DIGITAL STEREOPHOTOGRAMMETRIC SOLUTIONS FOR ORTHODONTICS

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ABSTRACT:

For many years orthodontic treatment is a successfully applied method in dentistry. By moving and rotating teeth a natural configuration shall be reached. The accurate determination of the three-dimensional position and orientation changes of every tooth is done by measuring distances between the fixed appliances bonded on the teeth using a standard electronic caliper. This method is not very accurate and on the other hand not very pleasant for the patient. Therefore an optical touchless measurement system shall be developed, that leads to more accurate results and that is more accepted by the patients.
During the 1980s the theoretical and practical fundamentals of digital close range photogrammetry were developed that can be adopted for that application. On the other hand many new developments have to be done that are caused by the specialty of the topic. Especially the problem of image acquisition caused by limited space left for acquisition devices and the problem of strong reflections caused by different materials used in the mouth have to be solved. At the moment usually well defined features like retroreflective targets are used to determine the three-dimensional position of objects. In this project only the natural structure of the teeth's surface and no artificial features like targets or structured light methods shall be used.
The goal of the project is the development of a more less fully automatic measurement system, that allows the determination of three-dimensional position and orientation changes of every single tooth with an accuracy better than 100 microns during an orthodontic treatment. The system must be applicable by an orthodontist, thus robust implementation is necessary. Last but not least this new system shell help to reduce the fear and pain of the patient by applying an optical touchless measurement system.

KURZFASSUNG:

Kieferorthopädische Behandlungen sind eine seit Jahrzehnten erfolgreich angewandte Methode in der Zahnheilkunde. Die genaue Bestimmung der dreidimensionalen Translationsvektoren und Rotationen der Zähne ist bislang auf optisch-berührungslosem Weg nicht möglich. Andere Meßmethoden liefern ungenaue Ergebnisse und sind in der Anwendung dem Patienten kaum zumutbar. Deshalb soll ein möglichst automatisches optisch-berührungsloses Meßsystem entwickelt werden.
Die in den Achtzigerjahren geschaffenen theoretischen und praktischen Grundlagen der digitalen Nahbereichsphotogrammetrie ermöglichen nun deren Anwendung und Adaptierung auf dieses spezielle Problem. Zusätzlich zur Verwendung bestehender Grundlagen müssen Weiterentwicklungen durchgeführt werden, die durch die spezielle Lagerung des Problems bedingt werden. Besonders sind dabei das geringe Raumangebot im Mund sowie die unterschiedlichste Beschaffenheit der Zahnkörperoberflächen (Zahn, Keramik, Amalgam, Gold,...) und deren verschiedene Reflexionseigenschaften zu berücksichtigen.
Allgemeines Ziel ist somit die Entwicklung eines möglichst automatischen Meßsystems bis hin zum Prototypen, das die Bestimmung der dreidimensionalen Verschiebungsvektoren und Verdrehungen der einzelnen Zähne während einer kieferorthopädischen Behandlung mit einer Genauigkeit besser als 0.1 mm erlaubt und vom Kieferorthopäden selbständig angewendet werden kann. Besondere Rücksicht ist dabei auf die robuste Implementierung zu nehmen, die bei Anwendungen dieser Art unbedingt notwendig ist. Vor allem aber muß an den Patienten gedacht werden, dem durch ein berührungsloses Meßverfahren Schmerzen gespart werden können.

1. INTRODUCTION

During an orthodontic treatment dentists try to move and turn one single tooth or groups of them to certain positions and orientations. Especially distal, mesial and torkquing movements have to be monitored, to ensure that the teeth will reach the desired position. At the moment the measurement is done manually using an electronic caliper and further equipment mounted to the brackets that are fixed on the teeth. This method of monitoring the teeth during an orthodontic treatment is not very accurate, due to small cutting angles of the distances measured between the teeth. On the other hand it's not very pleasant for the patients. Therefore a digital photogrammetric solution shall be developed and implemented. And much more photogrammetry has already been successfully applied in dentistry (Achilli 1992) and (Mollersten 1989).

2. CONCEPTUAL ASPECTS

2.1 Hard- and Software

The system consists of two PULNiX TM765 E black/white CCD cameras that are equipped with 16 mm lenses. The cameras are connected to a standard low cost video capture board miroVIDEO D1, that allows image acquisition from two different signal sources sequentially in video rate. Therefore there is no need for an expensive frame grabber that allows image acquisition simultaneously. Both cameras are equipped with a special illumination device, that consists of a ring of red LEDs. It is used to illuminate both the interior of the mouth and retrotargets fixed on a special mirror that is necessary to make image acquisition possible. For a detailed description of the mirror see chapter 4.
The video capture board is mounted in a standard PC that is equipped with a PENTIUM™ 75 MHz CPU. All software developed is written in standard C under Microsoft Windows™.

2.2 Theoretical Concept

Derivation of 3D position and orientation changes of every single tooth using a digital photogrammetric close range system needs a special technique. Many constraints originating in the nature of the problem make it very difficult to find an appropriate way to derive deformation parameters.
As described above the measurement system consists of two cameras and a video capture board that allows more less simultaneous image acquisition. The system has to be calibrated to be used for measurement purposes (see chapter 3.5). To make image acquisition possible a special mirror has been developed that is placed between upper and lower jaw. The mirror shows 11 retroreflective targets that are used for relative and absolute camera orientation. On the other hand no targets can and may be fixed on the teeth. To derive 3D deformation parameters three well defined points on every tooth are necessary. They may not be destroyed during an orthodontic treatment that lasts for several month. Obviously the use of artificial target points on the teeth's surface is not possible. Therefore deformation parameters are derived by 3D DSM-matching. In every time period of the orthodontic treatment a complete DSM (Digital Surface Model) of every tooth is processed. The deformation parameters can be derived by 3D matching of the DSM of the same tooth in different time periods. DSMs are derived from a stereo pair only by the use of the natural structure of the teeth surface. Image acquisition and proper illumination in the very close range of the human mouth is difficult enough. The use of structured light methods might lead to more accurate results but on the other hand it might introduce additional problems during image acquisition.

3. SYSTEM ANALYSIS

Digital close range systems have to be analysed and calibrated before they can be used for measurement purposes. For the user, who is usually not an expert in photogrammetry, it is very important to know how long the warm up effect of the system lasts. The photogrammtrist is much more interested in the performance analysis of the system including noise, repeatability and especially system calibration.

3.1 Repeatability

For this investigation as well as for the analysis of warm up effects images from a small testfield of 150 x 150 mm size showing 49 black targets on white background were taken. For repeatability analysis a set of five images was taken in video rate. The image coordinates were measured using LSTM. The averaged coordinate set of all five images was used as reference. No systematic trend was excluded. The average RMS values for the coordinate differences in x and y direction are 0.018 pixel and 0.019 pixel respectively. This corresponds to 1/55th of a pixel.
In a second test six images were taken sequentially every 10 minutes. Again an averaged image coordinate set was used as reference but systematic trends were excluded. In average the RMS values for the coordinate differences in x and y direction are 0.025 pixel and 0.024 pixel respectively. Taking into consideration that the frame grabber used is a low cost product for approximately 300 US$, a repeatability of 1/40th of a pixel over on hour is pretty good.

Version	Trend x [Pixel]	Trend y [Pixel]	RMS x [Pixel]	RMS y [Pixel]
5 frames			0.018	0.019
1 hour	0.024	0.018	0.025	0.024

Table 1: Results of repeatability analysis

3.2 Warm Up Effect of Camera

To achieve best results it is very important to know how long the warm up effect of an image acquisition system or any other electronic device lasts. The investigation is done in two steps: analysis of the camera and analysis of the frame grabber. To investigate the camera the frame grabber was turned on several hours before the test. After the camera was turned on 10 images were taken within 2 hours. The last image is used as reference, systematic trends are excluded. Figure 2 shows, that the warm up effect is not over after 2 hours. The RMS values are 1/30th of a pixel compared to 1/40 th of a pixel when the system is completely warmed up.

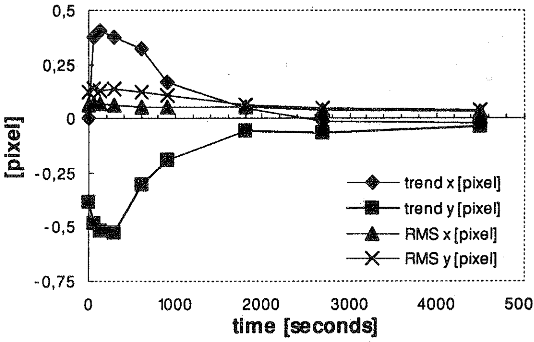


Figure 2: Warm up effect of camera

3.3 Warm Up Effect of Frame Grabber

Like every electronic device a frame grabber shows a warm up effect. Eight images were acquired within 2½ hours. The camera was turned on several hours earlier. The last image is used as a reference and systematic shifts are excluded. Figure 3 shows that the warm up of the frame grabber is not finished after 1½ hours. The RMS values are a factor 2 larger compared to the warmed up system.

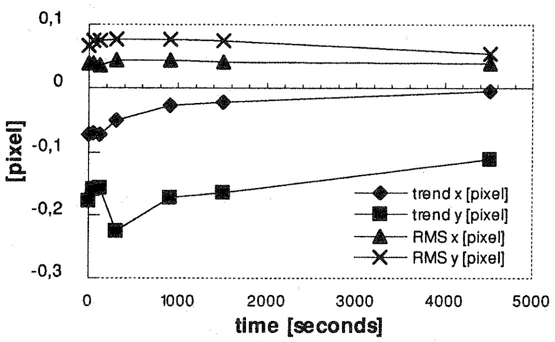


Figure 3: Warm up effect of frame grabber

3.4 Noise Analysis

To analyse the noise of the imaging system a set of five images was acquired in video rate. The averaged image was used as reference. The RMS of greyvalue differences is less than one greyvalue. This result is suprisingly good.

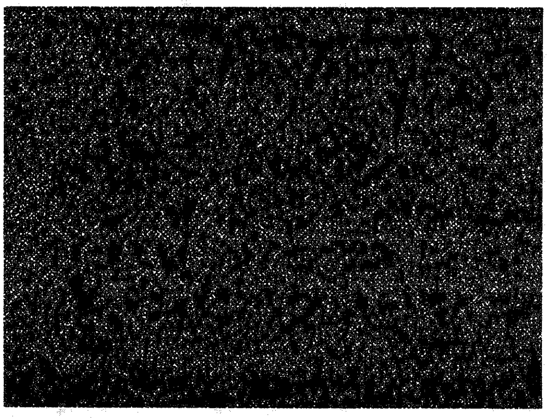


Figure 4: Noise of the imaging system

3.5 System Calibration

The system was calibrated using a small testfield of 150 x 150 mm size that shows 49 black targets on white background. Image coordinates were measured using LSTM. The average image scale was 1:20. A total of 8 images was taken from 4 stations with a roll of 0 and 90 degrees. Every target was imaged in average in 6 images. To compensate systematic errors a set of 10 additional parameters was used. Non significant and non determinable parameters were excluded from the estimation process (Gruen 1986). A RMS of image coordinate residuals of 1/10th of a pixel was reached corresponding to 20 microns in object space. (1 part in 7500)

4. IMAGE ACQUISITION

Due to many restrictions and constraints originating in the nature of the project image acquisition is very difficult. The problem can be divided into two parts: firstly image acquisition itself. This means how to place the cameras to be able to image teeth. Secondly the problem of illumination. The teeth have to be illuminated in a way that they can be measured by using their natural structure.

In accordance to a method that has already been used by orthodontists to acquire images for documentation purposes a special mirror has been developed. This mirror is placed between upper and lower jaw. The cameras are placed in front of the mouth and acquire a mirrored view of a the upper jaw or the lower jaw respectively. They are approximately 250 mm in front of the mirror an placed beside in a distance of 60 mm corresponding to the base. At the mirrors backside 11 retroreflective control points are engraved in the mirroring layer, so that they can be seen from the front. In addition they are placed in a special arrangement that shall minimize the overlay of control points and teeth in the images. Since the control points are retroreflective they are imaged as bright targets, the same way like strong reflections. By eliminating the influence of strong reflections on the measuring process the influence of overlaying control points can be eliminated too.

The illumination system consists of two parts: red LEDs that are fixed around the cameras lens and an additional diffuse illumination of white light. The red LEDs are used to illuminate the retrotargets fixed on the mirrors backside. The teeth's surface is illuminated by the diffuse light.

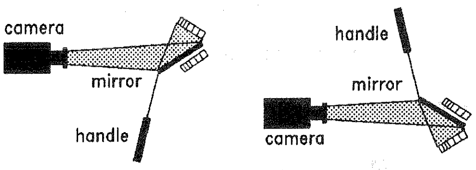
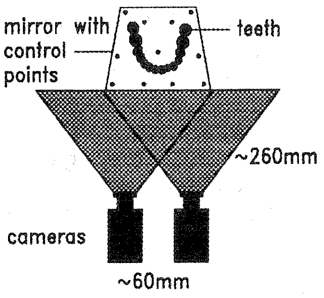


Figure 5: Camera configuration for image acquisition



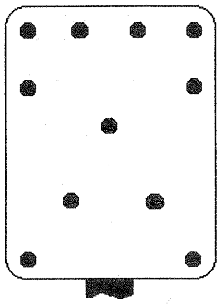


Figure 6,7: Camera arrangement, Control points

5. DSM PROCESSING

For every tooth of a jaw a DSM (digital surface model) is generated. The process can be divided into three steps. Firstly all image points that belong to one single tooth have to be defined, secondly the generation of the DSM and thirdly postprocessing including detection of gross errors and smoothing of the DSM.

5.1 DSM Preprocessing

During preprocessing the shape of every single tooth is determined. This is done semiautomatically. In a first step the center of every tooth is pointed manually in one image. In this step additional data (tooth number, ..) is set. Size and shape of the tooth is determined in a second step automatically. The gradient of the image is calculated in radial direction from the center pointed manually. If the gradient is larger than a certain threshold, if the direction of the gradient is rectangular to the radial direction within a certain range of tolerance and if the greyvalue of the pixel is smaller than a certain threshold the analysed pixel is classified as a point that belongs to the border of the tooth. All threshold values used are defined automatically by analysis of the greyvalues of the teeth and the gums. The shape of the tooth derived by this method is checked for gross errors and smoothed. In a final step the shape is approximated by an ellipse. All pixels inside the ellipse are classified as the image points that belong to one single tooth.

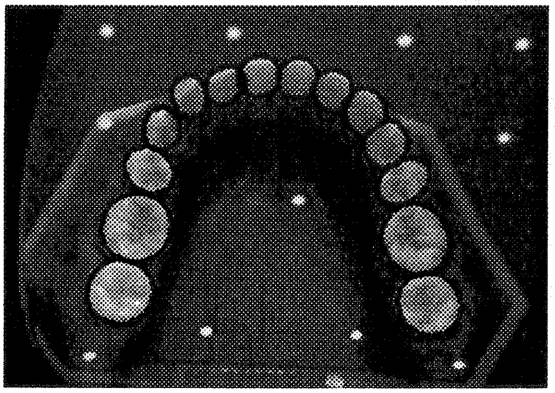


Figure 8: Shape of teeth extracted automatically

5.2 DSM Generation

Automatic DSM generation is done by geometric constrained template matching (Gruen, Baltsavias 1988) and (Baltsavias 1992). To apply this algorithm images must be oriented. This is done by measuring the control points on the mirror in both images. After orientation and preprocessing a DSM for every single tooth is measured consisting of up to 900 surface points for a molar tooth.
As usual for matching algorithms three problems appear: firstly the choice of a proper template size, secondly the derivation of approximations for the geometric parameters of the matching algorithms and finally the choice of a proper iteration criterion. The template size depends on the quality of the images. Molar teeth show more structure than front teeth and may therefore be matched with smaller templates (~15x15 pixels). Front teeth show, due to their smoothness, lower signals and have to be matched with larger templates of approximately 21x21 pixel size. (See results of tests reported in chapter 7)
The derivation of approximations can be done in two different ways, that can be combined for one solution. The relative configuration of mirror and teeth is similar for any image acquisition. Assuming that all teeth are placed in a plane the imaging ray of one image can be intersected with this plane. This leads to 3D approximation coordinates that can be projected into the other image. This method can be combined with a manual measurement of the parallaxes by applying the preprocessing algorithm for shape and size extraction of all teeth in both images. This method leads to the best approximations for the DSM generation process.
DSM generation using only the natural structure of the teeth is strongly influenced by reflections. Their bad influence on the measurement has to be eliminated. This is done by a very simple but also very efficient method. The influence of control points that overlay parts of teeth in the images can be eliminated too. Analysing the average greyvalue of all teeth during DSM preprocessing a threshold is defined. Any pixel that has a greyvalue larger than the threshold is skipped and eliminated from the estimation process. This method can be dangerous if too many pixels are skipped. In this case the surface point is eliminated from the DSM.
Finally a proper iteration criterion has to be chosen. This is as problematic as for unconstrained LSTM. The main problem is the oscillations of transformation parameters. The problem is solved the same way as it is done for LSTM (Beyer 1992). In addition non determinable parameters have to be detected and eliminated from the estimation process. Strongly correlating parameters have to be excluded too.

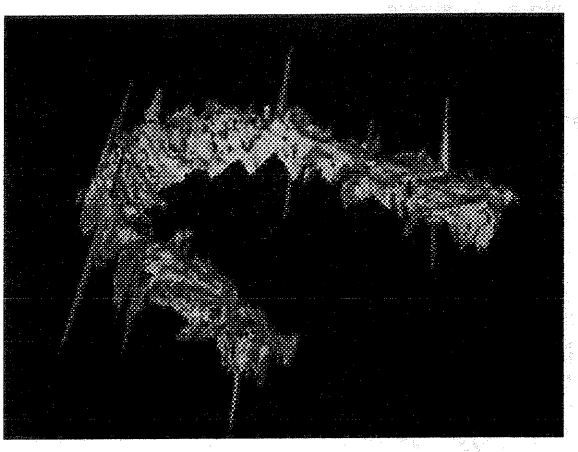


Figure 9: Result of DSM generation

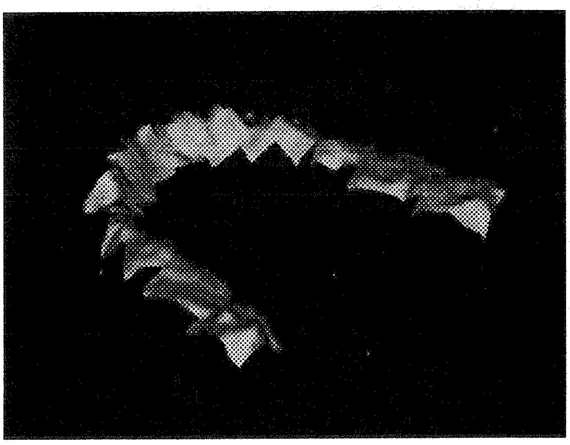


Figure 10: Result of postprocessing

5.3 DSM Postprocessing

Since DSMs are determined by the use of the natural structure of the teeth due to many degrading effects like strong reflections, occlusions or overlay of control points many mismatched DSM points appear, depending on the quality of the images corresponding to the quality of the illumination up to more than 30 percent. To overrun this problem every DSM is postprocessed. In a first step gross errors are eliminated. In a second step the gravity point of the DSM is calculated and every DSM point with a distance from the center that is larger than a certain threshold is eliminated. The threshold is set manually and is more less identical with the average diameter of a tooth corresponding to several millimeters. All DSM points that were eliminated are interpolated using bilinear interpolation. In a third step every DSM point is interpolated using its neighbor points. If the three-dimensional distance of the original point and the interpolated one is larger than a threshold that depends on the sampling rate of the DSM the original point is skipped and replaced by the interpolated one. In a last step the DSM is smoothed by using a moving average algorithm with a window size of 3 x 3 samples.

6. DERIVATION OF DEFORMATION PARAMETERS

The result of DSM generation is a digital surface model of all teeth of a jaw. The position and orientation in 3D space is defined by the coordinate system of the control points on the mirror. For deformation analysis a reference coordinate system is needed. The definition of this coordinate system is not very problematic and must be done by the orthodontist. Only the specialist can decide what reference coordinate system may be used, the photogrammetrist provides the tools for definition. Much more difficult is the definition of object and reference space for deformation analysis. All teeth that shall not move during the orthodontic treatment belong to reference space. Object space means all the teeth the orthodontist wants to move to a correct position. The 3D position and rotation changes of the teeth belonging to object space are calculated with respect to the teeth belonging to reference space. These teeth have to be defined by the orthodontist too. He knows what teeth shall move and what teeth shell serve as a reference. On the other hand the photogrammetrist may investigate whether the teeth belonging to reference space do really not move and turn. This can be tested applying methods of deformation analysis coming from engineering geodesy.

But the main problem is the derivation of position and orientation changes. Since no artificial target points can be defined on the teeth's surface deformation parameters have to be derived using the complete DSM. This is done by a three-dimensional surface matching algorithm. The algorithm is similar to least squares 2D greyvalue template matching. The observation is not a greyvalue difference, it is the coordinate difference in direction of the third dimension of the DSMs that shall be matched. The transformation is done using 6 parameters: 3 shifts and 3 rotations. A parameter for scale is not used. The algorithm is fully 3D, this means that any 3D object described by a DSM can be matched.

The z-coordinates of the DSM points can be described in function of their x and y values using the discrete functions f and g

$$z_I = f(X) \qquad z_{II} = g(X) \tag{1}$$

$$X = (x\ y) \qquad T = (\xi\ \eta\ \zeta\ \varphi\ \omega\ \kappa) \tag{2a,b}$$

Defining a vector T of unknown transformation parameters and a vector X corresponding to the coordinates of DSM points in xy plane the mathematical model of 3D DSM matching can be written as

$$f(X) - e(X) = g(T, X) \tag{3}$$

where $e(X)$ is a true error vector and g is a function of the transformation parameters and the planar coordinate vector X. As equation 3 is nonlinear it must be linearized leading to the observation equation

$$f(X) - e(X) = g^0(T, X) + \frac{\partial g^0(T, X)}{\partial T_i} dT_i \tag{4}$$

With

$$\mathbf{x}^T = (d\xi\ d\eta\ d\zeta\ d\varphi\ d\omega\ d\kappa) \tag{5a}$$

$$\mathbf{l} = f(X) - g^0(X) \tag{5b}$$

$$\mathbf{A} = \left(\frac{\partial g^0(T,X)}{\partial \xi}\ \frac{\partial g^0(T,X)}{\partial \eta}\ \frac{\partial g^0(T,X)}{\partial \zeta}\ \frac{\partial g^0(T,X)}{\partial \varphi}\ \frac{\partial g^0(T,X)}{\partial \omega}\ \frac{\partial g^0(T,X)}{\partial \kappa} \right) \tag{5c}$$

equation 4 results in

$$-\mathbf{e}(X) = \mathbf{A}\mathbf{x} - \mathbf{l} \tag{6}$$

Equation 6 forms a set of n DSM correlation equations, where n is the number of DSM points defining function f. The system is solved by standard least squares technique.

Two main problems appear for implementation. Firstly the derivation of approximations for the transformation parameters and secondly the choice of an iteration criterion. The derivation of approximations is done by a pre-transformation of both DSMs that shall be matched. In a first step both DSMs are reduced to their gravity points. As shown in chapter 7 the same DSM was measured several times. The coordinates of the gravity points do not change more than 0.1 mm. This leads to very good approximation values for the shift parameters. To derive approximations for the rotations and to reduce correlation of transformation parameters the DSMs are rotated in a way that their z-coordinates are minimized. Using this method better results for resampling and interpolation can be achieved. The choice of a proper iteration criterion is as problematic as for LSTM. The main problem is the oscillations of transformation parameters. The problem is solved the same way as it is done for LSTM (Beyer 1992).

To get more flexible and to reduce data and computation time derivation of 3D position and orientation changes is done in two steps. In a first step every tooth is treated independently. The DSM of one single tooth is transformed on the DSM of the same tooth that was measured in a different time period. In this step every tooth is described by a feature consisting of four points, the 'corner points' of the DSM. This has the advantage that the geometric description of a single tooth concerning its three-dimensional orientation can be done by one feature. From that point of view DSM matching is used to determine four identical quasi homologue points for every tooth to do deformation analysis. This leads to a very flexible solution for the derivation of 3D position and rotation changes since even one single tooth can be used as reference.

To derive the deformation parameters of every single tooth with respect to the choice of reference space the features of the reference points in one time period are transformed on the features in a different time period. The deformation parameters of the teeth belonging to the object space are derived by transformation of their features with respect to the transformation of the reference teeth. The final result is a set of 6 transformation parameters (3 shifts and 3 rotations) for every single tooth including the teeth belonging to the reference space. If they are really a reference their transformation parameters must be smaller than the inner accuracy of the measurement system.

7. TESTS AND RESULTS

To investigate the inner accuracy performance of the measurement system a dental testmodel was measured three times without moving or rotating any of the teeth. Image data was processed using different template size to investigate its influence on the results. The empirical accuracy measures are calculated from the deformation parameters treated like true errors corresponding to the RMS divided by the square root of two. The values given in table 11 are an average value of three transformations.

DSM I		DSM II		μ_{shifts} [mm]	$\mu_{rotations}$ [radians]
front-teeth	molar-teeth	front-teeth	molar-teeth		
21x21	21x21	21x21	21x21	0.091	0.044
21x21	15x15	21x21	15x15	0.096	0.048
15x15	15x15	15x15	15x15	0.167	0.061
15x15	11x11	15x15	11x11	0.186	0.071
21x21	21x21	21x21	15x15	0.103	0.027
21x21	21x21	15x15	15x15	0.260	0.139
21x21	15x15	15x15	11x11	0.298	0.122

Table 11: Empirical measures for inner accuracy

A total of more than 6000 surface points has to be measured automatically for every version. On a PENTIUM™ 75 platform approximately 2 hours of computation time is needed corresponding to 1 second per surface point (valid for version 21x21,15x15). As described in chapter 5.2 different template size might be used for front teeth (number 1-3) and molar teeth (number 4-8). Since front teeth do not show much natural structure, due to their smooth surface, they might be measured using a larger template size than for molar teeth. Table 11 shows, that best results can be achieved when all teeth are measured with a template of 21x21 pixel size. But the loss off accuracy when measuring the molar teeth with a smaller template of 15x15 pixels size is very small. On the other hand the usage of large templates increases computation time strongly. Table 11 shows that measuring the front teeth with a template size smaller than 21x21 pixels the accuracy is decreasing strongly by a factor of 2. Especially the comparison of version 21x21,21x21 and version 15x15,15x15 shows that strong degradation appears.

The same dental model was imaged under bad illumination conditions to show its importance. All teeth were measured with a template size of 15x15 pixels. Front teeth number 1 and 2 could not be measured. The empirical accuracy measures calculated from the remaining 10 teeth show an accuracy of the shift parameters of 0.625 mm and for the rotations of 0.193 radians. These results are a factor 4 worse than those that can be achieved under good illumination conditions.

8. CONCLUSIONS

The investigations show that low cost standard components can be connected to a powerful measurement system.

It is possible to measure three-dimensional position and orientation changes of teeth with an accuracy better than 100 microns for the shift parameters and better than 0.05 radians for the rotations without any artificial target points fixed on the teeth's surface, provided that appropriate illumination conditions are given.

Measuring position and orientation changes of teeth during an orthodontic treatment is an interesting application of digital photogrammetric techniques. The results given by the measurement system are shift and rotation parameters, simple numbers that have to be interpreted by the orthodontist. Visualisation techiques like photorealistic rendering and animation techniques are an excellent tool to interpret the movements of the teeth. The possibility to view the teeth three-dimensionally gives the orthodontist the opportunity to simulate and plan the orthodontic treatment even if the patient is absent. This shows the great potential of photogrammetric techniques in medical applications.

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