CHAPTER 1

1 Introduction

1.1 Why CAD/CAM

Reasons for the rapid development of CAD/CAM technology are manifold and it is difficult to name a primary trigger. Basically, the driving force behind all innovative developments in the history of mankind is certainly the curiosity of people regarding the question of "How does something work?". In the dental field, there is another decisive reason for the enormous growth of digital manufacturing technologies: the materials used in prosthetic dentistry. The requirements for materials that can or may be used in the oral cavity mean a reduction of possible material groups. The processing of suitable materials often leads to difficulties. Up to now, it has not been possible to process high-performance oxide ceramics in standard dental processes involving casting and pressing technologies. However, as materials scientists became convinced of the positive properties of the material, a way had to be found to make this innovative material machinable. The solution at the time was the subtractive machining of blank geometries (blocks or discs) using CNC technology. One thing is certain: Without the material zirconium oxide or zirconia (ZrO_2), the triumphal march of CAD/CAM technology would not have taken place, because other material groups could be formed with a variety of process technologies. It can be rightly claimed that zirconium oxide was the initial spark for the spread of dental CAD/CAM-supported fabrication. As a positive side effect, productivity and material diversity have increased.

As in industry and trade, individual work processes in dental technology are increasingly being automated. In addition, the price of dental work has now become a central point in therapy planning. Automation could contribute to producing restorations at a consistently high level, but even more effectively and efficiently. This in turn would make manual production in low-wage countries less attractive. Constant developments in hardware and software are already making it possible to economically manufacture individual items today. In recent years, this has led to a growing share of computer-aided production of dental work. Today, access to mechanical production processes is often part of the services offered by dental companies – be it in the form of systems for dental practices, dental laboratories or in-house production centres.

In the future, too, new software tools and further developments in the machine sector will enable the processing of innovative materials and allow the CAD/CAM sector to continue to grow.

Advantages of CAD/CAM

Essential advantages of CAD/CAM-supported manufacturing technologies:

- Access to new, virtually flawless industrially prefabricated restoration materials
- Quality improvement associated with the standardized process chain
- Storage of complex data sets resulting in simple reproducibility
- Increased security due to extended planning options
- Improved precision in many areas

1.2 The historical development of CAD/CAM technology

Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) have their roots in the early 19th century. As early as 1808, Joseph-Marie Jacquard used punched metal cards for the automatic control of weaving machines, which significantly increased the productivity of the machines. He is regarded as the inventor of the exchangeable data carrier. By further developing the loom, Jacquard made a decisive contribution to the industrial revolution.

In 1949/50, at the suggestion of the U.S. Air Force, the MIT (Massachusetts Institute of Technology) began to develop numerically controlled machines (NC machines) for the production of parts for large aircrafts. The templates and models required for shape milling were highly complicated and could only be produced using conventional technology in a costly and time-consuming manner. However, the contours of the large workpieces could easily be described by mathematical functions, so a control system was developed that could direct a milling machine. Initially, this was an NC control for a countersunk milling machine that received the necessary path and switching information via punched cards.

In 1959, Don Hart and Ed Jacks developed the first CAD system (DAC 1, General Motors and IBM), which was only introduced to the public in 1964. In 1959, a group of five started the DAC-1 project, initially called “Digital Design”. The aim was to develop a computer system to describe the geometry of vehicle bodies.

In the dental field, François Duret is regarded as the father of computer-aided manufacturing of dental prostheses (Fig. 1). As early as 1971, he began his theoretical and experimental research into the computer-aided manufacture of dental prostheses (the “Sophia” system). In 1979, Heitlinger and Rodder undertook the first attempts at computer-assisted manufacturing of dental prostheses (the so-called “DentiCAD” system). However, neither system was able to assert itself.

With the Cerec system, Mörmann and Brandestini succeeded in designing a CAD/CAM system that has been widely used in the dental market. Development began in 1980 and Cerec was launched in 1985 by Siemens Dental, which subsequently developed into Sirona Dental Systems (today Dentsply Sirona, Bensheim, Germany).

In 1983, Matts Andersson invented and developed the Procera method for the duplicable production of crowns. Five years later, this system was launched worldwide by Nobel Biocare (Kloten, Switzerland). In 1989, DCS introduced the Precident System (DCS Dental AG, Allschwil, Switzerland), which was used to process metals and densely sintered zirconia using water cooling. In 1993, Jef van der Zel presented the Cicero System (Cicero Dental Systems B.V., Hoorn, Netherlands), aimed at complete production of layered ceramic crowns and bridges using a digital process.

Another decisive step in the history of digital dental manufacturing technology is the introduction of the CAM all-ceramic system Cercon Smart Ceramics (DeguDent GmbH, today Dentsply Sirona, Hanau, Germany). This made it possible for the first time to mill the high-performance ceramic zirconia in a pre-sintered phase (white body) with enlarged geometry, and to let it shrink by a defined value in a downstream sintering process. This so-called DCM process (Direct Ceramic Machining) was developed by the Zurich scientists Professor Peter Schärer (University Dental Clinic Zurich/Switzerland) and Professor Ludwig J. Gauckler with his research group at the Institute for Nonmetallic Inorganic Materials at the ETH Zurich.

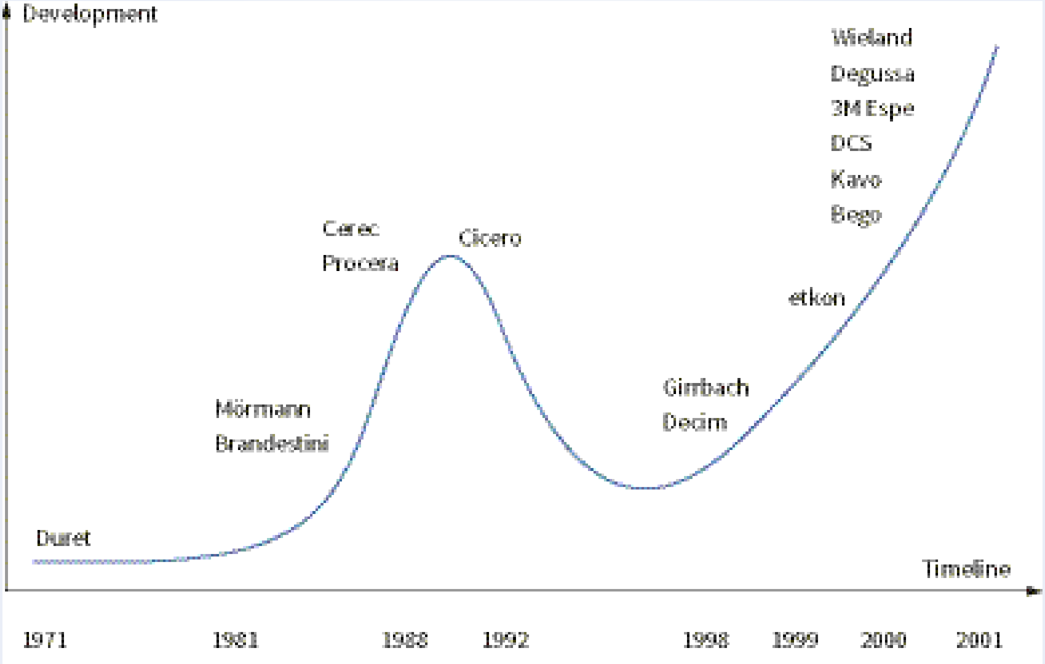

Fig. 1 Development of CAD/CAM technology in the dental field (according to Professor Mehl)

Karl Girrbach is one of the pioneers of dental CAD/CAM technology. In 1999, the company Girrbach (Girrbach Dental GmbH, Pforzheim/Germany) introduced Digident, an impressive CAD/CAM system handling a variety of materials for processing under water cooling.

At the International Dental Show (IDS) 2001, several different CAD/CAM systems were presented including Everest (KaVo, Leutkirch, Germany), Etkon (Etkon AG, Gräfelfing, Germany) and Lava (3M Espe Dental AG, Seefeld, Germany). In the following years, more and more dental manufacturers added CAD/CAM technology to their portfolios. Further milestones include selective laser melting with the Bego Medifacturing System (Bego Medical AG, Bremen, Germany), launched in 2002, and the development of digital veneering technology by Schweiger, Beuer and Eichberger in 2005 (market launch 2009/2010).

In the area of digital intraoral 3D acquisition, the Lava COS (2009) and the Straumann Cadent iTero (2010) systems were launched in addition to the Cerec acquisition unit. Other systems followed at the IDS 2011, 2013 and 2015, with the focus on the Trios scanner (3Shape, Copenhagen/Denmark).

All future developments will focus primarily on the complete digital workflow and treatment concepts that incorporate digital possibilities.

References/Further literature:

3M Espe: Startschuss ist gefallen: Offizielle Markteinführung des Lava™ Chairside Oral Scanner C.O.S. Pressemitteilung, 3M ESPE 08/2009

Baltzer A: Oxidkeramiken und CAD/CAM-Technologie: Atlas für Klinik, Labortechnik und Werkstoffkunde, Deutscher Ärzteverlag, 1. Auflage 2007, ISBN-10: 3-769-13342-0

Filser F, Kocher P, Weibel F, Lüthy H, Schärer P, Gauckler LJ: Reliability and strength of all-ceramic dental restorations fabricated by direct ceramic machining (DCM). Int J Comput Dent, 2001; 4:89-106

Lüthy H, Filser F, Gauckler LJ, Schärer P: High reliable zirconia bridges by direct ceramic machining process (DCM). J Dent Res, 1998; 77:1045

Mönkmeyer U, Poerschke F, Kurbad A, Reichel K, Scharl V: Die präfabrizierte, anatomische, polychrome CAD/CAM-Krone. Quintessenz Zahntechnik 4/2005, S. 368-380

Nitschke A: Gastkommentar. DIGITAL_DENTAL_NEWS 2010; 9: 3 (2010)

1.3 CAD/CAM: Principles at a glance

The terms CAD/CAM are currently used in dentistry as synonyms for “milled” restorations. Strictly speaking, this is not really the case. CAD is the abbreviation for “Computer Aided Design”. CAM stands for “Computer Aided Manufacturing”. The term CAD/CAM does not provide any information about the actual manufacturing process. This can be subtractive (milling and grinding) or additive (rapid prototyping).

All CAD/CAM systems consist of three different components:

- A digitalization tool/scanner for converting a real existing geometry into a data set that can be processed by computer.
- Processing software that prepares the existing data set and generates a data set for the product to be created, depending on the application.
- A manufacturing technology that converts the created data set into the desired real geometry.

Different ways to CAD/CAM-supported fabrication of dental prostheses

Depending on the location of the CAD/CAM system components, a distinction is made in dentistry between different manufacturing concepts:

- Chairside systems
  - In-office
  - Out-office
- Labside systems
- Systems for central production in production centres

Chairside systems

In-office

With this manufacturing variant, all CAD/CAM system components are located in the dental practice. The dental prosthesis is fabricated chairside without the need for a dental laboratory. The digitizing instrument in this case is an intraoral camera, which replaces a conventional impression in most clinical situations. This saves time and enables practitioners to provide patients with indirectly fabricated restorations in one treatment session.

Currently this option is offered by Sirona (Cerec system), Carestream, Zfx and Planmeca. The Cerec system works with water cooling. Different material classes from glass-ceramic blocks to high-performance oxide ceramics can be processed. Ceramic inlays have been manufactured with this strategy for more than 25 years. In the scientific literature, success rates for CAD/CAM-manufactured inlays are stated to be about 90 percent after ten years and about 85 percent after twelve and sixteen years respectively. The Cerec system is historically the oldest CAD/CAM system in dental medicine and is currently in its third generation. A particular strength of the system is the construction software, which has since been supplemented by an exact three-dimensional reconstruction of the occlusal surface.

Out-office

In these systems, the classic analogue impression is replaced by a digital intraoral 3D scan. The intraoral cameras are based on various physical acquisition technologies. In addition to classic strip light triangulation technology, the laser light section technique or the confocal laser beam principle are used. With out-office systems, data collected is not processed further in the dental practice but sent online to a central computer. From here, the dental laboratory can download data for further processing with the appropriate CAD software. Ultimately, dental technicians decide whether to manufacture the prosthesis themselves or send the design data to a production centre for implementation.

Labside systems

This type of production is based on the conventional treatment procedure between dentist and dental laboratory. The dentist sends the impression to the laboratory, where a plaster positive model is created and the further CAD/CAM work steps take place. A scanner is used to generate three-dimensional data from plaster models and process them using design software. Based on the generated data sets, the real geometry is produced on special milling machines that are also located in the dental laboratory. Accuracy and fit can be checked on the master model and, if necessary, corrected based on the model. The frameworks are finished by the dental technician using manual veneering techniques.

Systems for central production in the manufacturing centre

The third possibility for the computer-aided fabrication of dental prostheses is central production in manufacturing centres. For example, "satellite scanners" in the dental laboratory are connected to the production centre via the internet. Data sets designed in the dental laboratory are transmitted to the production centre, the restoration is produced using CAD/CAM support and then sent to the laboratory. Because work steps 1 and 2 take place in the laboratory and only step 3 takes place centrally, the design of the restoration remains in the hands of the dental technician.

The advantage of "outsourcing" CAM production is the lower investment needs. Only the digitization instrument and the software have to be purchased. Nevertheless, high-quality manufacturing processes can be accessed. In addition, this method offers a higher degree of independence, as there is no commitment to specific manufacturing technologies. It should be pointed out that many centrally used CAD/CAM systems are currently only available as closed systems. This means that when you purchase a scanner from a manufacturer, only its manufacturing chain and product range can be accessed. In addition, the dental laboratory does not generate any turnover for the manufacture of the frameworks, as these are manufactured in production centres. Many production centres offer dental laboratories that do not own a scanner the option of sending their master models to the centre and having the frameworks scanned and manufactured there. With this procedure, further processing of the frameworks takes place in the dental laboratory, too. In addition, dentists have the option of sending the impression directly to a production centre. This type of fabrication is available for inlays, partial crowns, veneers, crowns, bridges and implant abutments.

Intraoral data acquisition leads to further simplification in CAD/CAM-supported manufacturing, meaning the digitalization of a currently still "analogue" step in the process chain. This allows further quality improvement and cost reductions. Software developments allow a direct quality assessment of the preparation and draw attention to any possibly necessary corrections before the data is finally sent to the dental laboratory or the production centre.

References/Further literature:

Beuer F, Schweiger J, Edelhoff D: Automatisierte Herstellung von Zahnersatz. wissen kompakt 2007, 1, 17-29, wissen kompakt, Springer Medizin Verlag und Freier Verband Deutscher Zahnärzte e.V. (2007)

Beuer F, Schweiger J, Edelhoff D: Digital dentistry: an overview over recent development for CAD/CAM generated restorations. BrDentJ, 2008. 204: 505-511

Otto T, De Nisco S: Computer-aided direct ceramic restorations: a 10-year prospective clinical study of Cerec CAD/CAM inlays and onlays. Int J Prosthodont, 2002; 15(2): p. 122-8

Reiss B: Clinical results of Cerec inlays in a dental practice over a period of 18 years. Int J Comput Dent, 2006; 9(1): p. 11-22

Sjögren G, Molin M, van Dijken JW: A 10-year prospective evaluation of CAD/CAM-manufactured (Cerec) ceramic inlays cemented with a chemically cured or dual-cured resin composite. Int J Prosthodont, 2004; 17(2): p. 241-6

CHAPTER 2

1 Data acquisition

1.1 Data acquisition based on 3D scanning and indirect data acquisition

Basically, a distinction is made in 3D scanners between tactile (= mechanical) and optical operation.

Tactile scanners are very accurate. Even undercuts, sharp edges and depth structures can be detected. Their disadvantage is that the measurements take a relatively long time and that the objects to be scanned can be "scratched" on the surface by touching them.

Optical 3D scanners, on the other hand, scan objects contactless with light. The scanning process is faster than with tactile methods, since many points (point cloud) are captured. However, absolute accuracy is somewhat worse compared to tactile systems. Especially when composing data sets of individual recordings, errors can occur – so-called matching errors (stitching errors).

3D scanners

Classification

- Tactile (= mechanical) scanners
- Optical scanners
  - Principle of coaxial probing
    - Confocal technique (for example, confocal laser beam principle)
    - Interferometry (for example, conoscopic holography)
    - Runtime procedure
  - Triangulation-based methods
    - Photogrammetry
    - Structured lighting
      - Flying spot system (not established in the dental field)
      - Laser light section technique
      - Strip light projection

Tactile (= mechanical) 3D scanners

Operating principle

Mechanical 3D scanners (3D Coordinate Measuring Machine = CMM) detect objects by tracing their surfaces using tactile instruments (= digitizer pens). Precision mechanics guide the probe over the object and record the three-dimensional position of the individual measuring points. Scanning is done manually or controlled automatically. Spatial coordinates of objects are acquired either via the position of the articulated arms or the position of the scanning pin on an XY coordinate table. The high precision of mechanical 3D scanners is based on the fact that the acquisition of the 3D coordinates of the measuring points is always related to the zero point of the coordinate system. Errors due to the superimposition of individual data sets (matching errors) are therefore excluded. However, due to the tactile contact, mechanical scanners cannot scan soft surfaces. A further disadvantage is that the chosen scanning tip cannot be arbitrarily small. Because of this, areas with a radius of curvature smaller than the radius of the scanning tip cannot be detected. In addition, mechanical 3D scanners are generally slower than optical 3D scanning systems.

Measuring sensor

The measuring sensor (probe) in coordinate measuring devices and machines is called the measuring probe. It usually consists of a thin rod with flexible bearings (often ceramic), with a hardened ball or a spherical semi-precious stone (ruby) at its end. Ruby is a very hard mineral and has almost no wear when touching objects. Since the distance of the outer surface of a ball to its centre and thus also to the centre axis of the measuring probe is always the same, an exact determination of the position from any practicable approach direction to the object is guaranteed.

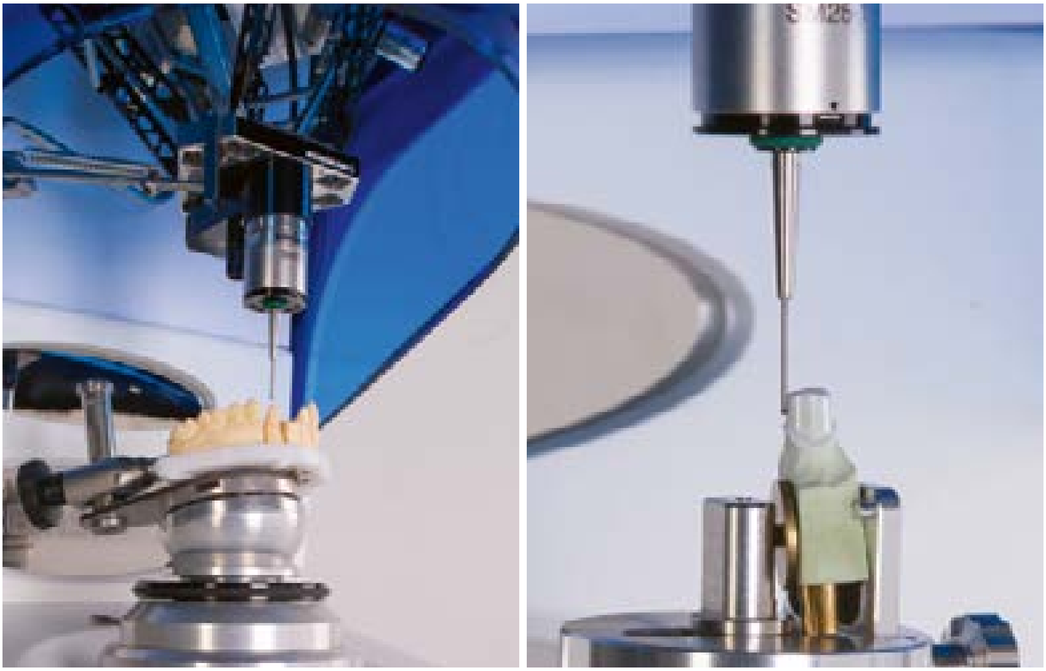

Fig. 2a & b Principle of a tactile measuring probe system (Photos: Renishaw)

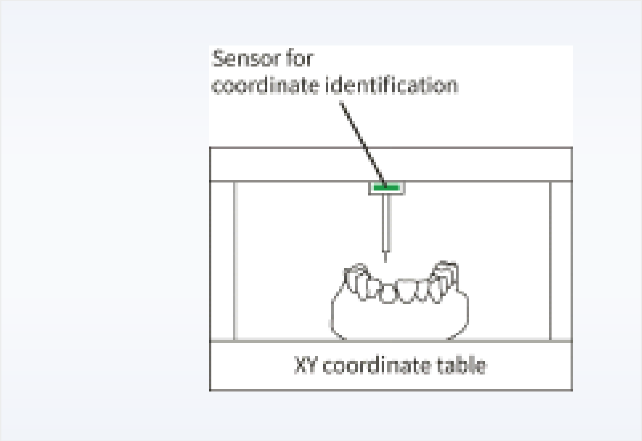

Fig. 3a Principle when scanning with a XY coordinate table (Illustration: Franke J., Ellermann J: 3D printer, 3D graphics software and 3D printing. Term paper)

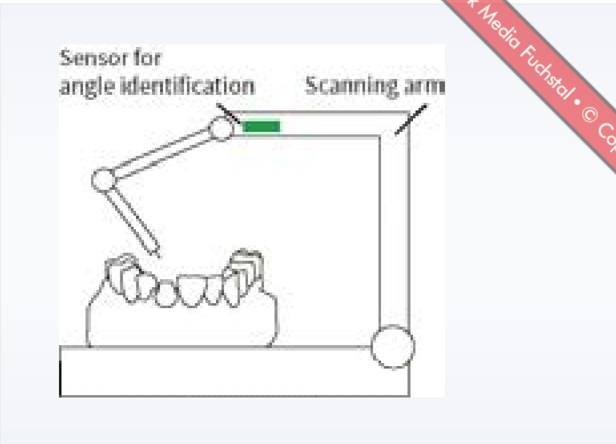

Fig. 3b Principle when scanning with an articulated arm scanner (Illustration: Franke J., Ellermann J: 3D printer, 3D graphics software and 3D printing. Term paper)

Touch probes

Touch trigger probes

These types of touch probes define the contact with the test object at the first deflection of the stylus. At the moment of deflection, the coordinates of the centre of the sphere and thus of the measured object are detected. For the next measurement, the probe must be retraced again. Then the next point on the measured object is scanned. This method is sufficient, for example, to determine workpiece positions (the workpiece zero point). Touch trigger probes are not used to capture numerous measuring points, for example, when scanning free-form surfaces. The scanning process would take a relatively long time due to the constant approach and retraction of the probe.

Measuring touch probes

Measuring touch probes are used to record many measuring points in a short time (Fig. 2). Although these touch probes are considerably more expensive, they are much more accurate, faster and universally applicable. A measuring system is integrated in the probe, determining the deflection of the stylus. This allows the 3D coordinates of the probe's ball centre to be determined successively at many measuring points without having to retract the probe from the measured object. The control system is able to move along the test object with a constant probing force and to continuously record data.

Mechanics of the measuring probe

With mechanical scanners, the measuring rod is flexibly mounted in all spatial axes. On the one hand, this prevents the measuring rod from breaking when it comes into contact with the objects to be measured. On the other hand, damage to the surface of the measured object can be avoided. The mechanical deflection of the probe is converted into electrical signals via highly sensitive switching systems.

Measurement process

The spatial coordinates of a measuring point are acquired by evaluating the XYZ coordinates of the stylus during the measuring process (Fig. 3a) or, in the case of scanners with articulated arms, by evaluating the angles (Fig. 3b).

Optical scanners

Optical scanners make it possible to digitize objects without touching them and to display them three-dimensionally. The acquired surface information is documented in the form of point clouds in the universal ASCII format. Optical scanners are differentiated according to their acquisition method after coaxial probing (Latin “coaxial”: with the same axis) and triangulation (Latin “triangulum”: triangle). The main difference between the methods is that the different measuring principles result in different acquisition angles (Fig. 4). The detection angle for coaxial probing is considerably larger.

The coaxial probing measuring principle

Confocal technology
(= confocal laser beam principle)

The principle of confocal technology is that the camera is directed at a specific point on the object surface whichit is focused on (Fig. 5 and 6). The position of the focal plane of the lens (Z value) is known. The X- and Y-values are captured during recording and the spatial coordinates are determined for all points in the focal plane. In the next step, the focus plane is shifted by a known value in the Z direction and the next surface focal points are determined. The surface is recorded layer by layer. The spatial coordinates of all measured surface points result in a 3D image of the object.

Interferometry (= conoscopic holography)

Interferometry is a physical measurement method based on the superposition of waves. Interferometric scanners use the wave characteristic of light to measure distances and thus to determine the Z-values of spatial points. This principle is based on the interference of two light waves. The phenomenon, called interference, occurs when two or more light waves overlap. The prerequisite for this is coherent light. This light is generated by a laser. In interferometry, a

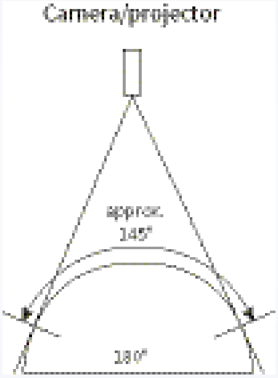

Fig. 4a The detection angle with the coaxial probing measuring principle

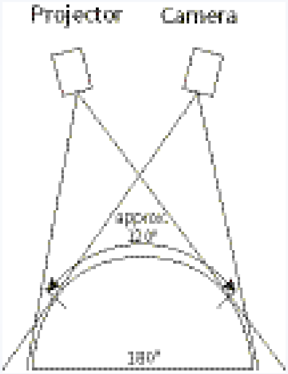

Fig. 4b The detection angle with the triangulation measuring principle

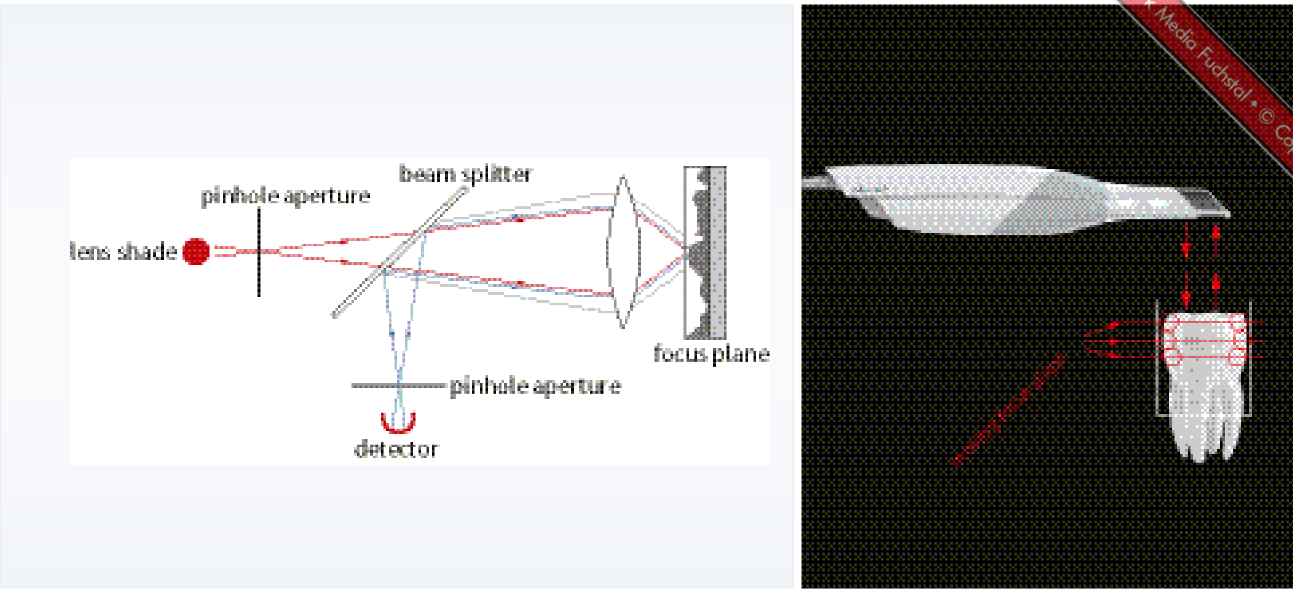

Fig. 5 & 6 Graphical representation of the confocal laser beam principle using the Cadent iTero (left) and cara Trios (right). The scanner uses the method of parallel confocal imaging, utilizing laser light and optical scanning to scan the surfaces and contours of the tooth and gum structures which are then recorded digitally. (Photo on the right: Heraeus Kulzer/3Shape/Fotolia.com/Sashkin)

light beam is split into two beams. One of the beams is sent directly to the object and the other indirectly. However, both partial beams hit the same object point and are reflected there. Due to the difference in the pathways of the two partial beams, characteristic overlapping patterns of the light waves occur.

These interferences result in a measurement of the distance to the object point. The interference pattern is recorded with the aid of a CCD sensor (charge-coupled device) and evaluated electronically. Information about the angle of the incident light beam is stored in the interference pattern. This angle is analyzed and the distance of the light spot is calculated from the angle information.

Runtime procedure (ToF = Time of Flight)

A further possibility in the area of coaxial probing are methods that measure the light signal transit time (Fig. 7). They measure the time it takes for a light signal to travel from the transmitter to the object and back to the receiver. Due to the speed of light, a

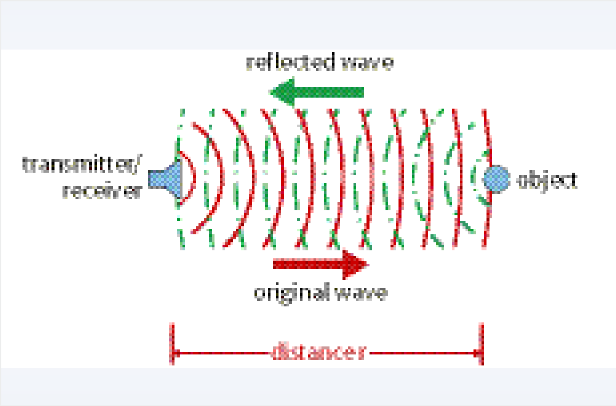

Fig. 7 Runtime methods make use of the echo principle.
(Illustration: Vierling F: Practical 3D | 3D-Praxis, 3D-Scanner. 2013)

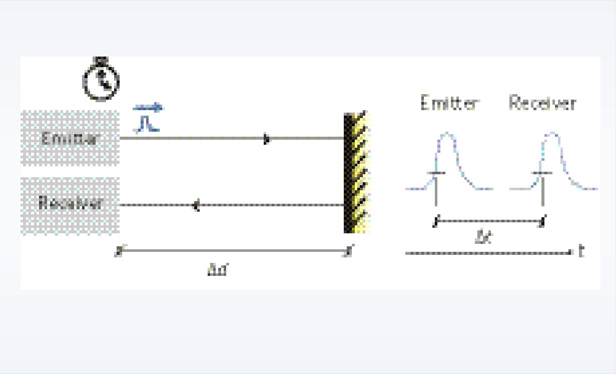

Fig. 8 Graphic representation of light pulse measurement (Illustration: Vierling F: Practical 3D | 3D-Praxis, 3D-Scanner. 2013)

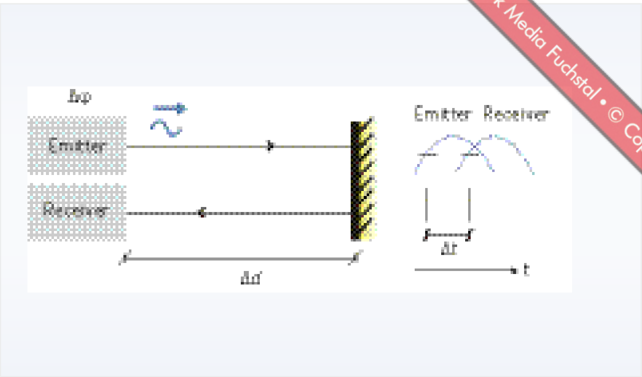

Fig. 9 Graphic representation of indirect transit time measurement (Illustration: Vierling F: Practical 3D | 3D-Praxis, 3D-Scanner. 2013)

temporal resolution of a few picoseconds (one trillionth of a second) is necessary. Basically, a distinction can be made between two methods of transit time measurement:

- *Light pulse measurement:*
  Short laser light pulses are sent and the time to re-arrival is measured (Fig. 8). For example, the distance between the moon and the earth is measured.

- *Indirect time of flight measurement:*
  The laser light source is operated continuously, but with limited power (Fig. 9). The measuring range is therefore limited to a few meters. To determine the distance, not only is the transit time used, but also the phase position of the reflected light intensity. Room scanners can be cited as an example of indirect time of flight measurement.

- *ToF cameras:*
  So-called Time of Flight cameras do not capture the objects point by point, but generate a complete 3D depth map covering the entire area. The cameras operate according to the principle of Time of Flight measurement, whereby the phase shift of the reflected light rays, caused by distance differences and pixel by pixel, are converted into depth values. This makes it possible to create a 3D reconstruction of the illuminated object with a single exposure. With ToF cameras, measurements are possible in extremely short times.

The measuring principle of triangulation

The principle of triangulation has long been known in measurement technology. Thales of Miletus used this principle to determine distances back in the 6th century BC. In the 19th century, the principle known as the “forward intersection method” was used in land surveying (geodesy). The Thales of Miletus theorem states: “The corner point of a triangle can be unambiguously determined if the length of the opposite side and the angles adjacent to it are known.” (Fig. 10 and 11). In practice, the angles α and β (see Fig. 10) are determined by targeting an object from two positions B1 and B2 with a known distance b (baseline).

The sine theorem can then be used to calculate the length of one of the two beams and then the distance of the object from the baseline (height of the triangle). To use this simple method to get accurate results, α and β must be determined with a minimal possible margin of error. An angle measuring instrument that makes this possible is the theodolite, which can be used not only for terrestrial, but also for astronomical position determination.

Depending on the task, different light qualities can be used as projection sources, such as laser light sources or light sources from the colour spectrum of visible light such as white light, short-wave blue light and others. The geometry of the projected structure can be punctiform (for example, laser dot), linear (for example, laser line) or planar (for example, strip pattern, colour pattern, stochastic pattern, etc.) (see Fig. 13). The measuring principle of triangulation is used for both laser scanners and strip light scanners.

Photogrammetry

Photogrammetry is the term used to describe all methods that can reconstruct surfaces of objects three-dimensionally through analysis of normal photos (Fig. 12). The system must have information about the camera and its orientation. In addition, the object must have distinctive points (corners and edges) that can be recognized or created by placing markers on them. In the simplest case, two images of an object from two different angles are adequate for calculating the three-dimensional geometry. The basic configuration of photogrammetry corresponds to human stereo vision with the two "cameras" (eyes) and the calculation of the two images in the brain. From the eyes' 2D images, the information is processed into three-dimensional information in the human brain.

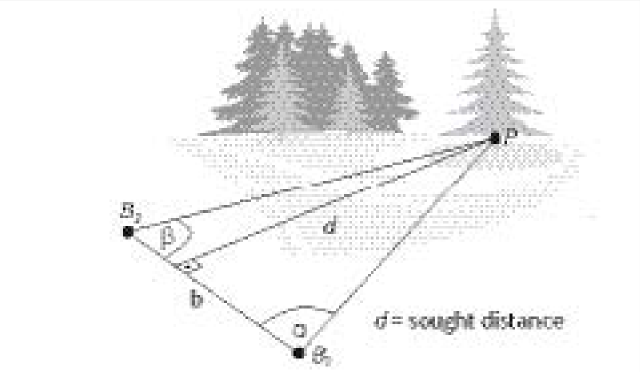

Fig. 10 The triangulation principle according to Thales
(Illustration: Gandyra M: Development of a 3D sensor for the shape acquisition of reflecting free-form surfaces on the basis of measured surface normal for CAD surface reconstruction. Dissertation, University of Kaiserslautern, Department of Mechanical and Process Engineering (2002); Image: Fotolia.com/Seamartini Graphics)

$$d = \overline{B_1B_2}\,\frac{\tan\alpha \cdot \tan\beta}{\tan\alpha + \tan\beta}$$

Fig. 11 Determination equation

Fig. 12 Scanning based on photogrammetry
(Photo: Imetric 3D SA)

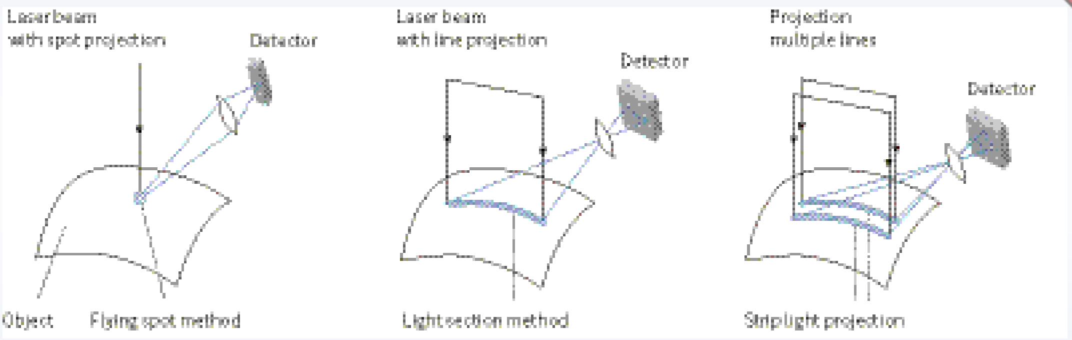

Fig. 13 Graphic representation of the different triangulation principles based on the methodology of structured lighting
(Illustration: Vierling F: Practical 3D | 3D-Praxis, 3D-Scanner. 2013; ISBN 9783000395826)

Structured lighting (Fig. 13)

- *Flying spot method*
  In the simplest case, structured lighting consists of a single point-shaped light beam, that scans the object spot by spot. The point-shaped scanning thus corresponds to the simple form of the triangulation process. The light beam transmitted and returned at a specific angle, as well as the distance between transmitter and receiver, form the sides of a triangle necessary for triangulation. In dental applications, flying spot methods have not become established due to the longer time required to capture the objects.

- *Light section method (for example, laser scanner = scanner with laser light section method)*
  Under a certain projection angle, a narrow light band (= sharp “light-dark boundary”) is projected onto the surface of the object to be imaged. Such light lines can be easily generated if a glass rod is positioned perpendicular to the laser beam axis. The laser beam incident on the glass rod is formed into a fan-shaped line of lights with a Gaussian intensity distribution along the line. More complex projection techniques make it possible to generate laser lines with almost homogeneous intensity distribution, increasing the resolution of the light section sensor.

  The light reflected at the object surface is captured by two-dimensional video camera CCD image sensors or by detectors. The line shown there is no longer straight. It appears slightly to strongly curved. This lateral offset in the registered image already represents a measure of the heights and depths along the light section of the illuminated object. If one imagines the projected line as a sequence of many individual spots, this corresponds to the laser triangulation already described. Each of these imagined light spots generates a reflection on the matrix field of the CCD chip, triggering electrical signals in the illuminated image pixels. These signals allow the exact point of contact on the chip to be determined. With additional knowledge of the exact position of the light source, the orientation of the light plane and the position and orientation of the camera, an image processing system can calculate the 3D coordinates for each individual point of the light section.

Fig. 14 Example laser light section scanner: 3Series and 7Series (Photo: Straumann)

Examples of dental laser light section scanners

- Current Scanners:
  - Dental Wings 3Series
  - Dental Wings 7Series
- Older Scanners:
  - Straumann es1 und cs2
  - 3Shape D200,D640, D700, D800, D810, D900, D910

- *Strip light projection (= strip light scanner)*

  Strip light projection is simply a logical continuation of the light section principle. In contrast to the light section method, certain light/dark patterns are projected onto the object in rapid succession. The pattern sequence must be known to the software. Otherwise, differentiation would not be possible by comparing the reference and real images. The evaluation is done by triangulating the depth values along the light/dark boundaries in the camera image.

The method of strip projection has only been used since the early 1990s and is therefore a relatively new possibility for 3D object capture. Strip light projection is widely used in dental scan systems. The strip projection technique is part of the group of 3D imagery measuring techniques. These are summarized under the generic term “topometry”. According to Breuckmann, they share the following characteristics:

- Triangulation measuring principles
- Measurement with structured lighting
- Pictorial acquisition of 3D measurement data
- Dynamic value measurement recording
- Computer-aided online processing

Strip light projection is a simple procedure to generate spatial information of an object. A light strip pattern is projected onto the object to be scanned. In order to be able to clearly distinguish the strips, they are coded. Several patterns, consisting of illuminated and non-illuminated strips, are projected onto the object one after the other. In order to image as many spots as possible on the surface to be scanned with a light/dark contrast, the strip pattern varies from one projection to the next. The detection of the light/dark contrast of the strip light projection also depends on the surface quality (Fig. 15). Thus, non-reflecting plaster surfaces can

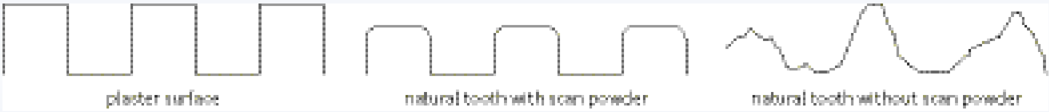

Fig. 15 Brightness distribution in the differential image with strip light projection. The quality of the signal of the strip light projection depends strongly on the surface condition (for example, reflection of a glossy surface).

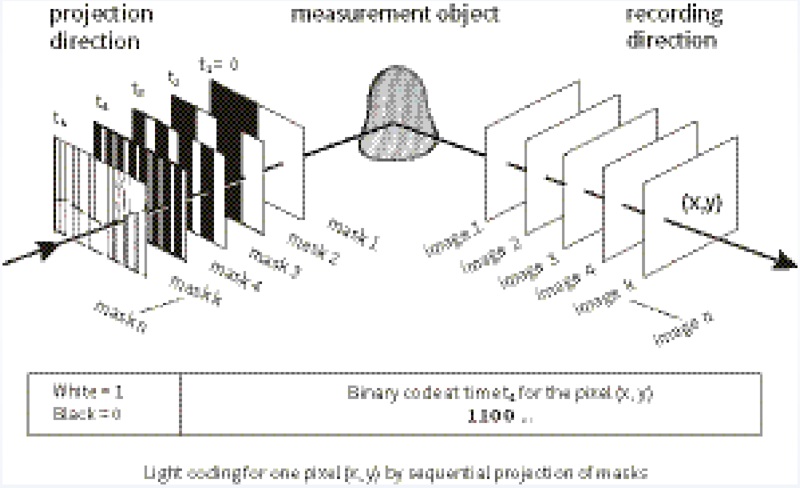

Fig. 16a Creation of a strip pattern using mask exposure (Illustration: Gandyra M: Development of a 3D sensor for the shape acquisition of reflecting free-form surfaces based on measured surface standards for CAD surface reconstruction. Dissertation, University of Kaiserslautern, Department of Mechanical and Process Engineering (2002))

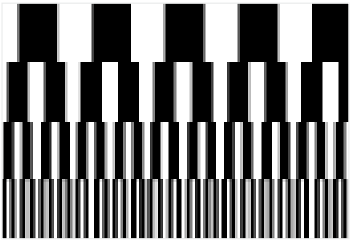

Fig. 16b Strip pattern in Gray code method

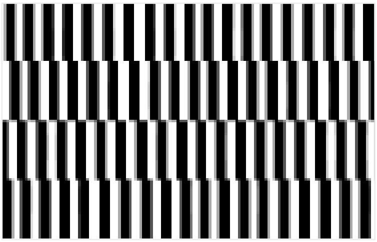

Fig. 17 Pattern in phase shift method

be scanned very well, while reflecting surfaces of natural teeth (without scan powder) often lead to very inaccurate signals.

Creation of the strip pattern

Following methods for the creation of strip patterns are common:

- Coded light approach with mask exposure = Gray code method
- Phase-shift procedure
- DLP projection (Moiré effect)

Coded light attachment (CLA) with mask exposure = Gray code method

The coded light section method is a strip projection method measuring absolute values (Fig. 16). The phase information f (projection direction) required to calculate the object coordinates is acquired via a defined space-time coding. For this purpose, different strip patterns are sequentially projected onto the object to be captured during mask exposure. The strips are coded so they can be clearly distinguished. Several patterns, consisting of illuminated and non-illuminated strips, are projected onto the object in a fixed sequence. The width of the strips is reduced by half from one mask to the next. The projected patterns are recorded with a camera one at a time. Each pixel is assigned an n-bit code; n is the number of projected patterns. This code clearly defines the origin of the incident light beam in the projector. This can be used to calculate which column in the projector generates which particular light beam and through triangulation, the space coordinates (in particular the Z coordinates) of the illuminated points in space can be determined.

Phase coding = Phase shift method

The phase shift method is one of the dynamic methods of strip analysis (Fig. 17). This technique also makes it possible to detect and evaluate points that are not directly on one of the projected lines. The phase shift method in principle works similarly to the coded light approach (CLA). However, the width of the projected strips is not changed, but the position on the model to be scanned is shifted. In the phase shift method, a sinusoidal line grid is projected perpendicularly onto the object to be measured and captured by a CCD camera at a fixed angle and distance. The sinusoidal intensity is modulated in the light, enabling unambiguous assignment of the origin of the light beam incident on the surface. As a result, this “sinusoidal strip pattern” generates a harmonic intensity signal at each measuring point on the scanned object, allowing exact phase position assignment. With the aid of the indirectly coded phase in one dimension and the assignment of an examined pixel to its phase, the required project coordinates can be obtained. Triangulation is then used to obtain the corresponding depth value (Fig. 18 to 20) analogous to the CLA method.

DLP projection

For some years now, so-called DLP projectors (Digital Light Processing) have also been used to generate strip patterns. The core of this technology is the Digital Micromirror Device (DMD), an integrated circuit with a tiny mirror that can be tilted by an electrical impulse for each individual pixel. The image is generated by selectively controlling the tilting mirrors so that the light is directed or deflected in the direction of the projection optics. This makes it possible to create illuminated and non-illuminated projection areas pixel by pixel and in turn generate strip patterns and change them. It can also be used to create other pattern projections for 3D scanning such as stochastic patterns.

DMD technology was developed by Texas Instruments (TI). TI is the sole owner of this technology. DLP projectors are used, for example, in the S900 3D strip light scanner from Zirkonzahn (Fig. 21) and in the Comet 6 3D strip light scanner from Carl Zeiss Optotechnik GmbH. Furthermore, DLP projectors are used in the field of additive manufacturing for the so-called mask exposure process.

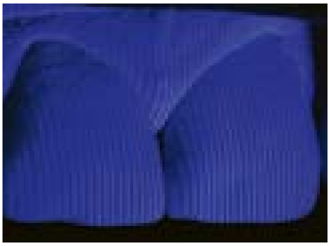

Fig. 18 Strip light projection of the intraoral acquisition system Cerec AC (Dentsply Sirona)

Fig. 19 Strip light projection of the laboratory scanner Lava Scan ST (3M Espe)

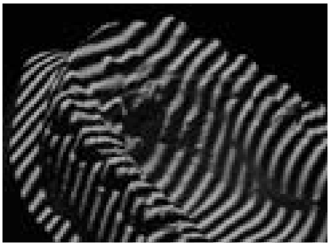

Fig. 20 Strip light projection of the S600 laboratory scanner (Zirkonzahn)

Fig. 21 Example S900 strip light scanner with articulator (Photo: Zirkonzahn)

Fig. 22 Example strip light scanner with optical referencing ring Imetric IScan D 101 (Photo: Imetric 3D)

Fig. 23 Hybrid solution: combination of mechanical and optical scanner Renishaw DS 10 (left) and DS 20 (right) (Photos: Renishaw)

Example of dental strip light scanners

Current Scanners:
- 3Shape E1, E2, E3 E4, D1000, D2000
- AmannGirrbach map 200+, map 600
- Evolution Plus (Zfx)
- CADStarCS Neo, CS Neo Pro, CS Ultra Pro
- Dental Wings Virtuo Harmony
- Zirkonzahn S300, S900
- Scan Box, Vinyl Open Air, Vinyl, Vinyl High Resolution (smart optics)
- Tizian Smart Scan Plus (Schütz Dental)

Older Scanners:
- KaVo Everest Scan, Scan Pro
- 3M Lava Scan ST
- AmannGirrbach Ceramill map300, map 400
- CADStar CS1
- Zirkonzahn S600

A special feature of strip light scanners is the optical referencing ring. With the aid of optical markers applied to the referencing ring, the individual images from the scanning process are assembled without serial addition of matching errors. Such scan systems are considered highly accurate. They are used, for example, for 3D measurement of implant models for the fabrication of CAD/CAM-manufactured bar constructions. Example: Imetric IScan D 101 (Imetric 3D) (Fig. 22).

- *Hybrid solution*
  With the Renishaw Dental Studio (RDS), Renishaw offers a hybrid solution (Fig. 23). The advantages of both acquisition methods – optical and tactile – are combined. While the jaw scan is performed with the optical system (Renishaw DS 20), the single stump is scanned with the tactile system (Renishaw DS 10) and fused into a single digital surface in the CAD software. The result is faster object detection with high precision in the relevant areas. The spiral scan with direct scanning of primary telescopes and abutment enables very good friction and fit. The associated Renishaw Dental Studio software integrates the tactile scan into existing processes and, according to the manufacturer, can be combined with existing optical scanners to form a hybrid CAD system.

Dental application

The technology of Nobel Biocare's mechanical scanner was already used in dentistry in the early 1990s. The three-dimensional structure of plaster models was initially recorded by manually scanning the plaster models with a so-called "digital pen". In further development, the scanning process was automated. This resulted in systems in which the surfaces of master models and dies are scanned fully automatically (Fig. 24 to 27). The Nobel Biocare Procera Forte scanner is one example. Since Nobel Biocare replaced

Fig. 24 Mechanical scan Nobel Procera Forte (Photo: Nobel Biocare)

Fig. 25 Mechanical scan Nobel Procera Piccolo (Photo: Nobel Biocare)

Fig. 26 Probe of the Nobel Procera Forte (Photo: Nobel Biocare)

Fig. 27 Renishaw DS 10 mechanical scanner (Photo: Renishaw)

mechanical scanning with a purely optical laboratory scanning system, Renishaw, a manufacturer of digitizing technology, has been offering a CAD/CAM system for dental restorations that incorporates a fully automated mechanical laboratory scanner.

Dental suppliers of mechanical scanners
- Nobel Biocare (Nobel Procera Forte, Nobel Procera Piccolo)
- Renishaw (DS 10)
- Tizian Smart Scan-System (Schütz Dental)

The measuring principle of coaxial probing

(See also explanations on page 18)

Conoscopic holography (Nobel Biocare)

Conoscopic holography is an optical measuring principle for non-contact three-dimensional measurement of surfaces (Fig. 28 to 31). The principle is based on the interference of two light waves. The prerequisite for interference is coherent light. This light is generated by a laser. The advantage of the conoscopic holography measuring principle is that the optical

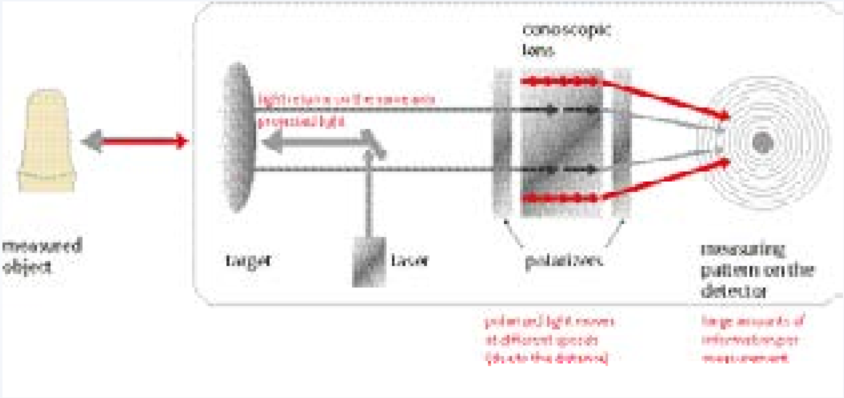

Fig. 28 Principle of conoscopic holography (Illustration: Nobel Biocare)

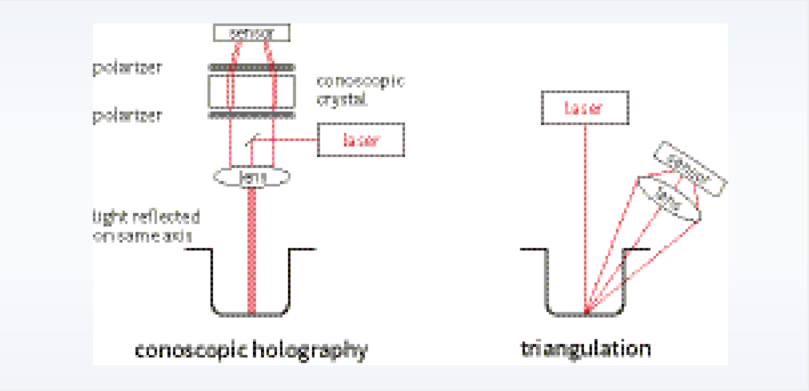

Fig. 29 Difference between conoscopic holography and triangulation
(Illustration: Nobel Biocare)

Fig. 30 Nobel Procera Scanner
(Photo: Nobel Biocare)

Fig. 31 Illustration of the Nobel Procera Scanner in function
(Illustration: Nobel Biocare)

axes for illumination and measurement are identical (collinearity). In contrast to the triangulation method (such as laser triangulation or strip light projection), components with a high aspect ratio and steep flanks (up to ± 85° to the measuring direction, see Fig. 29) can easily be measured with the conoscopic sensor. This is why conoscopic holography is ideally suited for measuring steep angles and deep depressions such as cavities (for example in impressions) or interdental areas.

References/further literature:

Breuckmann B: Bildverarbeitung und optische Messtechnik in der industriellen Praxis. München: Franzis Verlag, 1993

Buse K, Luenneman M: 3D Imaging: Wave Front Sensing Utilizing a Birefringent Crystal, Physical Review Letters. The American Physical Society, Vol. 85, 16/2000; S. 3385-3387

Franke J, Ellermann J: 3D-Drucker, 3D-Grafik-Software und 3D-Drucken. Hausarbeit

Gruber M, Häusler G: Simple, robust and accurate phase-measuring triangulation. Optik 89. 1992; 118-122

Gandyra M: Entwicklung eines 3D-Sensors zur Formerfassung spiegelnder Freiformflächen auf Basis gemessener Oberflächen- normalen für die CAD-Flächenrekonstruktion. Dissertationsschrift, Universität Kaiserslautern Fachbereich Maschinenbau und Ver-fahrenstechnik (2002)

Mugnier L: Conoscopic Holography: Toward Three-Dimensional Reconstructions of Opaque Objects, Applied Optics. Optical Society of America, Vol. 34, 8/1995; S. 1363-1371

Neuhaus M:
http://www.michaelneuhaus.de/cmm/koordinatenmesstechnik.htm

Tombers A: Einsatz der optischen 3D-Messtechnik in der Fertigung von Triebwerksbauteilen – Potenzialabschätzung zur Prüfzeitreduktion. Lehrstuhl für Technische Mathematik, Universität Paderborn 2006

Vierling F: Practical 3D | 3D-Praxis, 3D-Scanner. 2013;
ISBN 9783000395826

Wikipedia: http://de.wikipedia.org/wiki/Scanner_(Datenerfassung)#3D-Scanner