.113 mm, respectively. Absolute minimum values of mean deviation of 0.004 mm and standard deviations of 0.055 mm were obtained by 3D model with combined teeth,which was reconstructed by the proposed innovative approach. The obtained results indicate a higher accuracy of the innovative approach in relation to the use of a commercial 3D scanner that uses active stereovision principle.

Keywords: 3D digitization; CAI analysis; close-range photogrammetry

1 INTRODUCTION

With the rapid development and advanced research of diverse technologies and compatible materials, it is possible to obtain a single 3D scan of digital impressions, virtual 3D design, and 3D print of different types of orthodontic dental models [1]. Since dental restorations (fixed and mobile partial dentures) are characterized by personalization, ie. each must be designed to closely follow the ergonomics of the patient's jaws (upper and/or lower) and oral cavity, it is very important to accurately obtain information about the shape of the jaw, its oral cavity and teeth before their 3D design in software [2, 3] which is later made with advanced CAD/CAM systems or additive technologies [4].

The key step that enables all of this is the application of extraoral 3D digitization systems (the more popular term is 3D scanners), where physical, mechanical and optical properties of the materials that are used for 3D scanning are also very important [5, 6]. So far, a large number of systems for extraoral 3D digitization have been developed in the world, based on different methods, which are mainly characterized by higher costs and not so high accuracy. Most of these systems are based on structured light or laser light technology.

Extraoral 3D digitization systems, despite the development and increasing use of intraoral 3D scanning systems, are still an unavoidable process in the modern design of many dental restorations, as well as fixed and mobile dentures. Trifkovic et al. analysed how precision and accuracy differ among different optical 3D digitization systems. Their research included five high-end 3D scanners: Cerec AC, CerecInEos, Trios, KaVo Everest and Sinergia Scan. Their investigation showed that devices for extraoral 3D digitization showed a higher degree of accuracy when compared with intraoral 3D digitization systems [7]. In another research by Trifkovic et al., it was also found that extraoral 3D systems have significantly higher accuracy in comparison to intraoral 3D systems [8].

Budak et al. [9] besides the general overview and analysis of nine different 3D digitization systems, presented experimental results of comparative accuracy analysis of two high-end 3D digitization systems - Atos II Triple Scan and Zeiss Metrotom 1500, which confirmed previous findings that indicate the effective application of these systems in the field of prosthetics [9]. Wenceslao Piedra-Cascón et al.measured scanning accuracy (trueness and precision) on three nondental extraoral 3D scanners: Space Spider; Artec, Capture Mini; Geomagic, DAVID SLS3; David in comparison to an extraoral dental scanner Advaa Lab Scan; GC Europe, and they concluded their findings to not recommend non-dental 3D scanners for application in dental procedures [10].

Close-range photogrammetry (CRP) has not been widely used in this field so far, primarily due to the lower accuracy of 3D digitization results [11]. Photogrammetry can reconstruct digital dental 3D models from which crude quantitative size and shape data can be obtained. Finer scale surface details are not accurately reproduced on SfM (Structure from motion) models due to high levels of surface noise [12]. Photogrammetry can be used to perform 3D scanning, but more effort must be made to improve the accuracy of reconstructed 3D models [13].

Due to the possible accuracy improvement of this 3D digitizing method by applying digital texture design, new possibilities for its application are opened in areas where a higher level of accuracy is required, such as dental prosthetics. The design and application of digital textures in close-range photogrammetry has recently been the subject of numerous studies, which indicates the great potential of this method [14-18].

HosseininavehAhmadabadian et al. [19] developed an automatic and portable system that can provide a pattern on objects and capture a set of high-quality images, in a way that a complete and accurate 3D model can be reconstructed. The images are captured using SfM and Dense Multi-View Stereo (DMVS) method. Their system consists of three parts including a glassy turntable with a novel pattern projection system, a digital camera located on a mono-pod mounted on a length adjustable bar attached to the box of a turntable and a controller system to control the two mentioned parts. Another solution is a fully automated imagery-based 3D scanning system where images are captured at specific angles and elevations surrounding the model from all different views [20].

In contrast to previously discussed investigations, the emphasis of this research is on the development of methodology based on close-range photogrammetry, to increase the accuracy of 3D digitization results.

2 MATERIALS AND METHODS

The realization of this research was conducted according to the methodology shown in Fig. 1. The presented methodology was applied to two different physical dental models.

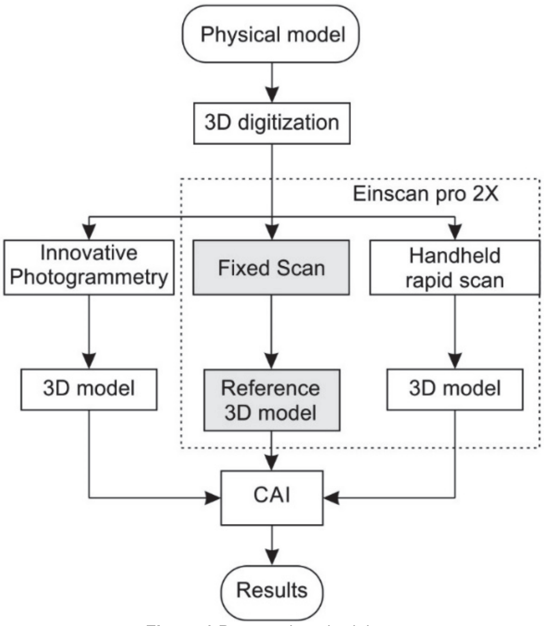

Figure 1 Proposed methodology

Tooth grinding was performed, after which the impression was taken by the two-phase method of impression, using addition silicone. The prints were then cast in super hard plaster and prepared for extraoral 3D digitization. In total, two gypsum working models with different optical properties were made. Afterwards, other materials, necessary for design of dental restorations, were added to the models. Fig. 2 shows the first final plaster dental 3D model with metal caps.

Figure 2 Plaster model with metal caps

The physical model consists of five grinded teeth, with the metal caps on the first and second premolars as well as on the first molar. The upper left canine tooth was prepared for the metal cap, while the lateral incisor was marked in purple for further processing. There were no teeth on the right side of the alveolar ridge. The plaster model had a base of light blue color, while the teeth and alveolar ridge had a predominantly orange color without pronounced characteristical points.

The second plaster model, used in this research, is shown in Fig. 3. This plaster model has a base and an alveolar ridge with five plaster teeth predominantly in light blue color. Next to them, the model has two temporary white acrylic crowns and two acrylic stumps, one of which is painted in red color and the other one in white color with a hole provided for casting upgrades.

Figure 3 Plaster model with combined teeth

The reason for selecting these two models lies in their different materials' structure, that also have different optical properties. After choosing the physical models the next step, according to the methodology from Fig. 1, was their 3D digitization, which was performed using three different methods.

The first 3D model was obtained by using innovative close-range photogrammetric system. Two mode 3D models were obtained using *Einscan pro 2X* structured light 3D scanner, of which the first, used as the reference 3D model, was obtained in *fixed scan* mode, while the second 3D model was obtained in hand held *rapid scan* mode. After 3D digital models of both plaster models were obtained, using all three mentioned methods of 3D digitization, the next step was the verification. This step involved the application of computer-aided inspection (CAI) for 3D geometric analysis of 3D digital models obtained using an innovative close-range photogrammetric approach and commercial 3D scanner in two working modes.

2.1 Innovative Photogrammetric System

Close-range photogrammetric 3D digitization requires capturing photographs of the observed object from close range and from several different positions and/or angles with the highest possible degree of photo overlap [21]. Also, for the successful reconstruction of the 3D model, the object must have a unique stochastic visual texture [22].

Since dental 3D models made of plaster are not ideal for 3D digitization by close-range photogrammetry (because of their monotonous visual texture), within the development of innovative photogrammetric approach for the 3D digitization of dental models special attention was dedicated to digital textures and their projection on all object's surfaces. Schematic representation of this innovative approach is given in Fig. 4.

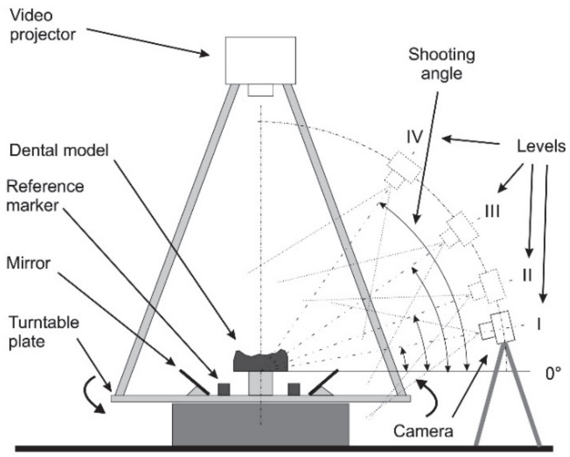

Figure 4 Innovative close-range photogrammetric system for 3D reconstruction

The innovative close-range photogrammetric system consists of a rotating table whose plate is mounted by a video projector using a tripod. The video projector is mounted in a position suitable for projecting of light i.e. digital textures perpendicularly on the turntable. From this position, a digital light texture can be projected onto the upper and inner surfaces of the dental model. In the center of the tabletop there is a cylinder of approx. 50mm in length and approx. 30 mm in diameter which serves as a stand for placing a dental model during 3D digitization.

For the purposes of determining the scale of the 3D model and to achieve higher accuracy, reference markers were placed on the turntable on prismatic rods. Prismatic rods are placed on both sides of the plaster dental model. The distance between the markers is adjusted to approximately correspond to the overall dimensions of the plaster 3D models.

Four flat mirrors with reference markers are placed on the turntable outside the prismatic rods so that they surround the dental model to form a square shape. The mirrors are positioned at a certain angle so that the projected digital light texture from the video projector is reflected on the side parts of the plaster model, which are hard to be covered by digital light texture in any other manner. In this way, the digital light texture is projected in a way that covers the entire surface of the plaster 3D model. Since the video projector and all other elements are mounted on the turntable, it is not necessary to move the camera while taking photos in one circular ring. When the photo capturing is completed in one level (circular ring), the camera is then placed in a new position and the photo capturing is resumed in order to cover all surfaces of the plaster model.

2.2 3D Digitization

Einscan pro 2X 3D scanner was used to obtain a reference 3D digital model of both plaster models. This 3D scanner comes with accompanying EXSCAN PRO software. It is a structured light 3D scanner that consists of two fixed cameras and a video projector, which are placed inside a compact design housing. This handheld 3D scanner enables easy and fast 3D digitization of smaller objects with higher accuracy. It supports 3D scanning in three different modes: Fixed scan, Handheld HD scan and Handheld rapid scan. It is also characterized by basic parameters such as: minimum point distance (Handheld HD/rapid scan) 0.2 mm, five align modes: feature alignment, markers alignment, turntable coded targets alignment, and manual alignment [23].

For the purpose of this research, *fixed scan* mode was used to obtain reference 3D models, while handheld *rapid scan* mode was used for reconstruction of 3D models which will be used for comparison with the innovative photogrammetric system.

Before starting the process of 3D scanning, the prepared plaster models are placed on the turntable. Reflective circular markers with a diameter of 7 mm were randomly placed on the turntable plate, which served for proper orientation and alignment of partial 3D scans in real-time.

The use of a 3D scanner requires prior calibration, which is used to properly scale 3D digitizing results and is performed using a calibration plate (which comes with the 3D scanner) that needs to be scanned from five different positions. The procedure is very straightforward with constant software guidance for easier use. After successful calibration, the 3D scanner is ready for use.

The scanner, while in *fixed scan* mode, must be placed in a proper holder and in a position in which both the object of 3D digitization and position markers are visible by cameras. In this mode, 3D scanner works as a standard structured light scanner [24] by projecting coded patterns on the object, which are then distorted due to the shape of the object's surface. From there digital cameras take digital photos at 30 fps. The scanning accuracy that can be achieved in this 3D scanning mode is up to 0.04 mm, and one partial 3D scan takes less than 10 seconds to complete. Due to the complexity of the geometric shape of plaster models, it was necessary to make between 10 and 15 partial scans that can then be aligned, based on detected markers placed on the turntable, and which will form a completely reconstructed surface 3D model.

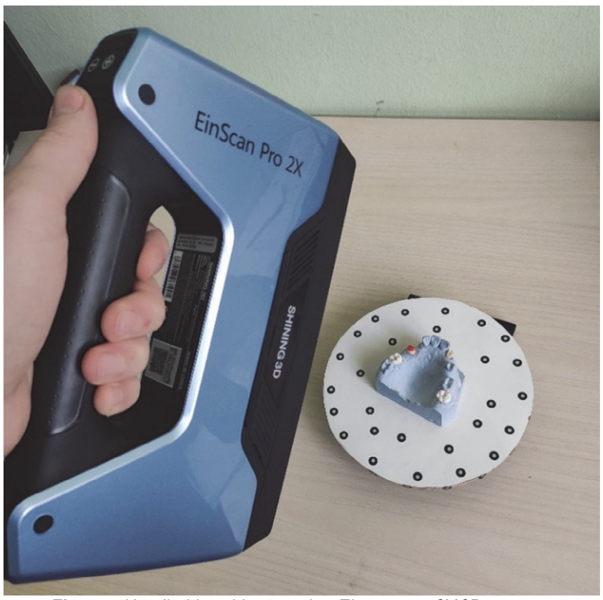

Figure 5 Handheld *rapid scan* using *Einscan pro 2X* 3D scanner

3D digitization in handheld *rapid scan* mode works in a slightly different way (Fig. 5). Different pattern in the form of electronic noise is projected onto the object, and the 3D scanner acts as a stereo vision system that can determine the positions of previously placed markers on a turntable and perform alignment in real-time.

This mode enables data acquisition at a very high speed and with ease of use, but it is also less accurate (from 0.1 to 0.3 mm) than the *fixed scan* mode.

2.3 Computer-Aided Inspection

Computer-aided inspection (CAI) has become a standard tool for quality control and dimensional analysis of 3D models with free-form surfaces. The methodology shown in Fig. 1 ends with this verification step and interpretation of obtained results. CAI is based on a geometrical comparison of two surface 3D models, one of which serves as a reference 3D model containing nominal data, while the second 3D model is the one being compared to the reference 3D model. Interpretation of the results is enabled on the model itself by presenting deviations for characteristic points in the form of tables, graphs, but also pictorially on the 3D model itself in the form of color deviations. Green color and shades of green are used to visually display a good match and small deviations of the analyzed 3D model compared to the reference one. Yellow, orange, red and burgundy indicate the regions (surfaces) of the 3D model above the surface of the reference model (positive deviations), and light blue, blue, dark blue and purple indicate the regions of the controlled 3D model below the surface of the reference 3D model (negative deviations).

3 RESULTS AND DISCUSSION

The measurement was performed in laboratory with controlled microclimatic conditions and with temperature of 21±1 °C.Using the *Einscan pro 2X* 3D scanner in *fixed scan* mode, reference 3D models are obtained and are shown in Fig. 6 and Fig. 7.

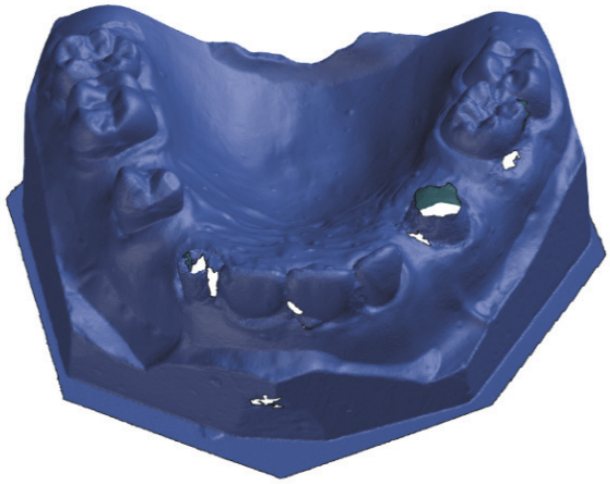

Figure 6 Reference 3D model with combined teeth obtained using *Einscan pro 2X* 3D scanner in f*ixed scan* mode

From these images, it can be seen that the 3D models are not completely reconstructed. Partial unsuccessful reconstruction of 3D models (Fig. 6) occurs on parts that are not made of plaster. These parts are stumps made of plastic, of which the stump painted in red color has not been reconstructed at all, as the red color was not visible to the 3D scanner.

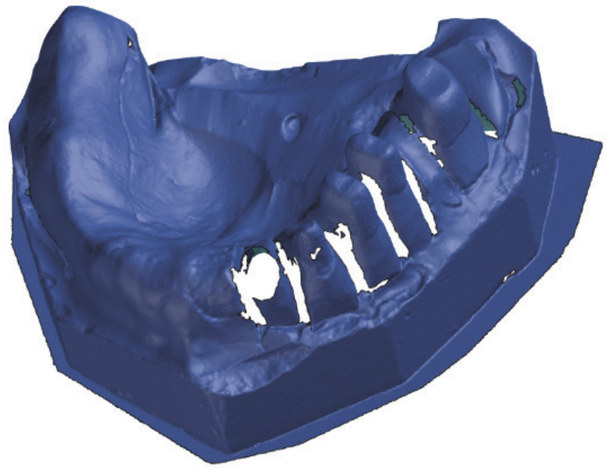

Figure 7 Reference3D model with metal caps obtained using *Einscan pro 2X* 3D scanner in f*ixed scan* mode

The second reference model, shown in Fig. 7, also has defects in form of the gaps between the teeth, which was due to the inaccessible geometry during 3D scanning.

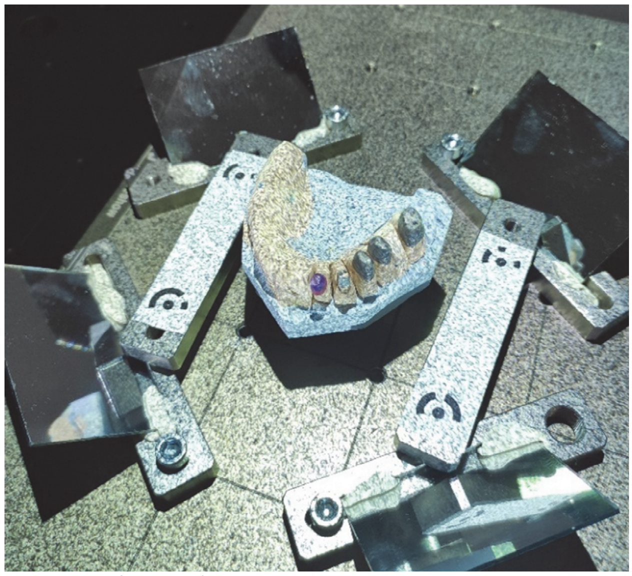

Figure 8 Close up of photo acquisition using an innovative close-range photogrammetric system

3D digitization with a novel close-range photogrammetric system is shown in Fig. 8 and Fig. 9. The dental model with metal caps is placed in the center of the turntable where a digital light texture is then being projected using an available liquid-crystal display (LCD) video projector Epson EB-1761W with native resolution of 1280 × 800 pix. This digital texture was developed based on the decimal of the irrational number *Pi*, where each digit in the decimal notation is represented by a certain shade of grey color. Digital texture has shown the best results in the research [17] in terms of the accuracy of 3D reconstruction of surfaces without characteristic features using a close-range photogrammetry method.

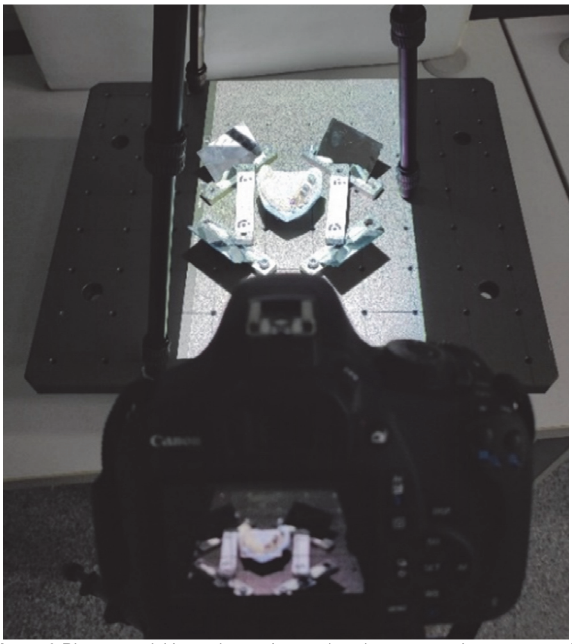

Figure 9 Photo acquisition using an innovative close-range photogrammetric system

Canon EOS 1200d digital single-lens reflex camera (DSLR) with a zoom (variable focal length) lens EF-S 15-55 IS II was used to capture photos. The camera was about 0.55m away from the object to fill most of the photography and a maximum focal length of 55 mm lens was used. F-number was set to 11 and with those settings is achieved about 40 mm depth of field. The resolution of the photos taken was 5184 × 3456 pix. The shooting plan with the number of photos and camera angles is shown in Tab. 1.

Table 1 Photo acquisition overview

Level	Shooting angle	Number of photos	Increment
I	10°	36	10°
II	20°	24	15°
III	35°	18	20°
IV	55°	12	30°

Photos were captured in four levels as shown in Fig. 4. Each level has a shooting angle in which camera was set, and number of photos are captured in a certain level. Angle between images is defined by the increment. On the basis of Tab. 1planned total number of captured photos was 90, but the total number of captured photographs was 92 for the combined teeth model, and 95 for the model with metal caps. The reason for deviating from the shooting plan was due to the obstruction of the camera's field of view by the tripod on which the video projector was mounted (Fig. 9). The photographs were processed in *AgisoftMetashape* [26] photogrammetric software, which is considered to be the leading software in this field. All 3D models are obtained with the same software settings. Point cloud reconstruction settings (sparse and dense point cloud) were set at a high level. Dense point clouds were then converted to mesh 3D models which will later be used for CAI analysis.

3.1 Accuracy Analysis by CAI

Comparative analysis was performed on 3D models obtained using novel photogrammetry method and structured light 3D scanner, which was set to work in handheld *rapid scan* mode. Accuracy analysis was performed using GOM Inspect 2021 software [25]. Best-fit method for 3D models alignment was used, and for easier comparison, all CAI graphs were set to the same deviation range of ± 0.2 mm.

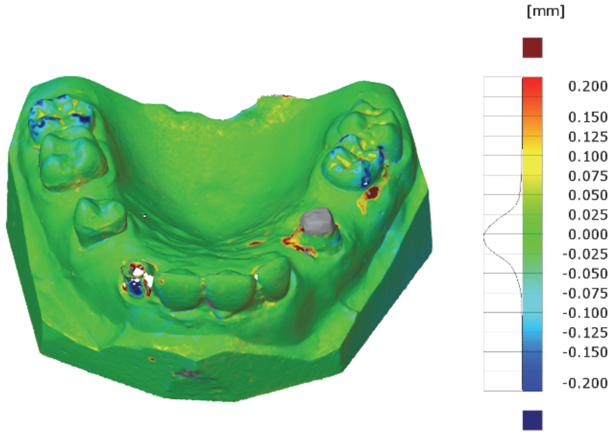

Figure 10 CAI analysis of model with combined teeth obtained by photogrammetric 3D digitizing method

Fig. 10 shows the CAI model of combined teeth obtained by photogrammetric method overlapped with reference 3D model. Histogram in the form of a normal distribution (Fig. 10) indicates the correct distribution of positive and negative surface deviations. A reconstructed stump can also be seen, which was painted in red color on the physical model. The stump with the hole on the left side has not been completely reconstructed, and regions with blue and red colors can be seen as a result of this. The problem regions are located on the last tooth on the left side and the second tooth on the right side, which have white ceramic crowns. Minor deviations can also be found in the base of some individual teeth.

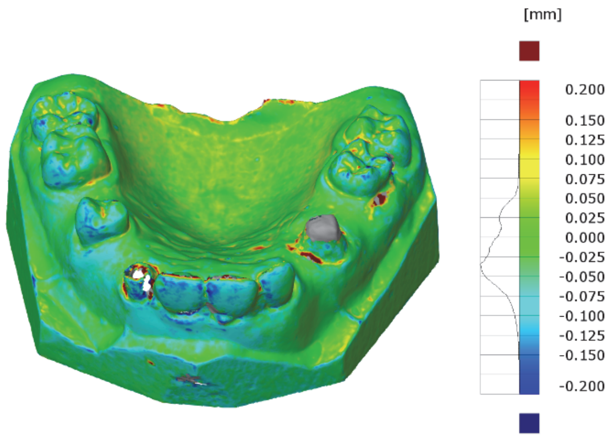

Figure 11 CAI analysis of model with combined teeth obtained by handheld mode using *Einscan pro 2X* 3D scanner

Fig. 11 shows the CAI analysis of the model with the combined teeth obtained using the handheld *rapid scan* mode on *Einscan pro 2X* 3D scanner.

Asymmetric histogram, that can be visually noticed, implies that regions with larger geometric deviations are present on the 3D model. This claim can be confirmed by the presence of regions with light blue color in the area of the front teeth and partially on the lateral sections of the teeth on the left side of the 3D model. The appearance of yellow color in the palate region was present as well. As with the photogrammetric 3D model, the stump, which is marked in red color on the physical model, was successfully reconstructed here, while the stump with the hole was not completely reconstructed.

The CAI analysis of model with metal caps obtained by photogrammetric method is shown in Fig. 12. On the 3D model, green color dominates, which, according to the histogram, includes deviations in the range of ±0.05 mm. The metal caps were successfully reconstructed, as were both stumps. The gaps between the teeth are better reconstructed than on the reference 3D model, but larger deviations of 0.2 mm occur at sharp transitions in the tooth root.

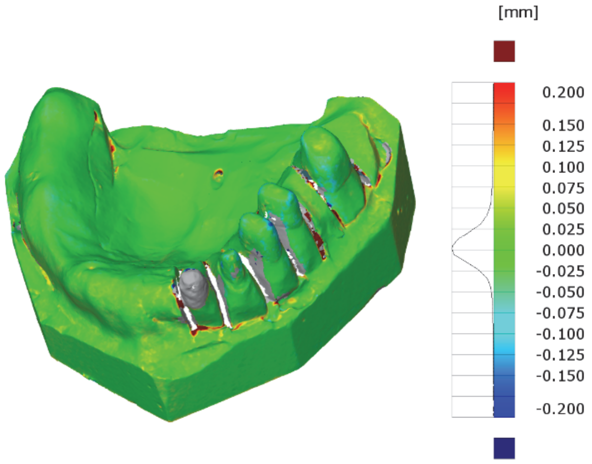

Figure 12 CAI analysis of model with metal caps by photogrammetric 3D digitizing method

The last CAI analysis was performed on 3D model with metal caps which was obtained using the handheld *rapid scan* mode using 3D scanner. The appearance of the histogram is asymmetric and slightly shifted. The concentration of most deviations is between −0.075 and −0.050 mm. Metal caps have been reconstructed with negative deviations which are more pronounced at sharper transitions in 3D model geometry. The first stump has not been reconstructed, while negative deviations are noticed on the side parts of the 3D model arch and on the base itself. The regions of the palate are shown in yellow color, which represents slightly positive deviations.

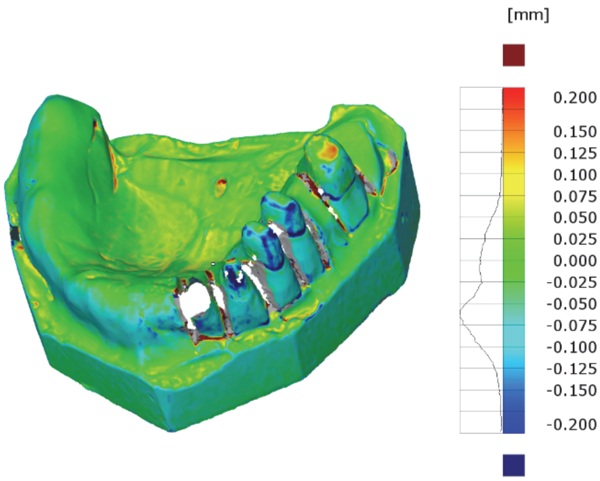

Figure 13 CAI analysis of 3D model with metal caps obtained by handheld *rapid scan* mode using structured light 3D scanner

Table 2 CAI analysis accuracy overview

Model	Mean distance / mm	Standard deviation / mm
3D model with combined teeth (photogrammetry)	−0.004	+0.055
3D model with combined teeth (handheld *rapid scan* mode)	−0.021	+0.058
3D model with metal caps (photogrammetry)	+0.015	+0.095
3D model with metal caps (handheld *rapid scan* mode)	−0.033	+0.113

Tab. 2 provides an accuracy overview of 3D reconstruction using the innovative photogrammetric method and active stereovision using the handheld *rapid scan* method by structured light 3D scanner. Mean deviation values, as well as standard deviation values, show that better results were achieved by innovative photogrammetric system.

4 CONCLUSONS

This paper presents an innovative system for extraoral 3D scanning based on close-range photogrammetry. Accuracy verification was performed against a commercial structured light 3D scanner. The results showed that an innovative system based on close-range photogrammetry, which allows the projection of digital light texture on all surfaces, is very efficient in terms of accuracy and accessibility, compared to a commercial 3D scanner which operates in handheld *rapid scan* mode. The main limitation of this 3D digitizing system lays in specific construction that requires additional components like a video projector and tripod that is placed on a turntable. The legs of the tripod may hide some important parts and cause a lack of data.The direction of future research will be aimed toward the adaptation of the developed system in terms of automation and flexibility of construction, as well as using spherical or parabolic mirrors and their arrangement.

Acknowledgements

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