Analysis of Layer Arrangements of Aesthetic Dentures as a Basis for Introducing Additive Manufacturing

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Abstract

Aesthetic dentures are highly individual products, needing to adapt to the patient's natural dentition in both color and shape. In general, dentures are geometrically complex structures, consisting of several layers of different materials, which are applied consecutively. This is why efforts are being made to introduce additive manufacturing into the production process of aesthetic dentures which is to date largely based on manual work of skilled professionals. In order to successfully apply additive manufacturing accurate models of the denture to be produced are essential. In this paper the layer arrangements of dental crowns from real patient cases are analyzed. Different approaches, based on normal vectors, cylindrical coordinates, spherical coordinates and paraxial rays, are compared to each other. The emphasis of this comparison lies on transferring layering strategies from analyzed patient cases to future patient cases where the geometry might be slightly different but a similar optical impression is desired. The most suitable approach for this purpose has been identified, implemented and tested.

Keywords: Dentures, CAD/CAM, Layering strategies, Thickness measurements

Introduction

The potential for additive manufacturing in dentistry is immense. Dentures are of highly individual shape and are produced in quantities of one [7; 9; 10]. Layering strategies must be applied to mimic natural properties of teeth and allow for a wide variety of shades [22; 23]. The strengths of additive manufacturing – capabilities for complex and small geometries [5], method-immanent use of layers [19], energy and material efficiency [25], wide range of usable materials and material combinations [5] – can be optimally exploited. Production time and costs can potentially be reduced as well as the quality of the final product improved if a shift is being made from manual work of dental technicians to machine-based production.

Typical materials for dental restorations include metals, polymers and ceramics [4; 6]. This work focuses on dental crowns, i.e. replacement of single teeth, in the form of milled frameworks which are veneered with ceramic materials. Translucency is a distinctive differentiation criterion for veneering materials [1; 28]. The framework material is usually opaque. Materials of following layers allow for light trespassing and therefore offer the technician possibilities to create an optical impression as natural as possible. For example, lighter colors at the cutting edge of a tooth, white spots or translucent effects of yellowish and greyish colors can be realized. Apart from their translucency properties the base colors of the materials are of

importance [20]. Professional suppliers of dental materials offer wide varieties of color palettes [17].

Layering strategies are essential to create dentures of high aesthetic value. Thicknesses of layers [24] contribute to the final color impression [16]. Generally speaking, the thicker a layer is, the less visible are color and shape of the underlying layers. Also, the less translucent a material is, the less visible are color and shape of the underneath. In addition, the base colors of the materials of all different layers have an influence on the color that is perceived on the outer surface of the denture. Until now, experience and skills of dental technicians are relied upon to adjust veneering layers of dentures correctly [11; 18; 29]. In order to enable the use of additive manufacturing it is important to create a digital representation of these layers. In this way, they become reproducible and can be passed on to material-applying machines. That is where this work sets in. Layer arrangements of existing dental crowns are analyzed by different approaches. The underlying aim is to be able to store layer arrangements and transfer them to future patient cases where the specific color impression is needed again.

Data base

For this work single crown dentures from 30 anonymized patient cases have been analyzed. They are all dentures to replace front teeth. These dentures have been produced by one and the same dental technician in a laboratory of current standards, namely Form For Function GmbH, located in Darmstadt, Germany. The dental technician at work digitized the dentures after every applied material. They are each available as 3D scans and photos. The files stemming from the 3D scans are in STL format. Fig. 1 gives an example of such a digitized production step.
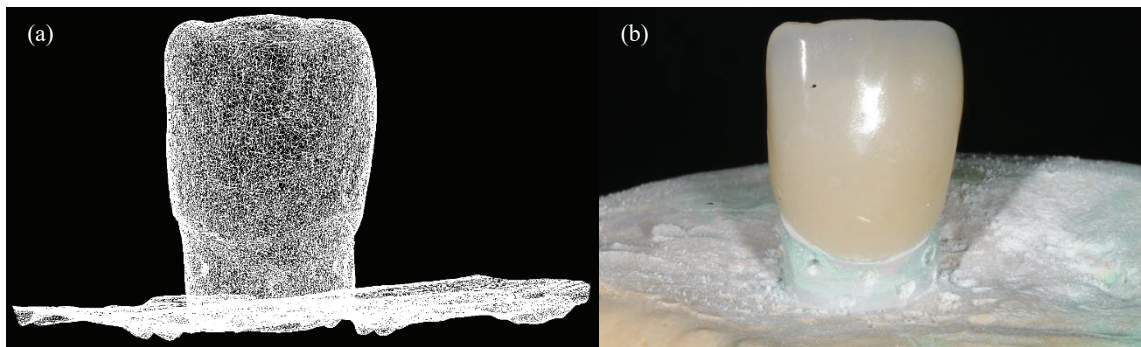

Fig. 1: (a) STL model and (b) photo of a denture

The dentures analyzed in this work are based on materials from VITA Zahnfabrik GmbH. Color 3M2 has been chosen as it is a common color in dental practice. Enamic is used as the framework material. LC flow is used for the veneering steps. Fig. 2 depicts the used materials.
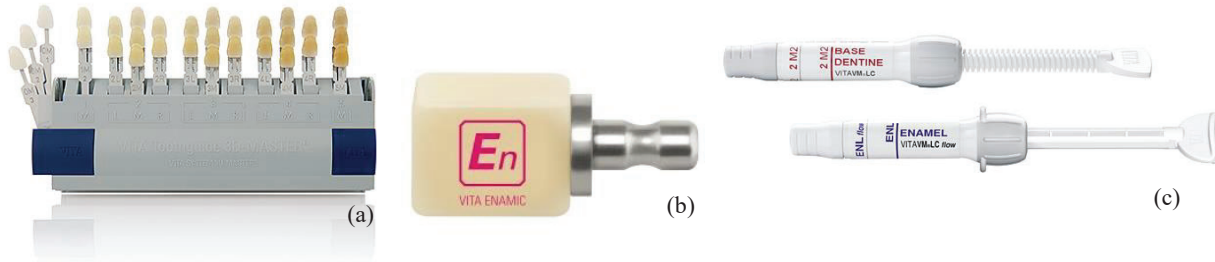
Fig. 2: (a) VITA Tooth Guide 3D-Master to determine a patient's tooth color, (b) VITA Enamic block for milled frameworks, (c) VITA VM LC flow for application of upper layers [26]

The most simple layering strategy consists of the framework milled out of Enamic, one veneering layer of dentine LC flow (to model the overall body) and one veneering layer of enamel LC flow (to model the cutting edge). Additionally, the tooth stump is relevant [7]. It is not part of the denture, but part of the remaining tooth substance in the patient's jaw. The finalized denture will be fitted onto the tooth stump. The stump therefore defines the inner contour of the framework and is for that reason included into the 3D STL models. Fig. 3 depicts one example of a simple layer arrangement. Further layers can become necessary when there are more complex color effects to be modeled.
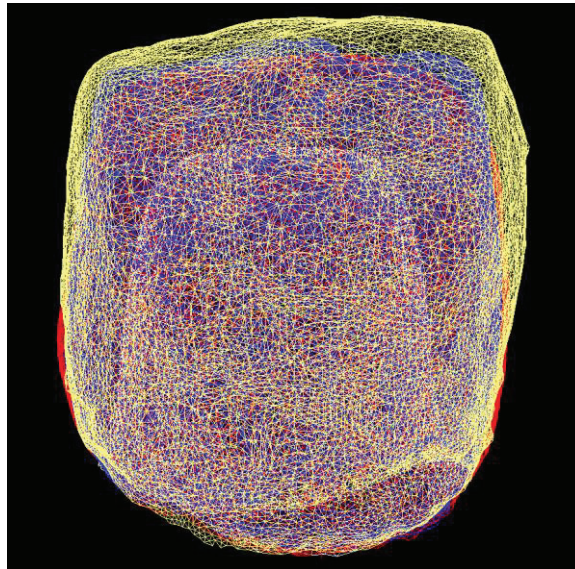

Fig. 3: Example of a layer arrangement (white = tooth stump, red = framework, blue = dentine, yellow = enamel)

Comparison of possible approaches

Determining the thickness of a layer as shown in Fig. 3 is a complex endeavor. Each layer is a three-dimensional object that varies in its thickness over the entire freeform surface, with the variations taking place in small value ranges. In addition to measuring the layer thicknesses, the approach this paper aims for should also be able to transfer the layer arrangement to a future patient case. It is assumed that for such a potential future patient case the contours of the tooth stump and the outer silhouette are given. The first being determined by what is left of the original tooth and how the dentist grinds it down. The latter being determined by the adjacent teeth in the patient's

jaw. Again 3D scanning devices, e.g. intra oral scanners, could be used to digitize these two limiting contours.

When discussing thicknesses, it should be pointed out how the term thickness is understood. Generally, thickness is conceived as a cross-sectional expansion of a body [27], measured in the direction of the surface normal from a lower surface to an upper surface. This paper complies with this definition. For all layers of translucent materials the actual thickness measured along the surface normal is what defines to which extent underlying structures are visible and contribute to the color impression. Only if this thickness is applied to a new denture in a new patient case it is ensured that the color impression at a certain point resembles the color impression of the original denture at the corresponding point. Whenever thicknesses are not measured in normal direction in the approaches presented in the following sections it will be pointed out in their description.

I. Normal vector approach

Since the 3D models at hand are available as STL files, i.e. with triangulated surfaces, it is an obvious choice to use the existing normal vectors of the model's triangles. The analyzed files contain between 50.000 and 75.000 triangles per layer surface. Even higher resolutions could be achieved in the scanning process. Thus, information about layer thicknesses at an almost unlimited number of locations can the obtained. Fig. 4 shows how normal thicknesses are measured in a dental crown model.
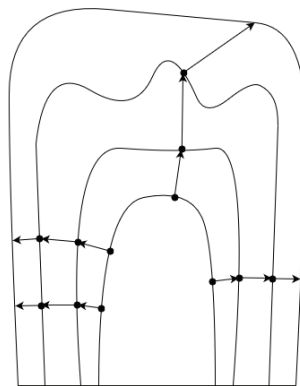

Fig. 4: Schematic representation of the normal vector approach with some exemplary measuring points

The main advantage of using the normal vector approach is that the correct thicknesses (i.e. thicknesses in surface normal direction) are measured and no need for error handling arises. Apart from that, all areas of the tooth are included into the calculation as all normals of all triangles are used. However, one difficulty of the approach is to determine in which direction it should be applied. When working with normal vectors it does make a difference whether distances are measured from the lower to the next-highest layer or the other way around. Fig. 5 illustrates this fact.
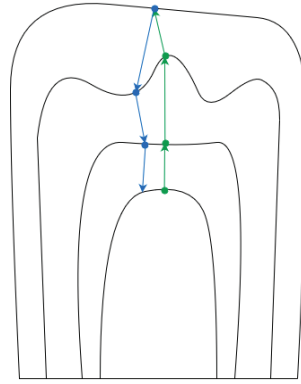
Fig. 5: Visualization of the directional dependency of the normal vector approach
(green = thicknesses measured from the inside outwards, blue = thicknesses measured from the outside inwards)

In both cases, when measuring from the inside to the outside and when measuring from the outside to the inside, extremely large values for layer thicknesses can occur. This is the case whenever a triangle exhibits a large slope. The upper arrow in Fig. 4 is an example of this phenomenon. These values are not to be considered incorrect as they do capture the distance to the next layer in the defined way. However, such values may cause difficulties when it comes to transferring the layer arrangement to another patient whose tooth's inclination angles are not as severe. In even more extreme cases, the normal vector of a steep surface may not hit the next layer at all, but the current layer again. This effect occurs in particular when measuring from the outside to the inside. The respective values should be excluded because they don't contain any information about the layer's thickness. Fig. 6 illustrates both cases of normal vectors on steep surface areas.
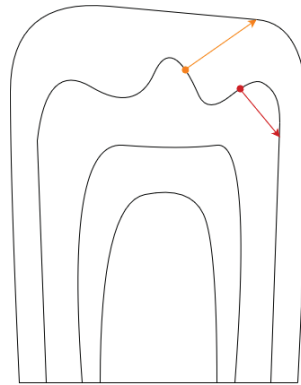

Fig. 6: Examples of extreme values for the normal vector approach
(orange = extreme thickness that can still be used, red = no thickness information)

The task of transferring layer arrangements measured along normal vectors is problematic as a whole. The triangles of the meshes of the target denture (of the new patient) will differ greatly from those of the analyzed denture (from another patient). Both tooth stump mesh and outer contour mesh are highly individual. It cannot be assumed that similarity in position and orientation of normal vectors exists. Thus, a complex mapping of the measured thicknesses onto the new surfaces would need to be developed.

II. Cylindrical coordinates approach

Working with an approach based on cylindrical coordinates can be imagined as if an enveloping cylinder was placed around the denture to be analyzed. With the help of the coordinates z (height), ρ (radius) and φ (angle) the denture can be measured in slices. Slices increase by a defined increment Δz. A number of angles φ_1 to φ_n has to be defined at whose positions the thicknesses of the layer arrangement are measured. The resolution of this approach can be improved by increasing the number of slices and angle positions. Fig. 7 illustrates the approach.
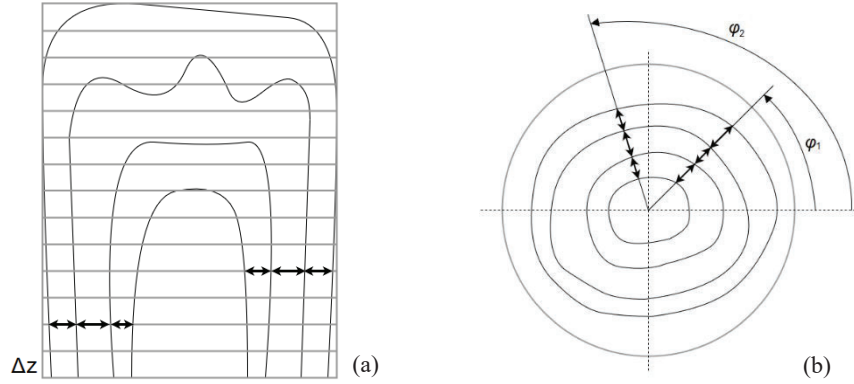

Fig. 7: Schematic representation of the cylindrical coordinates approach with some exemplary measuring points; (a) side view, (b) top view

This approach is not direction dependent as the normal vector approach is. Whether thicknesses are measured from the coordinate system center outwards or from the cylinder surface inwards makes no difference. Another advantage is that implementation becomes easier compared to the normal vector approach. No loops are needed to go through all triangular facets and gather the respective normal vectors. For this approach only the bounding cylinder has to be determined based on the dimensions of the denture. Thickness measurements are then based on this cylinder and its segmentation.

A downside of the cylinder approach is that the bounding cylinder is not always easy to find. It has to be reflected upon which position the point of origin shall take. It could either be determined purely based on the outer contour of the denture or it could be chosen to coincide with a dentistry relevant point such as positions of cusps or fissures or the tooth's center of mass. Further, it could be argued that the orientation of the cylinder should follow the orientation of the tooth stump or that of the insertion direction of the finished denture. However, even if factors are chosen that are prominent on the tooth or significant for the dentist, the difficulty of transferring it to the next patient still arises. As all tooth geometries are very individual, the transfer process might not yield satisfying results for the new patient.

Assuming that a reference system for the cylinder has been found, there is still a necessity for a scaling step from the existing denture to the new patient case. This concerns the cylindrical slices. If the second tooth is larger than the first one, they need to be upscaled. Fig. 8 gives an example of such an upscaling process. Otherwise, if the second tooth is smaller, the slices need to be downscaled. The angles φ_1 to φ_n are retained as they are.
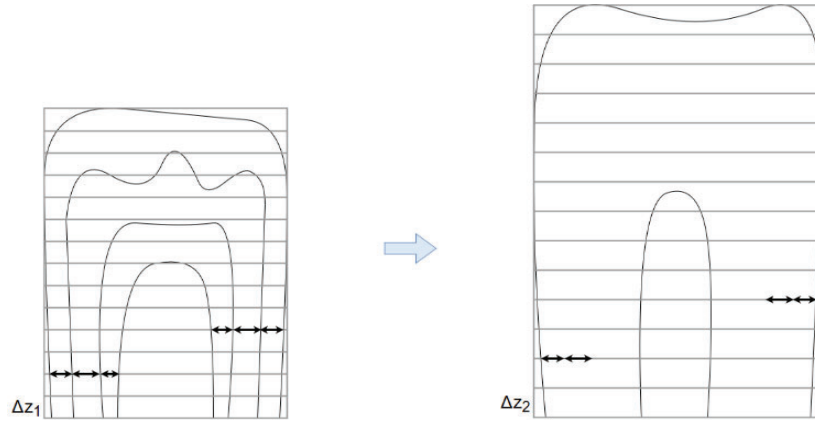
Fig. 8: Transfer of a layer arrangement onto a new tooth for the cylindrical coordinates approach

What is more, when working with cylindrical coordinates there will be areas of the tooth that are poorly covered. Especially in the upper region, when a cylindrical slice does not contain all layers anymore, measurements of thicknesses become infeasible. The reference of the next-lower layer is then missing. The phenomenon is illustrated in Fig. 9.
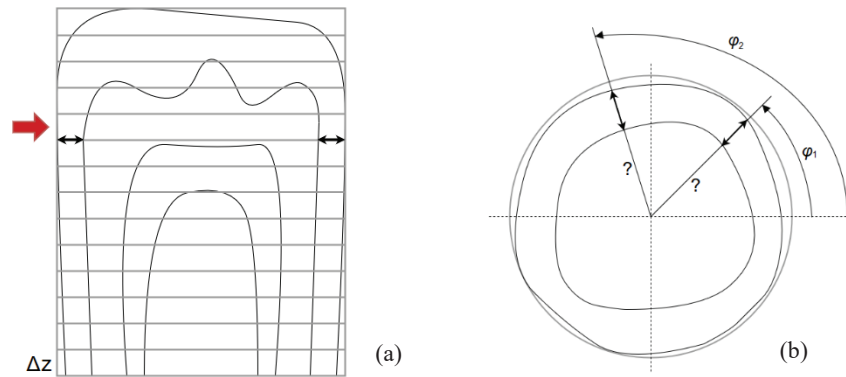

Fig. 9: Missing thickness information in the upper section of the bounding cylinder; (a) side view, (b) top view

Apart from some missing thickness values in the upper tooth regions, it should be stated that the thickness values in general vary from those obtained in the normal vector approach. The values here are not measured along surface normals and are therefore not as accurate when it comes to capturing what determines the color impression. Fig. 10 shows how these two types of measured thicknesses can differ from each other.
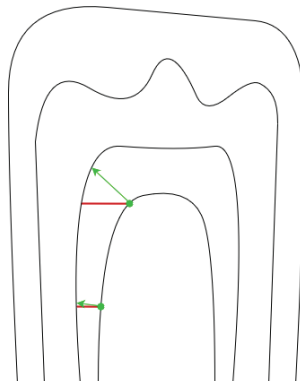

Fig. 10: Deviations between normal thicknesses (green) and horizontal thicknesses (red)

The differences become particularly large in areas with steep gradients. However, it can be argued that the error that is committed by not using normal directions for measuring can be minimized by increasing the resolution.

III. Spherical coordinates approach

The approach based on spherical coordinates is similar to the one based on cylindrical coordinates. Except that an enveloping sphere is chosen here. The sphere and positions within the sphere can be described by r (radius), θ (polar angle) and Φ (azimuthal angle). The radius is defined by the size of the tooth. The more rays, each described by the respective pair of θ_i and Φ_i, are used, the higher the resolution. Fig. 11 shows some rays cast through a denture in a bounding sphere.
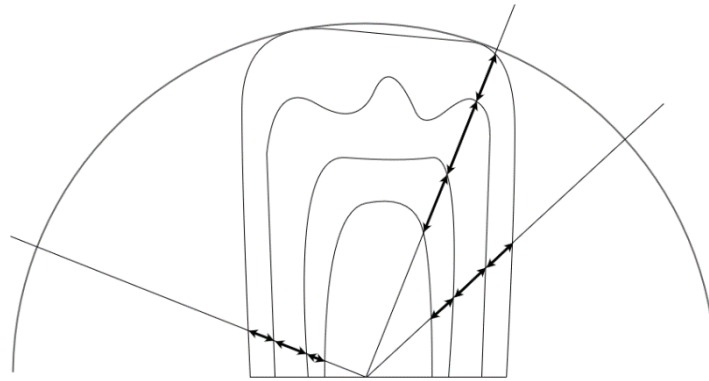

Fig. 11: Schematic representation of the speherical coordinates approach with some exemplary measuring points

The benefit when compared to the cylindrical approach is that it does not leave regions of the tooth uncovered. Again it is independent of the direction of application. Whether thicknesses are measured from the sphere's surface inwards or from the center point outwards is irrelevant. Implementation is as convenient as described for the cylindrical approach. The effort to create loops over all normal vectors can be avoided here as well, since only the sphere and its division are needed as a basis.

However, the problem of finding an adequate reference system for transferring layer arrangements from one patient to another remains. It is as critical to find a suitable center point for the sphere as it is for the cylinder. Again the center of mass of the stump or the final denture might suggest themselves, yet they vary greatly from person to person. The only advantage gained is that the sphere only needs a center point, not the additional longitudinal direction the cylinder needs.

When working with spherical coordinates no scaling is needed for a new patient case. Only the radius of the sphere will be different, but all pairs of θ_i and Φ_i stay exactly the same. Only these rays are needed to determine the layers for the new patient along them.

Similar to the cylindrical approach, it has to be taken into account that the thicknesses measured are not normal distances. Fig. 12 shows how the two types of thickness values may differ from each other. In this case, they show these deviations independent of surface inclinations.
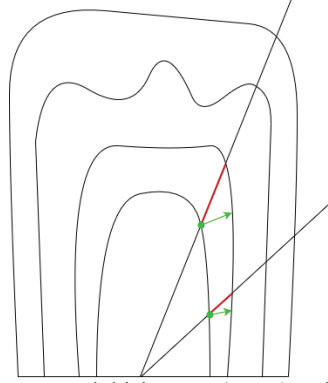
Fig. 12: Deviations between normal thicknesses (green) and spherical thicknesses (red)

IV. Paraxial ray approach

The enveloping body for the paraxial ray approach is a cuboid. This bounding box has its dimensions defined according to the axes of a Cartesian coordinate system, typically denoted by x (length), y (width), z (height). The fact that Cartesian coordinates are the ones most commonly used and that today's CAD systems offer built-in functions to create bounding boxes for a body makes this approach especially convenient to apply.

Paraxial rays in this context mean straight lines that go through the bounding box. They are placed through the cuboid in all three coordinate directions, with defined intervals Δx, Δy and Δz. By reducing the intervals, the resolution of the approach can be scaled up. If there is an interest in one particular direction, e.g. because the tooth exhibits peculiarities on the cutting edge, the interval for this direction can be reduced in a targeted way. For each ray the thicknesses of the layers are measured in the direction of the ray. Fig. 13 shows an example of a bounding box and the casted paraxial rays.
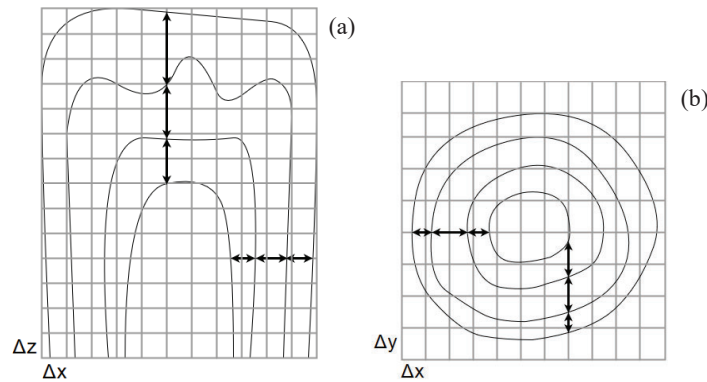

Fig. 13: Schematic representation of the paraxial ray approach with some exemplary measuring points; (a) side view, (b) front view

The major advantage of this approach is that no reference system has to be chosen if the layer arrangement is to be transferred. Only the outer contour of the existing tooth and the outer contour of the new tooth need to be known as they are what defines the bounding boxes. These contours are known by definition of the use case discussed in this paper. However, scaling becomes necessary to determine the layers for the new patient case as it cannot be assumed that the bounding boxes will be of identical size. This is carried out by adjusting the intervals. The number of rays

per direction stays the same so that no information is lost nor artificially generated. Fig. 14 illustrates the scaling process for the case that the new tooth is bigger than the original one.
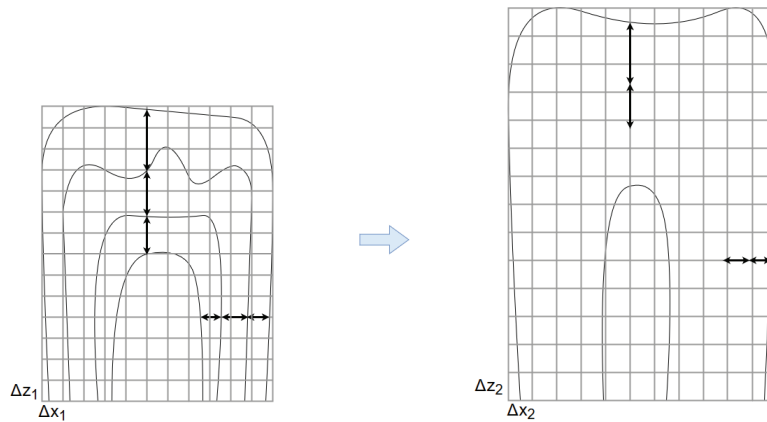

Fig. 14: Transfer of a layer arrangement onto a new tooth for the paraxial ray approach

Again it is an approach that is independent of the direction in which it is carried out. It does not matter whether thicknesses are measured in or against the respective coordinate direction. It should only be considered that in two directions there will be two sets of thicknesses (front – back and left – right) while in one coordinate direction there will be only one set of thicknesses (upwards to the cutting edge). This is due to the fact that the denture is open in the lower area where it is to be placed on the tooth stump in the patient's jaw. It can be assumed that the entire tooth is well covered by taking into account all three coordinate directions. Implementation is even more feasible than described for the spherical and cylindrical approach.

A challenge that remains is to account for the fact that distances are not measured along surface normal direction. Similar to the cylindrical approach (see Fig. 10), paraxial thicknesses may differ from normal thicknesses. Differences are especially significant when slopes are steep. The issue can partially be resolved by keeping the resolution high.

V. Conclusion

Based on the discussion of the approaches in the above sections, a decision is being made to pursue the paraxial ray approach further. The advantage which particularly drives this decision is that this approach offers independence from a reference system. This is of great importance for the use case this paper deals with, namely the transfer of a layer arrangement from one patient to another.

Furthermore, implementation of the paraxial approach provides a solid foundation for further development. It can be experimented with different resolutions and different patient cases for the transfer process. If it can be proven that results of sufficient quality are produced by this approach, the elaborate development of a reference system can justifiably be disregarded. If the opposite scenario occurs, the implementation of this approach can nevertheless act as a benchmark against which it can be measured how much other approaches improve accuracy.

Implementation

For programming purposes the CAD (Computer Aided Design)/CAM (Computer Aided Manufacturing) software Pictures by PC 3.8 [21] has been used. It comes with its own object-oriented programming language, which is based on BASIC (Beginner's All-purpose Symbolic Instruction Code) [2]. Thus, one and the same environment can be used to load, align and modify dental models as well as to apply self-written algorithms to them.

When implementing any of the approaches mentioned in sections I to IV the questions of how to detect intersection points arises. Since all models are in STL format, i.e. are assembled of a multitude of triangles, and all approaches apply some kind of lines cast through the model, it is important to know when a line hits a triangle. The distance from an intersection point of a line and a triangle to the next intersection of the same line and a triangle of the next-higher layer is what defines the thickness in the respective approach.

A ray-triangle-intersection (RTI) algorithm that is well established is the one proposed by Möller and Trumbore [15]. It stems from the field of computer graphics where it is commonly implemented for ray tracing computations [14]. In this work it is chosen because of its computational efficiency. The reason for this characteristic is that it does not require a pre-calculation of the plane in which the triangle containing the intersection point lies.

The algorithm is based on barycentric coordinates [8]. This means that a transformation from the overall global coordinate system to a system based on the vertices of the triangle is made. In barycentric coordinates a point T that lies within a triangle defined by vertices V_0, V_1 and V_2 can be described as follows [15]:

$$T(u,v) = (1 - u - v)V_0 + uV_1 + vV_2 \qquad (1)$$

with u and v being the coordinates which must satisfy the conditions $u \geq 0$, $v \geq 0$ and $u + v \leq 1$.

A parametric definition of a line, i.e. of the ray in this scenario, is the following [15]:

$$R(t) = P + tD \qquad (2)$$

with R being an arbitrary point on the line, P being the starting point which has been chosen to define the line, D being its direction vector and t the distance traveled from the starting point in the direction of D to end up in R.

If now a triplet (t, u, v) is found that satisfies both equations it is the intersection point between ray and triangle. For further implementation matters the reader is referred to [14].

To ease the interaction with the user, a graphical user interface (GUI) is desired for the application presented in this paper. The user shall have the opportunity to enter values for the number of rays in x, y and z direction. The interval values Δx, Δy and Δz are then calculated by dividing the size of the bounding box by the number of rays + 1. Fig. 15 shows how this GUI is realized in the Pictures by PC software.
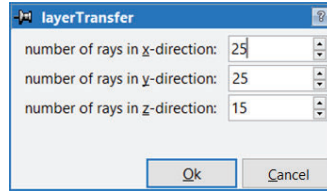
Fig. 15: Graphical user interface for the implemented layer transfer algorithm

To give an overview of the entire implementation for the analysis of the layer arrangement of a denture and for the transfer of this arrangement onto a new tooth with only the outer contour and the contour of the tooth stump known, a flowchart is given in Fig. 16.
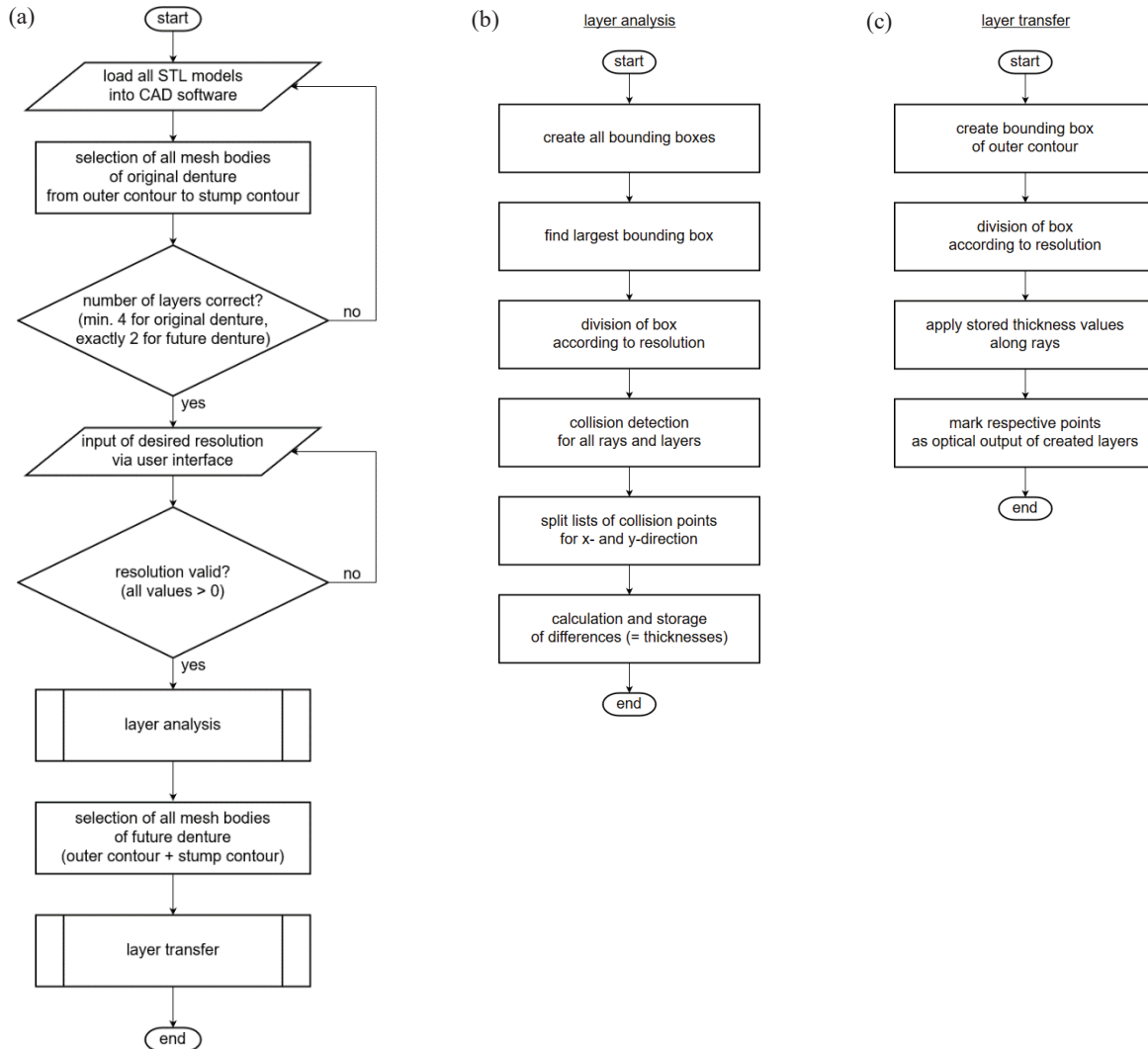

Fig. 16: Flowchart of the implemented layer analysis and transfer algorithm; (a) entire process, (b) analysis subroutine, (c) transfer subroutine

The fact that the first rhombus in Fig. 16 (a) checks the number of mesh bodies originates from the considered use case (transfer of a layer arrangement from one patient to another). It is assumed that all dentures have at least 3 layers (see Fig. 4 for example). 3 layers equal 4 mesh bodies, namely the tooth stump contour, the framework outer contour, the dentine outer contour

and the enamel outer contour. For the new denture it is assumed that only 2 of these meshes are known (see Fig. 8, right part, for example). Those two are the tooth stump contour as it is captured by an impression or 3D scan created at the dentist and the outer contour which is determined by the adjacent teeth and captured by the dental technician via CAD software. The boundaries of the inner layers of the new denture are calculated by the algorithm.

Results

Thicknesses of the different layers a denture consists of could successfully be measured by the paraxial ray approach and the respective implementation. Within the available patient cases as described under **Data Base** thicknesses of the core layer (first layer on the tooth stump, created out of VITA's Enamic material) vary around a mean of 1.9 mm in their maximum values. Maxima of the dentine layer (middle layer, created out of VITA's 3M2 LC flow dentine) vary around a mean of 0.2 mm. For the enamel layer (outermost layer, created out of VITA's 3M2 LC flow enamel) maximum thicknesses fall around a mean of 0.5 mm. These results are plausible when considering that the core layer is the most massive one, responsible for the structural integrity of the denture [13], and that the enamel layer is the one used for creating the cutting edge and therefore contributes to large values in height direction. Other layers for more complex color effects are not listed here, but can nevertheless be measured by the same described means.

Fig. 17 gives an example of a layer transferred to a new denture. Green dots stand for the intersection points between rays and triangles which were recorded for the original denture and then applied onto the new one shown here. Another point cloud would appear on top of the green one to make the simple three-layer strategy complete.
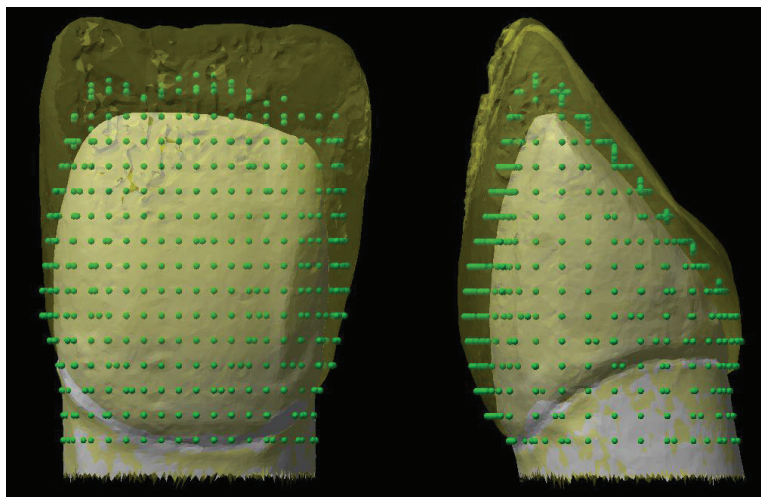

Fig. 17: Result of a layer transferred onto a new denture

Summary and Outlook

The approaches to analyze layer arrangements of dentures that have been compared in this paper include a normal vector approach, a cylindrical coordinate approach, a spherical coordinate approach and a paraxial ray approach. Advantages and shortcomings of each of these approaches have been pointed out. The direction of thickness measurements and the choice of a reference

system for the transfer to new patient cases have turned out to be a particular focus. Even though measurements along normal vectors are desirable as they are in line with the general definition of thickness, a decision has been made for the approach based on paraxial rays for transferability and implementation reasons. Implementation steps using the software environment Pictures by PC 3.8 have been explained. Finally, exemplary results of layers measured in dentures stemming from the data base at hand have been presented.

The work presented in this paper is of initial, fundamental character. Further steps must be taken in order to make the chosen and implemented approach fully operational for additive manufacturing of dental prostheses. These steps involve the creation of surfaces through given points. So far, as can be seen in Fig. 17, the layer arrangement when transferred to a new tooth is present in form of point clouds. Delaunay triangulation [3] or Marching Cubes [12] could be used to create surfaces out of these points and thus define the exact dentine and enamel layers for the new patient.

Assuming that materials and machines are sufficiently adapted to be utilized for additive manufacturing in dentistry, the implementation described here could be used to produce prototypes of dentures. With the availability of real physical prototypes it can be checked whether the optical impression, especially in terms of colors, is achieved as expected. For example, the so-produced prototypes could be compared to others from manual production, could be exposed to different light conditions or inserted into a patient's jaw to assess the optical interaction with the natural teeth around. If the aesthetic aspirations are not met, it is recommended to compare the proposed approach to the normal vector one. The normal vector approach, even though more elaborate with regard of implementation and transfer, ensures the exact measurement of thicknesses. If necessary, modifications must be made to the existing approach, e.g. adjustments of the resolution, or it may even become necessary to switch to the normal vector approach and find a suitable reference system for transferring it onto new teeth.

Acknowledgments

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