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A challenge in dental computerised photogrammetry

Dr Olivier Landwerlin, Prof. Michel Fages & Dr Gérard Subsol, France

Introduction

Developments in 3D digitisation processes in dentistry have been continually evolving over the past decade. Advancements have included tabletop scanners for dental plaster casts, intra-oral scanning¹⁻⁴ for prosthetic purposes, and 3D face scanning for use in diagnostic instruments, namely for analysis of smile aesthetics.⁵⁻⁷



Fig. 1: 2D images captured with an HK790 USB 2D intra-oral camera.

Notably, the number of dental surgeons who use intra-oral scanners in their practice is increasing. Many commercial models of intra-oral scanners are available, and according to manufacturer data, existing scanners can be characterised by the following features:

- The weight of cameras varies from 70g to more than 600g.⁸
- The scanning accuracy (under metrological conditions) varies from 5µm to 30µm.^{9,10}
- The dimensions of the camera heads vary from 15×15mm to 20×30mm.
- Scanner costs vary from \$12,000 to \$50,000,¹¹ amounts too high for many dental practices.

However, the costs of intra-oral scanners are expected to decrease owing to the growing number of scanners available on the market,² including TRIOS4 (3Shape),

CEREC Primescan (Dentsply Sirona), iTero Element2 (Align Technology), EmeraldS (Planmeca), CS3700 (Carestream Dental) and Medit i500 (MEDIT).

Technical principles for 3D measurement are based on various methods, such as confocal parallel microscopy, fringe projection with microphase shifting, and photogrammetry.¹² In photogrammetry, a minimum of two small cameras are placed on the head of the device, and these acquire photographs of the tooth from two slightly shifted points of view. Based on the triangulation principle, it is possible to compute the distance to the tooth and then reconstruct a 3D model of its surface. The measurement can be performed with or without using structured-light projection, and this is referred to as “active” and “passive” photogrammetry, respectively.

Historically, photogrammetry was first developed to obtain 3D measurements of teeth.¹³ In initial experiments, contour maps of teeth from a study cast were generated using a custom-built camera with an accuracy of 0.025mm. Quantitative 3D representations of the tooth surface could also be acquired using the contour maps. Several recent studies have shown that photogrammetry can also be used in implantology, thereby enabling a computerised analysis of implant positions¹⁴⁻¹⁸ in cosmetic and maxillofacial surgery¹⁹ or for digitisation of a plaster cast.²⁰

Moreover, 3D surface reconstructions obtained by photogrammetric methods can be matched with the actual structures in the patient’s mouth or objects created by 3D modelling software.²¹ General computerised photogrammetric software is now available, giving anyone the ability to capture 3D representations of any object using multiple photographs taken from a single digital camera.

Photogrammetric reconstruction requires finding correspondences between the pixels of the different images. It is then possible to estimate both the displacement of the cameras and the depth of the object. Most algorithms that automatically compute correspondences are based on similarity or photo-consistency measures; in other words, they compare the pixel values between images. These measures can be defined in either the image space or object space.²²

Multi-image photogrammetric software may be a viable technique for dense 3D reconstruction. Moreover, the cost of such software is low, and some software packages can be leased. Furthermore, some software is even available for free.²³

In this paper, we evaluate this technology for use in everyday dental practice. First, we describe a procedure for obtaining 3D reconstructions of teeth based on intra-oral photographs taken with a low-cost intra-oral camera and using commercial software on a standard computer. Then, we assess the results qualitatively and quantitatively with respect to a state-of-the-art intra-oral 3D scanner. We test several applications, and in particular, we show that the resulting reconstruction can be used under practical conditions to design and mill a dental crown. The key features of the method reported on in this article are its cost-effectiveness and ease of use.

Materials and methods

The equipment comprises 2D digital recording methods and various imaging accessories. The 2D images are processed by close-range photogrammetric software to reconstruct a 3D mesh file of the object. The mesh file can then be imported into 3D simulation software and used in various ways.

Hardware

Computer

We used a standard laptop computer (Intel Core i7, 8GB memory with a 500 MB solid-state drive and a mid-range 3D graphics card, NVIDIA GeForce 820M) of a very affordable cost (less than \$1,500).

Camera

We used a low-cost USB 2D intra-oral camera (HK790, EHANG Beauty Equipment) to acquire intra-oral photographs. The camera was equipped with a pedal to capture the photographs and integrated software to record the data.

The camera has a working distance of 5–50mm with a permanent autofocus, which is a favourable selection criterion. The speed at which a sharp image can be captured is directly related to the ability to easily and rapidly focus on the object. The position of the focus control on the camera, if any, also influences the ability to focus rapidly.

The camera has a 5MP resolution (1,600 × 1,200 pixels), according to the manufacturer, and is comparable to the best USB cameras on the market. Note that resolution is not always an accurate indicator of the image quality of an intra-oral camera, as image quality also depends on many associated variables, such as overall design, lighting, lens quality and software.²⁴

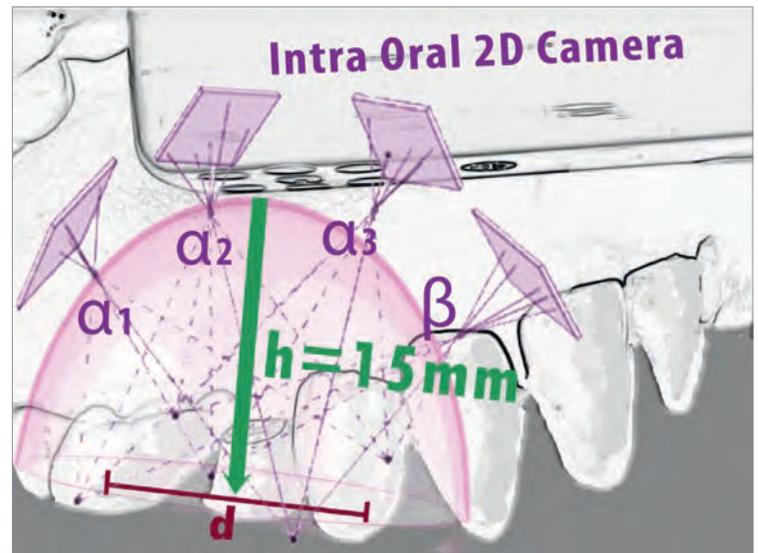


Fig.2: Principle of the bundle adjustment method applied to intra-oral reconstruction.

Optical quality allows distinguishing between a good intra-oral camera and suboptimal intra-oral camera. The best optical systems are created by placing the charge-coupled device (CCD) chip at the end of the wand next to the lens, but this is more expensive than placing the CCD chip in the middle of the wand. When the CCD chip is in the middle of the wand, an additional prism is used to direct the incoming image further down the wand to the CCD chip, and it degrades image quality.²⁵ The HK790 camera we used is sold commercially for \$200, which is very affordable for dental practices. However, this camera is not as accurate as the highest-quality intra-oral camera in terms of image quality and available features, such as depth of field and



Fig.3: Digital calliper (75 mm mini digital calliper, Faithfull CALDIG 75, Faithfull) measurement for calibrating the reconstructed surface. Points are marked directly on the tooth surface with a surgical skin marker pen.

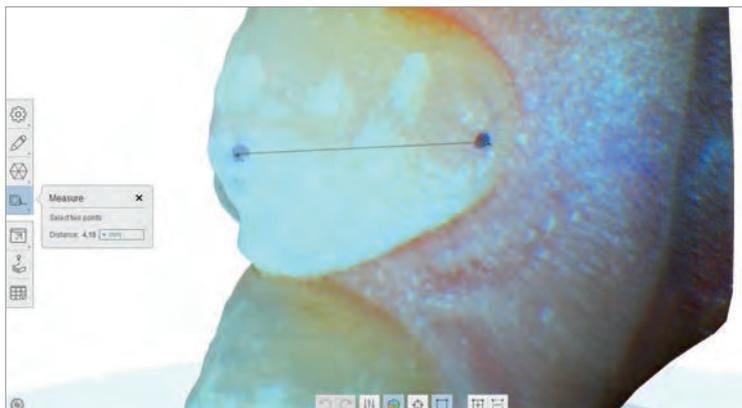


Fig. 4: Control of the distance between the two points after calibration in Autodesk ReMake.

focusing options. A comparison of 14 intra-oral cameras was performed by an independent laboratory through a controlled test, in which cameras were rated for image quality (clarity, colour, sharpness, brightness and contrast). No camera under \$900 was included in the evaluation. In fact, intra-oral cameras range widely in price, from \$16 to more than \$6,000. However, many dental practitioners have subjectively pointed out that inexpensive intra-oral cameras often appear to produce equivalent or even superior image quality to that of higher-end cameras, whereas higher-end cameras may cost two to three times more.²⁵

Reference 3D scanner

To assess the results obtained by photogrammetry, we used a 3D intra-oral scanner, CEREC 3D Red Cam CEREC (Dentsply Sirona), with CEREC Version 3.85 software. This scanner (sold for approximately \$50,000 in 2003 but no longer available) was designed specifically for a single visit for a one- to three-unit all-ceramic aesthetic dental restoration.²⁶

The scanning accuracy of the scanner under metrological conditions is 25µm.²⁷ All devices currently used in dentistry for intra-oral digitisation have a metrological resolution of below 20µm.²⁸ Recently developed intra-oral

scanners are smaller and faster, and they acquire an impression of the entire mouth.²⁹ Nevertheless, in clinical situations, the precision of digital quadrant impression models for more recent intra-oral scanners remains between 41.1µm and 76.7µm.³⁰

Software

For close-range photogrammetric software for reconstruction of the 3D mesh of the tooth from 2D images acquired from various angles into 3D, we selected Autodesk ReMake (Autodesk; educational licence) for the following reasons:

- A free educational version with an acquisition limit of 250 photographs is available.
- It includes an easy-to-use mesh editing tool that offers a fast and comprehensive toolset for fixing, optimising and exporting complex 3D scan data.
- It includes additional relevant tools and services, among them an upscaled web-based interface and cloud storage. The cloud storage provides the ability to use Autodesk’s photogrammetric engine online without utilising personal computer resources, which can then be allocated to the 3D reconstruction.
- The software is a more complete and stable version than similar software offered by the company, such as Memento and 123D Catch (discontinued).
- Moreover, Autodesk has a large user community, and the software is frequently updated.

Since 1 December 2017, the photogrammetric service of ReMake has been part of ReCap Pro under the name ReCap Photo and requires a subscription licence. ReCap Pro is available as a subscription for \$40 per month or \$300 per year in the US and €48.40 per month or €393.25 per year in Europe. An advantage is that Autodesk has increased the maximum number of photographs from 250 to 1,000.³¹

Methods

Intra-oral photograph acquisition

Digitisation consists of recording a shape from multiple angles for reproduction at full scale. OptraGate (Ivoclar Vivadent) is used to retract the soft tissue to acquire intra-oral photographs of a tooth that needs a crown.

Despite the camera’s autofocus, which ensures optimal sharpness at different distances, it is advisable to capture photographs at a distance of approximately 1.5 cm for several reasons:

- A constant distance between the camera lens and the tooth is recommended by the supplier of the photogrammetric software.
- This constant distance is necessary to record characteristic details that will be visible on several views to ensure good correlation among the different photographs. In addition, if the camera is too close to the dental surface, the white LEDs of the camera

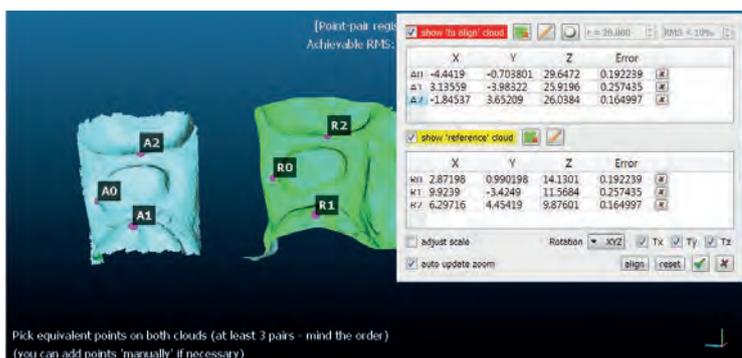


Fig. 5: CloudCompare: alignment of 3D models.

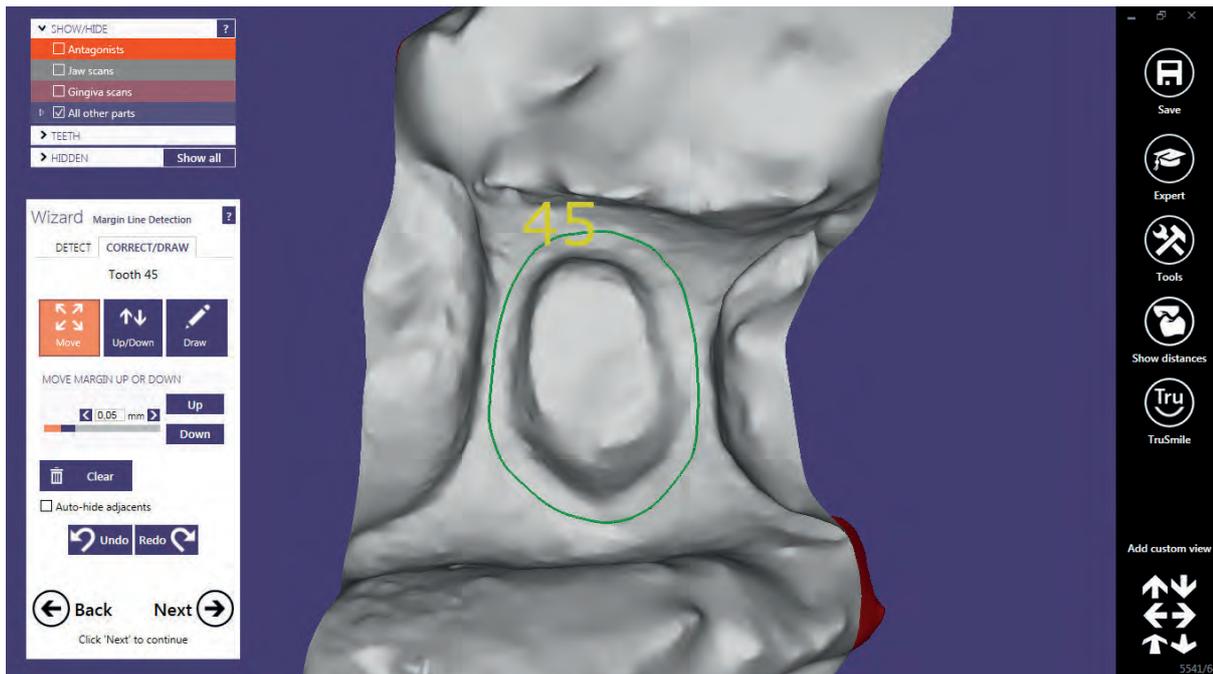


Fig. 6: exocad: drawing the limit of the preparation for the crown.

may blur some details that could be used in the photogrammetric correlation owing to overexposure and artifacts may be created owing to excessive reflection of light.

- Taking into account the limited space of the mouth opening, this distance makes it possible to observe the tooth to be registered and half of each tooth on either side of the tooth to be registered. Such a distance could be difficult to maintain without a good manual support point for stabilisation. The patient must keep his or her mouth open during the acquisition.
- Note that the photographs provide no metric information, and therefore, a complementary manual procedure is required to define the scale of the reconstructed surface.

Photogrammetry applied to intra-oral measurements

Photogrammetric systems used in dental research are of the close-range type, as the object-camera distance is less than 300 mm.³² The principle of reconstructing a 3D surface by photogrammetry is based on a method called bundle adjustment. This method involves simultaneously refining the 3D coordinates of surface points, the different positions of the camera and the camera's optical characteristics.

More precisely, let us take a 3D point on the surface, which is captured in n photographs from different viewpoints by the same camera located at n different positions. Let us assume that we have a first estimation of the 3D coordinates of both the point and the n camera positions. For each viewpoint, we can construct the line of sight from the surface point to the optical

centre of the camera. We can then intersect this line of sight with the optical plane of the camera and infer the 2D position of the projected point in the photograph. If we can detect the actual observed 2D position of the point in the photograph by image processing techniques, we can compute an error between the projected and observed points. By minimising the sum of errors for the n photographs, we can find the actual positions of the camera and, by triangulation, the position of the surface point.³³

Practically, we position the intra-oral camera at angles $\alpha_1, \alpha_2, \alpha_3 \dots \alpha_{50}$ to take 50 photographs of the tooth from different points of view in a 15 mm radius hemisphere. An overlap of 60 per cent between the successive photographs is considered necessary to automatically find some correspondences between the points of a photograph and the subsequent photograph.

In the case of extreme angulation (β), photographs are difficult to obtain owing to the position of the teeth. The best results are obtained when we do not change the distance to the tooth between successive photographs. Each photograph is centred on the tooth, with approximately half of the adjacent tooth in the field of view.

All photographs are then sent to the Autodesk cloud via the Internet to be transformed into 3D models. Three uploads are performed separately for each image acquisition series (images of the tooth of interest and adjacent teeth, images of the opposing teeth, and images of the teeth in occlusion). Within 10 to 15 minutes, three

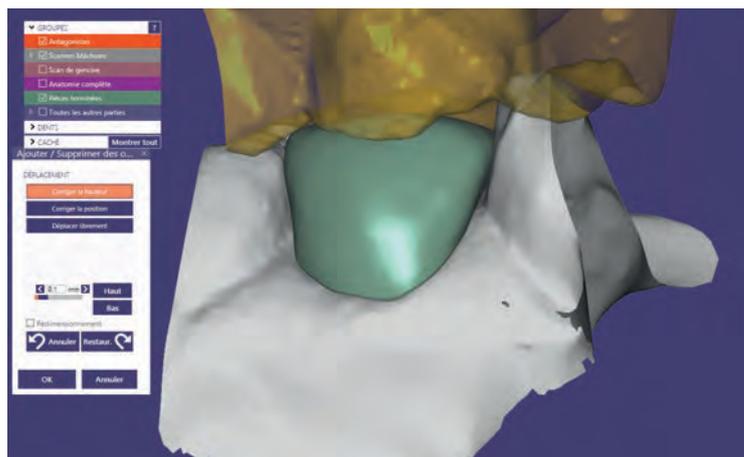


Fig. 7: exocad: CAD of the crown in the occlusal situation.

reconstruction files can be generated and visualised with ReMake software.

Calibrating the surface reconstruction

The intra-oral camera is not calibrated and thus does not produce photographs with metric information. Therefore, it is not possible to understand the scale of the reconstructed surface. The idea is then to plot two landmark points on the tooth and to measure their actual distances and the corresponding distances on the reconstructed surface.

Two points are marked with a pen on the prepared tooth, and on the opposing tooth during occlusion. These six reference points make it possible to report distance measurements in the software using a mini digital calliper. Distance measurements between each pair of points were taken in millimetres, with an accuracy of two decimals. On the reconstructed 3D model surface in ReMake software, we click on the visible reference points to report the measured distances in millimetres to calibrate the reconstructed surface. Such a method has already been used by Knyaz and Gaboutchian for photogrammetric measurements on a plaster cast dental arch.³⁴

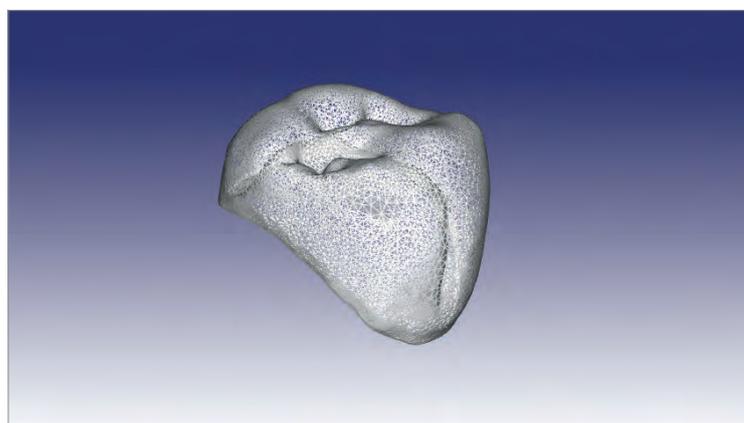


Fig. 8: STL file showing the crown design ready to be sent for milling.

Comparison of 3D meshes

We used the following procedure with CloudCompare software:

- rough alignment by manually pointing 6 corresponding points on the two 3D meshes;
- accurate automatic superimposition of the two 3D meshes (Fig. 13);
- computation of the distances between the 3D meshes.

Deviations between photogrammetric acquisition and the reference model are then calculated. Thus, we can investigate the difference between the whole surfaces. This difference is converted into a representative colour scale map (Fig. 14).

Dental CAD and CAM

The three parts of the photogrammetric models (prepared tooth, antagonist and occlusal) are imported as an STL file into exocad (exocad), which is a dental CAD software program. The shape of the crown is then digitally designed.

First, exocad helps identify the occlusion in a manner identical to the situation in the mouth. After drawing the finishing line on the model representing the gingival margin of the crown, the software is able to recreate, within a few minutes, the complete anatomy of the tooth by referring to both the morphology of the adjacent teeth and the opposing tooth and by using a library of teeth. The operation is finalised by minor editing of the design of the future tooth with a digital tool palette (adding or removing material and smoothing). Once the shape has been finalised, the file is saved and exported in STL format via a cloud server to a milling dental centre for CAM processing. The CAD crown is then milled in a hybrid resin-ceramic block (VITA ENAMIC, VITA Zahnfabrik).

Assessment of the results

We used two different methods to measure the precision of the reconstructed mesh. First, we quantitatively and three-dimensionally compared the mesh obtained from photogrammetric computation with the mesh obtained with the intra-oral scanner. Second, we performed empirical control of the adaptation in the mouth of the crown milled from the photogrammetric mesh. More precisely, we clinically verify the adaptation of the crown to the core and to the adjacent and opposing teeth.

We should note the larger density of points on the photogrammetric 3D reconstruction (20,374 vertices) with respect to the mesh acquired by the CEREC scanner (only 13,636), even though recent intra-oral scanners may yield a much higher mesh density.

When we compare the 3D meshes, the pre-alignment of both models is a manual procedure that can take

several minutes. The difficulty with this procedure is that the models must be placed side by side and visualised in a similar way. Similar points on relatively flat and rounded surfaces with few characteristic angular areas must be identified in both models. For each comparison, adjusting the colour level to a definite scale is also time-consuming to obtain a representative and explicit map with a display range (distance map) of between -0.6 mm and 0.6 mm .

We calculated the distances between the two meshes. From CloudCompare software, we obtained a mean distance of -0.028857 and a standard deviation of 0.212223 . The statistical distribution of the distances between the photogrammetric and the scanned meshes is represented in Figure 14. Most of the distance values in the histogram (from -0.1 mm to 0.1 mm) are below the threshold for clinical use, while the values above the threshold correspond to areas that are not directly related to future prosthetic restoration. The estimation of approximate distances between the two meshes shows that the results are within clinically acceptable limits. Recent research indicates that most CAD/CAM systems are capable of producing restorations with an acceptable marginal seal of less than $100\text{ }\mu\text{m}$.³⁵

Clinical assessment of the crown milled from the photogrammetric model

The clinically developed crown yielded entirely satisfactory results in terms of the following:

- internal adaptation to the core;
- external adaptation to the opposing tooth;
- marginal adaptation to the gingiva; and
- proximal adaptation to the adjacent tooth.

We reduced the occlusal thickness to adapt the surface of the crown to the surface of the antagonist in order to adapt the occlusion to the lateral movement of the mandible, and this is the same procedure employed for the manufacture of crowns by conventional methods (Figs. 15 & 16).

Discussion

The described photogrammetric method does not require any specific equipment or technical skills, and it is very easy to set up at low cost. We have shown that temporary or definitive crowns can be made using a CAD/CAM workflow within the limits of acceptable clinical precision. However, some difficulties persist, especially during the acquisition phase.

Technical difficulties

Limitation of intra-oral camera optics

In dentistry, high-quality intra-oral photography depends on a satisfactory depth of field focus and good illumination.³⁶ Single-lens reflex (SLR) cameras with macro

lenses are currently used in practice,³⁷⁻³⁹ but this was not possible in our experimentation. In fact, photographing all the surfaces of a tooth requires a mirror with SLR. This would create many practical problems for the image acquisition procedure, and it would be time-consuming owing to:

- positioning of the mirror with a constant angle in the mouth;
- moisture accumulation on the mirror; and
- post-processing of the image (symmetry of the photographs).



Fig.9: Crown milled in VITA ENAMIC block.

Nevertheless, SLR offers superior image quality, which makes analysis far easier using photogrammetric software. This advantage is mainly due to the increased degree of acutance, or sharpness of edges, in images obtained with SLR cameras.⁴⁰

Like conventional cameras, intra-oral cameras allow the focal distance to be changed, for example, to capture a single tooth, a full arch or even the face of the patient. Therefore, there is no need to manually change the focus during the acquisition process. Intra-oral cameras have an automatic focal length, which is necessary because the depth of the field is quite variable when one approaches or moves away from the tooth (relative to the average distance). Fixed lenses have no focal change, which is good for the photogrammetric process. Autodesk engineers also recommend capturing photographs with a fixed lens. According to the ReMake user guide, a 50 mm lens is optimal for photogrammetric reconstruction. The small diameter and convex nature of the lenses, notably in close-up images, as well as the necessary approximation for the automatic variation in focal length, lead to geometrical distortion and blur at the periphery or within the photograph. However, the width of the lens seems to be sufficient if we take into

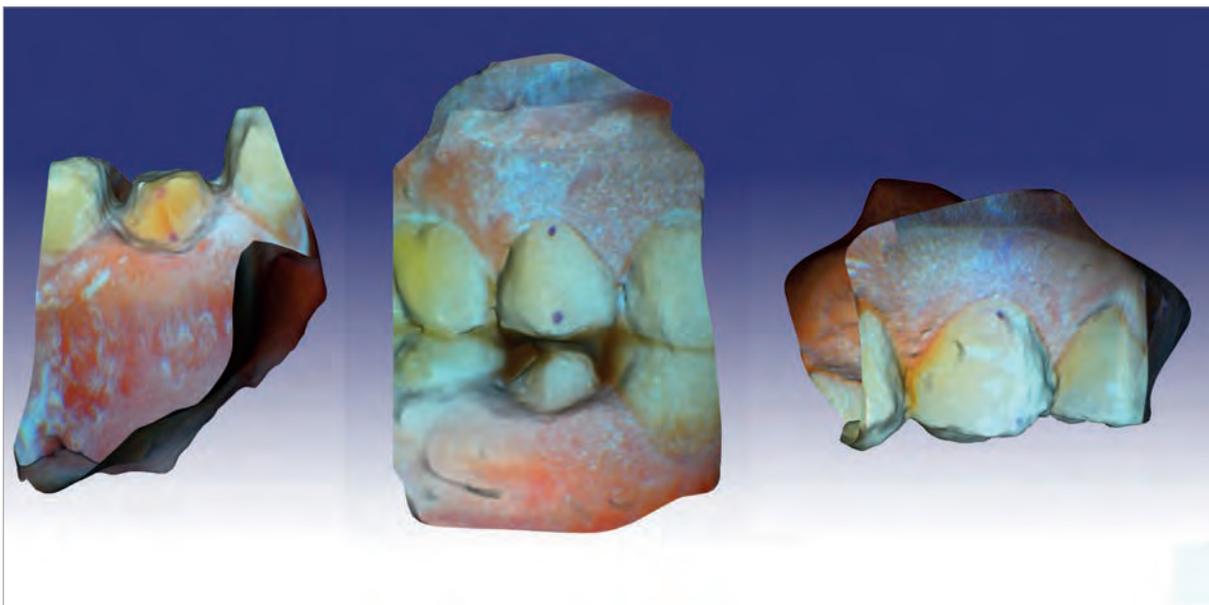


Fig. 10: Photogrammetric reconstruction of the intra-oral clinical situation.

account the fact that deformations in images occur at the periphery, which is not the area of focus during the recording, because the camera is always centred on a particular tooth.

Limitations due to image preprocessing

Most economical digital cameras, such as the intra-oral USB camera, are not specifically designed for photogrammetry, and the implementation of automatic correction procedures of raw acquired images may introduce distortions and chromatic aberrations⁴¹ for our application. Good-quality intra-oral cameras maximise point matching, and a metric potential intra-oral camera with autofocus and an adaptive camera lighting system could increase the quality of the captured photographs (by decreasing artifacts and deformation due to light reflection on the surface).

We have observed that intra-oral USB cameras do not have as high an accuracy as SLR cameras do, but to our knowledge, SLR cameras cannot save photographs in raw format.⁴² This format may yield significant improvements in photogrammetric accuracy over results obtained with JPEG imagery. A standard JPEG image is a 24-bit image (256 tones per channel), which corresponds to 16.8 million colours, whereas a raw file contains 65,536 tones per channel, which corresponds to 281.4 trillion colours.⁴³ A good colorimetry range improves the sharpness and clarity of the edges in an image, which is very important in photogrammetry. The best image quality is supplied by raw image data, but the amount of data increases drastically with reconstruction time and the size of the generated file.^{44,45} These factors would also increase the price of the camera.

Practical difficulties

We encountered the same problems using both the intra-oral USB camera and the 3D intra-oral scanner. The use of sheaths and gloves negatively influenced the ability to adequately and consistently control the camera and tune its image quality.

The camera chosen for our experiment is controlled by a pedal, which provides limited blurring due to movements. This feature is relevant because even pushing a small control button risks moving the camera and blurring the image.⁴⁶

For good 3D reconstruction, the photogrammetric software requires distinguishing between the background and the foreground and finding various features in the images. However, teeth are quite uniform objects with minimal photometrical and geometrical landmarks. For that reason, we propose using a small amount of powder to create a random-texture surface not only in the foreground but also in the background. All surfaces must be cleaned and dried prior to application. The spray must be carefully aimed to ensure that the area for the impression is properly coated. The spray nozzle should be held approximately 10 to 15mm away from the object. The tongue or cheek and lips should not be in contact with powdered surfaces, to avoid changing the random pattern of powder created. It is important to note that all surfaces do not require coating, because the goal is to create a random pattern suitable for photogrammetric recording. Therefore, we press gently on the spray button to deliver a minimal amount of powder each time.

Interference created in the background of the photograph by the movement of soft tissue (tongue, cheeks,

lips) during photography leads to some problems when using the photogrammetric software, as such features are not able to be correlated among the different photographs, and some parts are hidden. Correlation of the vestibular and lingual surfaces is difficult. Blind spots (parts of the scene that are visible from one angle but not visible from another angle) can create point matching problems. It then becomes impossible to correlate these parts of the image, preventing 3D reconstruction. Moreover, saliva can create specular reflections which appear as white areas.

As body temperature is 37 °C, when the temperature of the intra-oral camera lens is lower than 37 °C, the moisture in the breath of the patient condenses on the camera lens, which leads to fog on the lens. The intra-oral camera has no anti-fog mechanism. Some photographs must be retaken at the same angulation to account for this limitation. Visual assessment of the quality of each photograph after capture is important. Although ReMake has an automatic procedure for ignoring poor photographs (due to fog or blurring problems), if too many photographs are contaminated, the correlation images will not be properly generated.

Imaging the last posterior tooth is extremely difficult because mouth opening is limited. It is not possible to introduce the intra-oral camera close enough to the tooth with respect to the short focal distance. Under this condition, 3D reconstruction is not possible or the deformations will be such that the obtained model would be unusable. It would be interesting to investigate whether using another intra-oral camera with a shorter focal length (rather than automatic focus) could be used to solve this problem.

Changes in light can occur from one photograph to another. The intra-oral camera has a built-in LED illumination device. Excessive lighting when the camera is brought very close to the tooth and shadowing can disturb image correlation in the photogrammetry process, and reflected light is also a problem.

Influence of the metric calibration

CAD/CAM applications require the reproduction of physical dental arches to scale 3D models. The problem is that the estimation of metric information on the resulting photogrammetric model depends on the parameters of the camera, which are not known by the user, such as the exact focal length of the lens, the coordinates of the centre of projection of the image, and the radial lens distortion coefficients. These parameters can be retrieved via a camera calibration process.⁴⁷ Precise calibration is then required to produce a model with metric information. A fast camera calibration procedure based on a printable plane pattern can compute the camera focal length, principal point, aspect ratio and lens distortion.⁴⁸



Fig. 11: 3D mesh obtained with 50 2D photographs acquired with an HK790 intra-oral camera and reconstructed by ReMake 3D photogrammetric software (13,636 triangles).

Some photogrammetric software (such as Agisoft Metashape, Agisoft; or PhotoModeler, PhotoModeler Technologies) directly use parameters such as sensor size or focal length, which are either included in the EXIF metadata of photograph files or provided in the manufacturer's specifications. However, in our case, no such information was provided by the USB intra-oral dental camera or its manufacturer. Therefore, it was impossible to obtain the sensor size of the digital camera, although such estimation may lead to imprecise measurements. Nakano and Chikatsu proposed an EXIF-dependent camera calibration.⁴⁹ By this method, the camera is able to integrate the EXIF data into each image, and the photogrammetric software is able to interpret this data, from which metric information can be extracted.⁴⁹

Some commercial photogrammetric packages use predefined printed patterns for the automated calibration phase. These methods automatically calculate focal length, lens distortion aspect ratio and principal point. We tested such a method using PhotoModeler, although

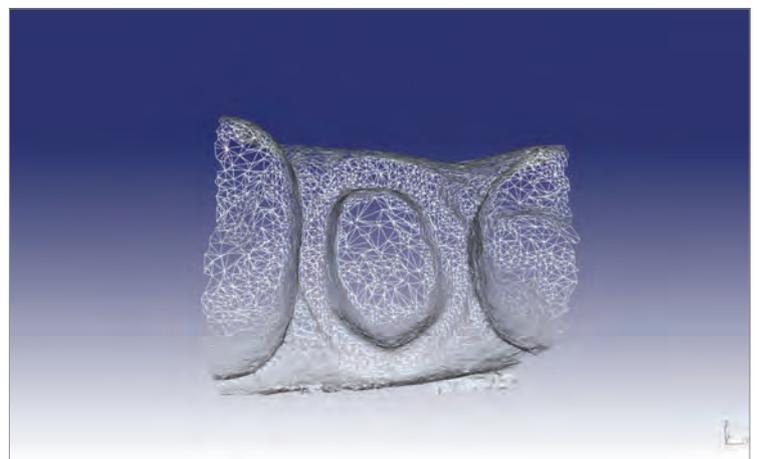


Fig. 12: 3D mesh acquired by the CEREC intra-oral scanner (20,374 triangles).

the software did not result in good calibration because the pattern was not adapted with respect to the very short acquisition distance of the USB intra-oral camera and the large deformation of its lens.

We also tested another calibration method based on 3DF Lapyx (3Dflow), a free camera calibration software program associated with the close-range photogrammetric software Zephyr (3Dflow). The measurement quality and the reproduction of details were not satisfactory because the measured parameters were not constant after different calibration sessions. The data to be reported did not correspond strictly to the type of data to be entered in the software, and the instructions for this procedure were very limited. We were unable to obtain a 3D metric model using this software. Moreover, the calibration software is no longer available on the manufacturer's website. In addition, photogrammetric reconstruction tests using Zephyr showed a less dense point cloud and a large portion of incomplete or distorted areas on the final image compared with ReMake. Zephyr also has an EXIF-dependent⁵⁰ automatic calibration procedure, but it is not useful for our experiment because the EXIF parameters of our camera are unknown.

The tclcalib application written in MATLAB language, which is freely available, could be an interesting tool for extracting all the camera parameters, including effective focal length, lens distortion parameters and CCD chip size. However, these parameters would then have to be included in the close-range photogrammetric software, and ReMake has no functionality to import these parameters. Some authors have also proposed targetless

approaches based on self-calibrating bundle adjustment algorithms.⁵¹⁻⁵⁴ According to Barazzetti et al., targetless calibration can provide camera parameter values with the same theoretical accuracy as the standard target-based procedure.⁵⁵ Nevertheless, for photogrammetric projects that require high precision, we believe that the target-based camera calibration procedure currently remains the best solution.

Solving problems of digitising tooth surfaces in photogrammetry

The correlation of photographs is based on intensity differences, is very sensitive to illumination differences and is not reliable in poorly textured or homogeneous regions. Owing to the high reflectivity of the enamel of teeth, some photographs of the white tooth surface are unsuitable for the photogrammetric process. In addition, the inevitable coating of saliva induces some imaging difficulties.

An object with a rough surface may be required by some techniques to initialise the correlation of photographs,⁵⁶ but the reconstruction must also be performed in regions with poor textures or illumination. To solve this problem for smooth tooth or gingival surfaces, Mitchell and Chadwick made the enamel surface opaque and textured by painting the tooth with a weak water colour solution.⁵⁷ The purpose of spraying the surface is not to create a uniform pure specular reflection surface but rather for fringe pattern projection.⁵⁸

The optical conditioning of CEREC preparations using scan sprays has been reported. Some sprays have been specifically developed for intra-oral scanners:

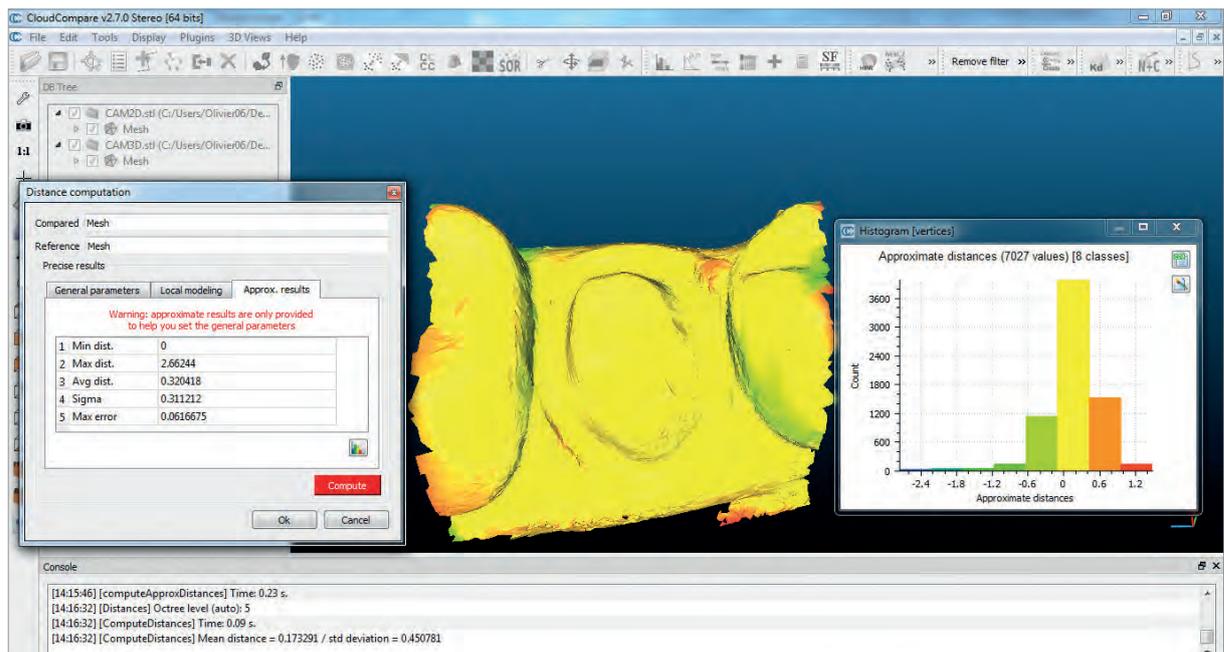


Fig. 13: Automatic superposition of the meshes by CloudCompare.

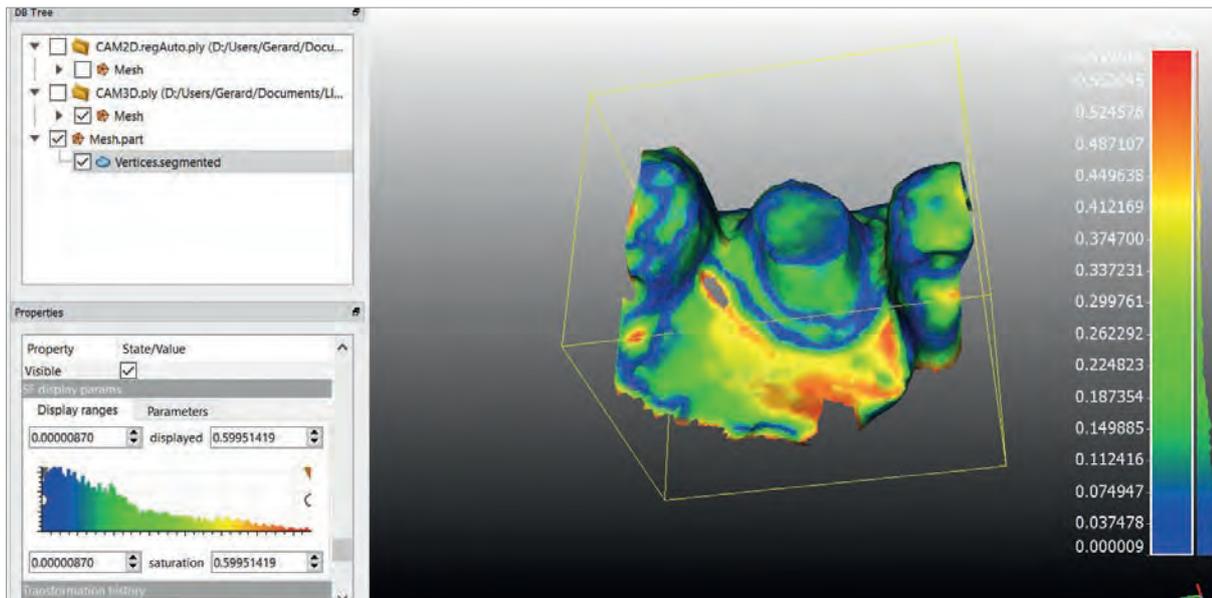


Fig. 14: Computation of distances between the 3D meshes by CloudCompare software.

- APOLLO DI SpeedSpray (Dentsply Sirona) contains grey particles and provides high contrast and resistance to saliva humidity, but it is not designed to completely cover the tooth.
- MyCrown HD spray (FONA Dental) produces a thin layer of black and white particles that can be traced and measured to produce a precise model while maintaining the colour of the restoration.

Further investigation of different parameters of light (colour and intensity of the LED) could be performed to determine which photograph can produce better 3D reconstruction results and may avoid the need to powder surfaces.

Alternatives to ReMake

As mentioned already, at the end of 2017, Autodesk ended development of ReMake software and launched similar software called ReCap Photo. Other concurrent software, 3D Zephyr (3Dflow), RealityCapture (Geovast 3D), Agisoft PhotoScan (Agisoft) and 3DF Zephyr (3Dflow), could be interesting alternatives, and further investigation is necessary to compare their use in intra-oral photogrammetry.

In some situations, the reconstruction process of ReMake is surprisingly effective at ignoring background differences (such as small movements of the tongue). However, if an error occurs or if the model is incorrect, only the ReMake log file can be referenced, which does not provide sufficient information for determining the source of the error. This disadvantage could be considered a detraction to non-expert users in everyday practice. Moreover, ReMake has no manual stitching correction functionalities, as in other photogrammetric

software (Autodesk ReCap 360, Autodesk; PhotoModeler), that can assist the correlation algorithm by prompting the user to select equivalent landmarks in multiple photographs. In conclusion, ReMake is simple, time-saving and user-friendly, but it is not possible to manually correct errors in the software without repeating the entire analysis process.

3Dflow recently introduced a completely free version of Zephyr for Windows with a 50-photograph limit. The software directly competes with the free version of ReMake.

Other possibilities for using photogrammetry in dental offices

Close-range photogrammetry in dentistry not only can be used for intra-oral applications but may also be interesting for use in several extra-oral applications,⁵⁹ such as:

- smile analysis;
- 3D visualisation or simulation of the situation before and after facial surgery; and
- scanning of dental plaster moulds to create, for example, custom dental trays or to evaluate the occlusion between two models.

In addition to these applications, 3D photogrammetric models could be used for diagnostic purposes, as the colour provides an added advantage in comparison with plaster models (visualisation of dental and gingival tissue in cosmetic periodontic surgery). These models could also be used for student training purposes to present 3D simulations, which can be visualised from different viewpoints for a better understanding of clinical situations.



Fig. 15

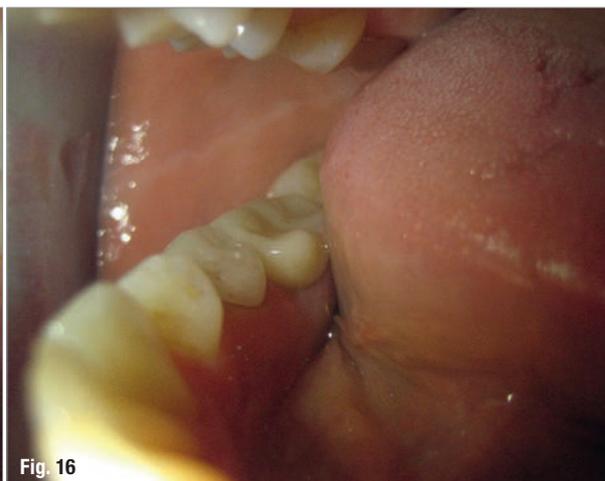


Fig. 16

Fig. 15: Adaptation of the crown in occlusion. Fig. 16: Adaptation of the crown in the lingual view.

Conclusion

In this paper, we have demonstrated that photogrammetry can also be used for intra-oral applications. Given the ease-of-use and the low investment required in terms of equipment, we believe that this technology could be of interest to the dental community. In our experiment, we were able to not only reconstruct the 3D dental anatomy of a patient but also manufacture a dental prosthesis using the 3D model. The dental prosthesis was successfully tested in the patient's mouth.

A quantitative evaluation of the 3D surface reconstruction revealed small statistical differences between the 3D model generated herein and the 3D model obtained with the conventional intra-oral 3D scanner. We have also provided some guiding principles for the optimal acquisition of usable photographs for photogrammetric software.

We propose the following future developments of this method:

- Additional experiments should be conducted on other teeth, which could be more difficult to photograph. Additional devices may be necessary to scan different types of teeth (posterior, anterior maxillary and mandibular).
- This method should be tested with other cameras or software. Various close-range photogrammetric software and different types of intra-oral cameras could be compared to enable the fastest, most accurate 3D reconstruction.
- A reliable technique should be developed for metric calibration of the 3D model if the photogrammetric software does not include this feature.
- Photogrammetric methods could also be tested using video images rather than photographs.

Future studies are necessary to analyse the accuracy of the measurements of these 3D models compared with measurements obtained from other intra-oral scanners.

In addition, further assessments are needed to determine whether these 3D models could be used in current dental practice for CAD/CAM of prostheses.

Editorial note: A list of references is available from the publisher.

about



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