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Virtual Plaster Model Reconstruction for Dental Application

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ABSTRACT

This paper describes a system for the reconstruction of the virtual dental plaster model. A structured-light optical scanner is used to digitize the dental study model, and then an automatic occlusion algorithm is utilized to bite the maxilla and the mandible with the centric occlusion relationship. For the creation of the virtual model, the system allows the user to adjust the parameters of the profile and the shape of the boundary, and we present an efficient and robust method to construct a smooth surface between the study model and the profile. The mass-spring algorithm is used to relax the mesh to a balanced condition. Automatic bite registration and virtual occlusion are also developed for matching the maxilla and the mandible. After reconstruction, some analysis software tools are provided to generate the measurement information that is significant to orthodontic treatment planning. If necessary, the physical plaster model can also be produced by 5-axis machining.

Keywords: dental CAD/CAM, virtual plaster, automatic occlusion, blending surface.
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1. INTRODUCTION

Plaster casts or study models are widely used in current dental practice for prosthesis production and treatment planning. However, the traditional production process is a labor-intensive and error-prone procedure. First, the dentist takes an impression from the patient's mouth. Then, the impression is transferred into a plaster study model. However it is quite difficult to build a highly accurate model, and the procedure is laborious and time-consuming. In addition, the storage and management of the plaster models can also become expensive overtime. In particular for orthodontic treatment, many countries require that the study models be preserved for an extensive period of time (7 or 10 years for example). This has caused significant medical issues if the study models are damaged or lost. Fortunately, with the development of 3D digitization and customized CAD/CAM technology, virtual study models can be created and, if necessary, physically fabricated by 3D printing technology or 5-axis milling. Indeed, the technology of laser or optical scanning at present has the capability to digitize the dental plaster cast. The main challenge is how to reconstruct the virtual plaster model with sufficient accuracy.

[1] introduced a method which acquires the 3D data of a plaster model form different viewpoints by a non-contact optical scanner. In order to speed up the process, they attach some marks on the model manually for data registration and integration. A dental cast digitization system developed by [2] and

[3] focuses on 3D modeling and automatic digitization procedure in the context of medical applications, in which a useful simulation of error propagation in 3D modeling is proposed. Hirogaki Y. et al. [4] attempted to achieve the complete 3D data retrieval of the shape of dentition, with the casts being measured from four directions. Then, a method called perceptual grouping algorithm, using one of pattern-recognition theories, is used to reconstruct 3D models.

Our task is to build a virtual plaster model with a correct occlusion relationship between the maxilla and the mandible. Occlusion means the maxilla and the mandible touch each other in a natural biting condition. It will be affected by the alignment and the shape of the teeth. For orthodontic treatment, two significant occlusion types are centric occlusion (CO) and centric relation (CR) [6]. CO is defined as the configuration that the opposing teeth come together at maximal area of contact with a maximum amount of force; CR is defined as the occlusion condition that the opposing teeth touch each other at first contact with only minimum amount of muscular force. So far, the technician still occludes the teeth by hand, which is called bite registration. A polymer material is used to record the positional relationship of the upper and lower jaws to each other. Bite registrations help to achieve successful restorations with harmonized occlusion and articulation. For the registration of upper and lower jaws of the virtual study model, this paper also presents an automatic registration algorithm to put the maxilla and the mandible at the CO condition.

In this paper, the structure of our system is shown in Fig. 1. More related literature survey is presented in Section 2. Model digitization, automatic occlusion and blending surface algorithm are provided in Section 3. In Section 4, we present a measuring system and some computer assisted analysis tools for treatment planning. Examples are discussed in Section 5. Section 6 concludes the paper.

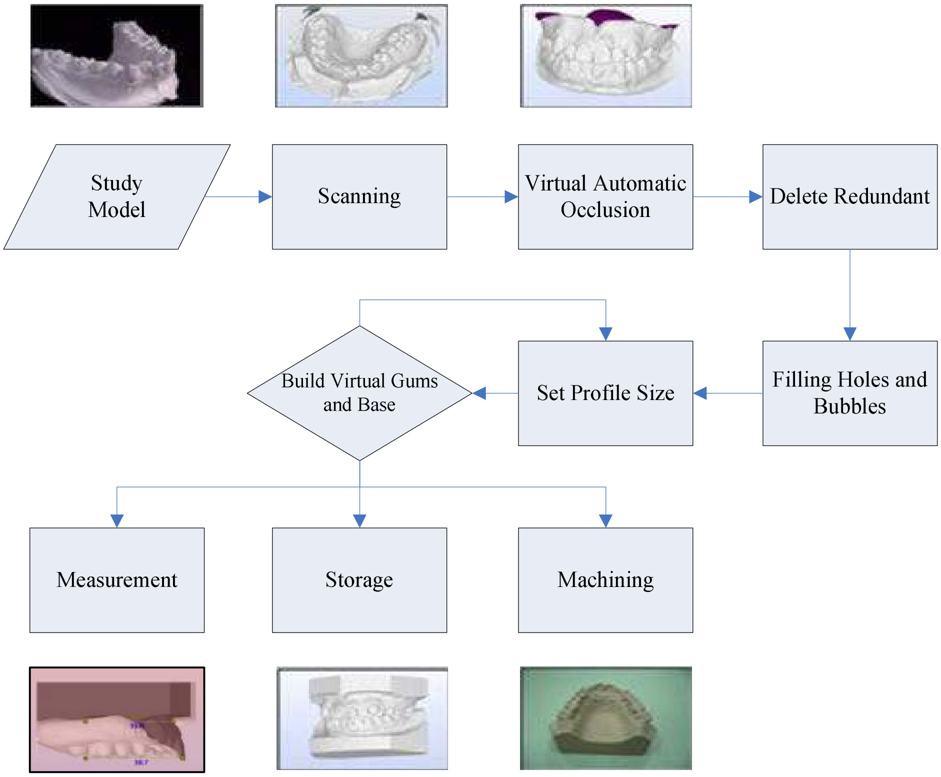


Fig. 1: The structure of this development work.

2. RELATED WORK

Dental cast (or plaster model) plays an important role in dental diagnosis, treatment planning and prostheses making. Currently, there are already several dental CAD /CAM systems and publications using digital or virtual plaster models to plan corrective treatments. Some of the systems will be described in the following.

2.1 Dental CAD/CAM System

OrthoProof USA™ develops an analysis system called DigiModel™[17] to obtain the diagnosis and planning information from digital plaster models. OrthoCAD™ [15] is a computer-guided system mainly for bracket placement planning and also provides digital models for orthodontic analysis. In emodels™ [16] system, Bite registration and condylar displacement analysis can be manipulated to correct the occlusion. Then the digital model can be segmented into individual tooth for correction arrangement. Cecile3™ and iDOL™ are also dental analysis system with friendly user interface. Orapix [18] system includes two subsystems, 3Dxer and 3Txer. The 3Dxer allows the user to browse the models in any direction and check the differences between two overlaying cases. Besides, the system supplies the user a simple selection mode to choose the suitable arch form. The pattern of arch form has a big influence on the effect of corrective treatment. However, the systems mentioned above mostly focus on the design of bracket, and pay less attention to the building of virtual study model.

2.2 Dental Occlusion

The automatic occlusion of teeth is still an open research issue in orthodontics. In the case of physical plaster casts, the technician bites the casts manually. Then both upper and lower physical models are usually trimmed smoothly, making the base and the side of the models planar and parallel. Hiew, L. T. et al. [6] exploited this property to perform initial alignment, then proposes a simple algorithm to detect the collision between the upper and lower. DeLong, R. et al. [7] tried to bite the teeth using iterative closest point (ICP) algorithm [19] by selecting corresponding points manually.

2.3 Mesh Deformation, Editing and Blending

Deformation is a natural behavior when objects are subject to external forces. Terzopoulos, D. et al. [9] is a pioneer in using mass-spring-damper (MSD) system to model deformable objects. Up to now, the physical-based modeling has been applied to many kinds of deformable field, including facial animation [10, 11], clothing animation [12, 13], and recently, surgical simulation [14].

3. ORTHODONTIC MODEL RECONSTRUCTION

In this section, the architecture of the proposed system is shown in Fig. 2. The first step is to digitize a study model. Second, automatic occlusion must be accomplished. Finally, the blending surface algorithm is used to build a continuous surface which connects the profile and study model smoothly. The detail of the algorithm is described later.

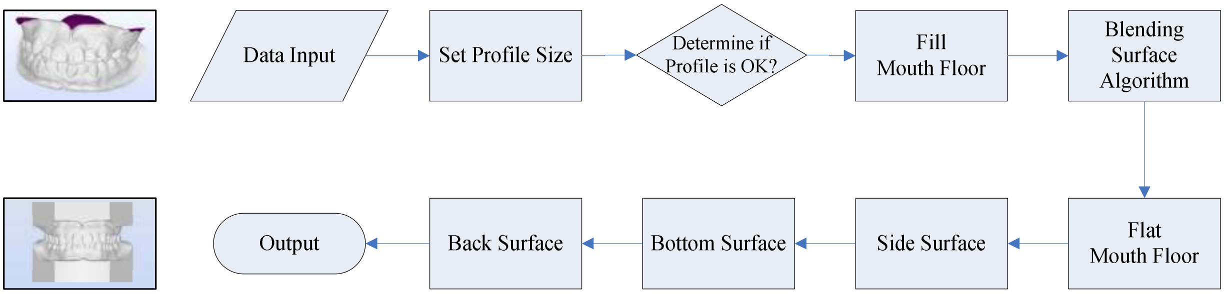
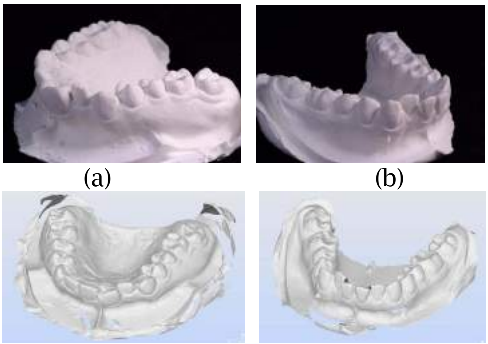


Fig. 2: The flow chart of orthodontic model reconstruction.

3.1 Impression Digitization

Model digitization is the first step for virtual plaster reconstruction. Asada, M. et al. [20] proposed an optical range scanning system to acquire 3D surface data. Sansoni, G. et al. [21] published a phase–shift algorithm to improve the performance and efficiency. This paper utilizes a structure light scanner to capture the surface data of impression from several directions, and the results are several 3D patches. Because the adjacent patches share a common portion of their surface, the ICP [19] algorithm is used to find a set of matching points on the overlap of the two 3D patches for data integration. Fig.3 shows the physical study model and the virtual study model respectively.



(a) (b) (c) (d)

Fig. 3: The Tweed model: Physical model of (a) maxilla and (b) mandible. Virtual model of (c) maxilla and (d) mandible.

3.2 Virtual Occlusion

After impression digitization, the first problem we meet is how to occlude the two sides of the virtual model. We first need to understand the working principle of the traditional manual occlusion procedure. During the occlusion process, the teeth of maxilla and mandible receive opposing forces from each other. Finally, the teeth reach a balanced state after the upper and the lower are perturbed or offset by incremental collision steps. Therefore, the technician simply puts the plaster casts of maxilla and mandible together on an articulator, and exerts pressure upon the plaster casts. The technician moves one object on both sides to make sure if the two are "embedded" or "locked in" with each other. If embedded, the occlusion position can be obtained correctly. However, virtual objects do not know how to simulate the physical laws. Hence how to occlude teeth correctly in a virtual environment is not an easy task. The idea of our algorithm is similar in spirit to the physical collision simulation, such as garment simulation and natural collision. Collision response means deforming or displacing the colliding objects to avoid collision or object intersection. In this work, we assume the colliding objects as rigid body, hence there is no deformation to the objects needed.

The digital models in our system are all composed of triangles. The collision detection of two triangular models is to check the intersection of every triangle on the model. However, the algorithmic complexity for two meshes A and B is $O(n^2)$ in the worst case, where n is the number of triangles of the bigger mesh. When many meshes are involved the complexity increases even more. In this paper we use Open library V-Collide [24] developed at the University of North Carolina by the GAMMA team to detect the interference. The V-Collide is designed to operate on large numbers of polygonal objects. It uses N-body test algorithm to find possibly colliding pairs of objects rapidly, and works on arbitrary models. After detecting the contact pairs, another library called RAPID [22] is utilized to process these objects to find triangle intersections.

In Fig. 4, it shows the flow chart of our automatic occlusion algorithm. The coarse occlusion is to provide an initial approximate and robust estimate of the transformation. The registration should be fast and yet be able to avoid local minima. This method extracts partial crown data by a depth threshold first. Then arch form poly-line can be calculated by the crown data. Assume p_i and q_i are the arch form poly-line points of the maxilla and the mandible respectively. When we denote q_i as reference, there will be a transformation $q_i = Rp_i + T$ between the maxilla and the mandible where R is the rotation matrix and T is the translation matrix. With $N+1$ corresponding pairs $P = (p_0,..., p_N)$ and $Q = (q_0,..., q_N)$ the equation can be extended to

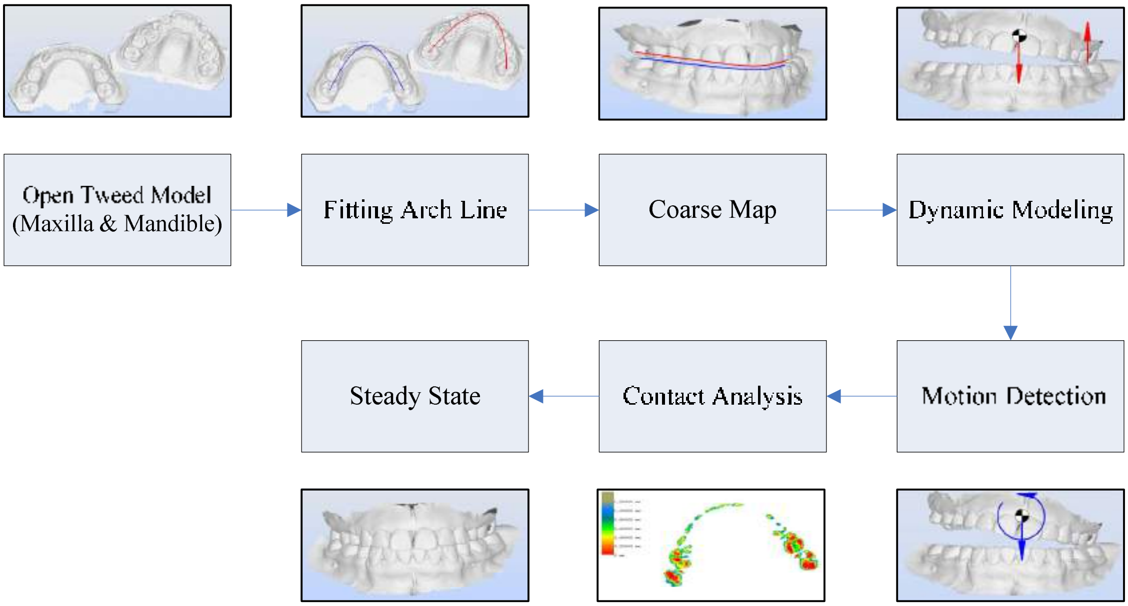


Fig. 4: An overview of the automatic occlusion algorithm.

$$Q = RP + T \tag{1}$$

With P and Q being given, the initial transformation R and T can be quickly determined by least-squares method. Then, we take the mandible as base. O_c is the mass center of the maxilla. The maxilla is now simulated as being falling from the initial position to collide with the mandible due to gravity. Once collision has been detected we need to produce a collision response, that is, to calculate the forces F_r acting on the maxilla according to the collided triangles. Since the maxilla model is always affected by gravity, the total force applied on the maxilla can be equal to $mg + \sum \vec{f}_i$. For translation, the force equation is $F = m\vec{a}$. The acceleration, velocity, and the position can be obtained by the equation

$$\vec{a} = \frac{mg + \sum \vec{f}_i}{m} \tag{2}$$

$$\vec{v} = \vec{v}_0 + \vec{a}t \tag{3}$$

$$p = p_0 + v_0 t + \frac{1}{2}\vec{a}t^2 \tag{4}$$

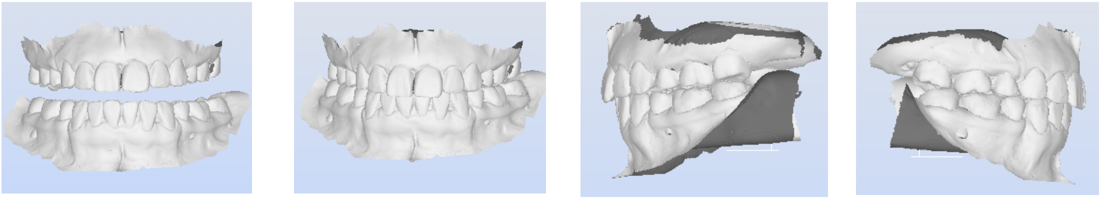
For rotation, the angular acceleration, angular velocity, rotation angle can be presented as follows.

$$\vec{\alpha} = \frac{\sum \vec{M}_i}{I} = \frac{\sum \vec{r}_i \times \vec{f}_i}{I} \tag{5}$$

$$\vec{\omega} = \vec{\omega}_0 + \vec{\alpha}t \tag{6}$$

$$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2 \tag{7}$$

where m is the mass of maxilla, I is the moment of inertia of maxilla, g is the acceleration of gravity, a is the acceleration of translation, α is the angular acceleration, v is current velocity of maxilla, v_0 is the velocity of next state, ω is the angular velocity of maxilla, ω_0 is the angular velocity of next state, p is the position of center of mass of maxilla, p_0 is the center of mass of next state, θ is the angular velocity of maxilla, θ_0 is the angular velocity of next state, f is the force applied to maxilla, M is the moment caused by f, and r is the closest distance from mass center to the force contact point. When collision occurs, the equation set will be used to calculate the next position and rotation. The iteration continues until the convergence is reached within a certain criterion. A sample case of the automatic occlusion algorithm is shown in Fig. 5.



(a) (b) (c) (d)

Fig. 5: Auto occlusion: (a) After fitting arch line (b) The result of automatic occlusion in front view (c) Left view (d) Right view.

3.3 Blending Surface

Blending surface can be regarded as a bridge which connects two parts smoothly. After matching the study model, this section describes a method to construct a connector surface between the study model and the profile which is treated as virtual gum. Some commercial systems utilize parametric surfaces to display the virtual gum. Unfortunately, the shape of the gum is so sophisticated that it is difficult to present as parametric surface. In our system, the virtual model is represented as high quality triangle mesh. Hence, the only problem to present a delicate model is how to produce a mesh exactly. In [23], the proposed algorithm can build a connected surface smoothly according to the position and normal of the end points. However, slight ridge may occur because of the jiggle end points. This paper presents a method that can solve the problem and produce a connected surface smoothly and efficiently. When the user sets up the position of the study model, the closest pairs between the boundary of the study model and the profile can be detected automatically. Then, the constructed surface can be divided into three parts. For the first two parts, the closed poly-line loop is projected on a grid mesh to form a patch. The patch can be re-mapped to the original loop automatically. By way of the construction, our method can build the frenum rapidly. For the third part, the boundary points are provided by calculation. Thus, the algorithm [23] can be utilized to construct the blending surface efficiently.

However, the method mentioned above can build a connected surface but the continuity of the surfaces is not good enough to blend with the study model. Our method uses again the iterative mass–spring-damper system. The first step is to decide the mass of the node M, and the total force $\vec{F}_i$ applied to each node M_i at time t_i can be calculated by Eqn. (8). Simultaneously, the velocity $\vec{V}_i$ and the position $\vec{P}_i$ of the node can be obtained. For the next time step Δt, the new velocity $\vec{V}_i'$ and position $\vec{P}_i'$ can be calculated by Eqn. (9) and Eqn. (10).

$$\vec{F}_i = \vec{f}_i + \sum_{j \in N_i} \vec{f}_{ij} \tag{8}$$

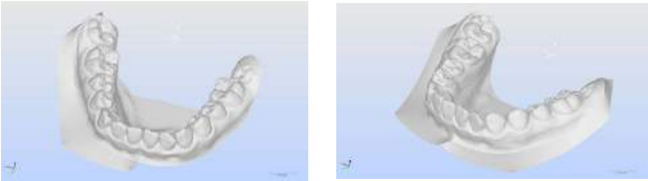
where $\vec{f}_i = K_D \cdot \vec{V}_i$, and $\vec{f}_{ij} = K_D \cdot \vec{V}_{ij} + K_S \cdot (\vec{L}_{ij} - \vec{l}_{ij})$.

$\vec{V}_{ij} = \frac{(\vec{V}_i - \vec{V}_j)\cdot \vec{L}_{ij}}{|\vec{L}_{ij}|}\cdot \frac{\vec{L}_{ij}}{|\vec{L}_{ij}|}$. $\vec{L}_{ij} = \vec{P}_i - \vec{P}_j$ is the new distance between P_i and P_j . $\vec{f}_i$ is the reacting force of the node M_i provided by damping component. $\vec{f}_{ij}$ is the related force provided by M_i M_j . K_D is the damping coefficient. K_S is the spring constant and l_{ij} is the original length between M_i and M_j .

After we obtain the force of each node M_i , the Newton Second's Law can be used to calculate the new velocity $\vec{V}_i'$ and new position $\vec{P}_i'$ at time t_{i+1} . In this work, we assume K_S =1500、 K_D =4.5 , m =0.1 g. The result of blending surface construction method is presented in Fig. 6. Our method can build the surface completely, and the frenum is displayed.

$$\vec{V}_i' = \vec{V}_i + \frac{\vec{F}_i}{m}\cdot \Delta t \tag{9}$$

$$\vec{P}_i' = \vec{V}_i \cdot \Delta t + \frac{1}{2}\cdot \vec{a}_i \cdot \Delta t^2 \tag{10}$$

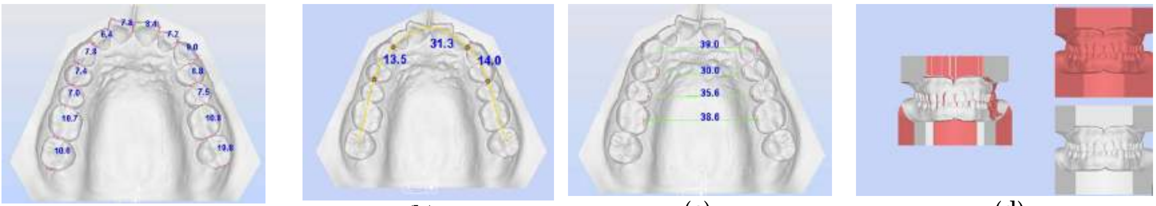


(a) (b)

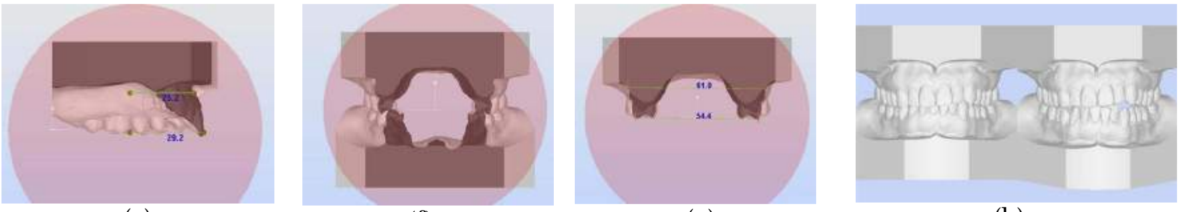
Fig. 6: (a) the blending surface of the first part. (b) The result of blending surface construction.

4. MEASUREMENT ANALYSIS

In this section, the paper presents a measuring system which provides dentists useful tools for analysis in a virtual platform. In treatment planning, some important information such as teeth width, arch form, arch width etc are needed to assist the doctor for diagnosis. Traditionally, the technician obtains the measurement information by hand-held gauges. The operation is time-consuming and difficult. Now with the digital study model available, one can simulate the measurements digitally as shown in Fig. 7. Fig. 7(a) measures the width of the teeth. Fig. 7(b) scales the length of arch form. The system can determine the shape of arch form automatically. The user can adjust the shape slightly and measure the widths and lengths easily. Fig. 7(c) measures the width of the arch form. Fig. 7(e) and Fig. 7(g) scales basal width and basal length separately. In addition, clipping plane shown in Fig. 7(f) allows the user to examine the cross-section of the teeth. In Fig. 7(d), overlaying of "before" and "after" models can contrast and compare the difference between pre-treatment and post-treatment. CO/CR comparison is shown in Fig. 7(h), the user can compare the change of occlusion between two occlusions. In the end, the measuring results can be tabulated in a report for treatment assistance.



(a) (b) (c) (d)



(e) (f) (g) (h)

Fig. 7: Measurement analysis results of digital measurement: (a) dental width (b) Arch space (c) Arch width (d) Lapping comparison (e) basal length (f) Clipping plane (g) Basal width (h) CO/CR comparison.

5. RESULTS AND DISCUSSION

This section examines the performance of the proposed digital plaster reconstruction method shown in Fig. 9. The method this paper proposes can construct three types of digital plaster model, usually referred to as "Tweed" model, used specifically in orthodontic treatment. Besides, during the automatic occlusion algorithm, the choice of the coefficients decides the convergence of the calculation. In this work, the input data is a study model scanned from an optical range scanning system. The scanned data is usually fragmented and incomplete. To make matters worse is that there may be some bubbles on the physical plaster model. Traditionally, the technician addresses the defects manually by patching with smooth plaster. But in our digital system, a method which is similar to mesh hole-filling algorithm is utilized to solve the problem smoothly and efficiently. Moreover, the mandible model often lacks the large portion of data at the bottom covered by the tongue during impression taking. The solution is to decide the height of the plane and generate a planner surface that is blended into adjacent soft tissue surfaces. For the base of orthodontic model, this system provides a tool to allow the user to edit the shape of profile. Finally, the virtual orthodontic model can be built completely after constructing the base of the model.

5.1 Base Type

In the process of orthodontic treatment, three types of plaster cast shown in Fig. 9 are used for diagnosis assistance. They are Tweed Original, Tweed Modified and Gnathostatic (GNA). The difference between Tweed Original and Tweed Modified is the angle on the side of the mandible. For the GNA, the occlusion plane has an oblique angle about 12 degrees. The detail parameters of the three types are listed in Tab. 1 and shown in Fig. 8. Once the parameters are set, the system can automatically construct the Tweed model. The user can then decide if he wants to adjust the profiles of the shape interactively.

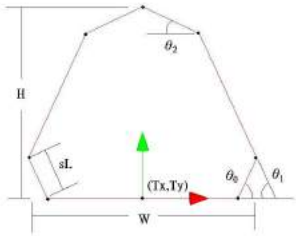
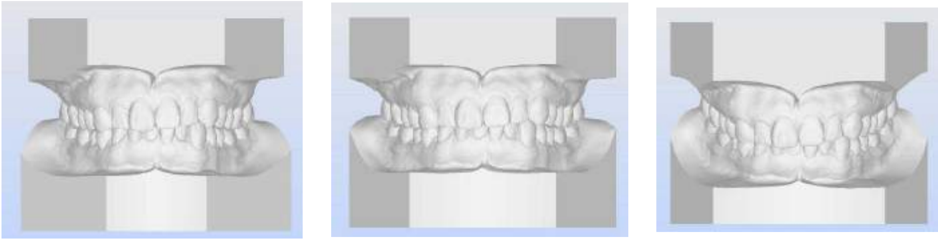


Fig. 8: Example of the base profile.

	Tweed Modified	*Tweed Original*	*GNA*
θ_0 (^{o})	65	60	50
θ_1 (^{o})	65	T:65 B:55	70

θ_2 (^{o})	25	25	25
sL(mm)	10-15	T:10-15 B:T+5	10-20

Tab. 1: The parameters of the Tweed profile, where T is the maxilla and B is the mandible.



(a) Tweed Original (b) Tweed Modified (c) GNA

Fig. 9: The three type of Tweed model built by our system.

5.2 Efficiency of Occlusion

In our system, the behavior of the maxilla works just like a mass-spring system during the process of occlusion. Thus, a damper which facilitates the system stabilization should be inserted. Obviously, smaller damping coefficient creates larger "vibration" and longer iterations. On the other hand, the system converges quickly if the coefficient is sufficiently large. Approximately, the system converges to stabilization less than 20 seconds. The idea of our algorithm is similar in spirit to the physical collision simulation, such as garment simulation and natural collision. Collision response means deforming or displacing the colliding objects to avoid collision or object intersection. In this work, we assume the colliding objects are rigid bodies. There is no deformation to the objects needed. However, since the shape of the teeth is highly complicated, once the collision occurs, it is very difficult to calculate the penetration depth of the collided objects. Generally, the penetration depth decides the responsive force. In physical collision simulation the correct assessment of the responsive force would be important. Fortunately, for our work, we do not need the accurate evaluation of the responsive force; what we care the most is the final position after the collision. The virtual occlusion iteration will be terminated when the vibration is smaller than a predicted threshold value. In this paper, the number of vertices of maxilla and mandible is about 40K separately. The total computing time is about 20 second. For geometric registration, an overlapping area between two data sets is needed for initial registration. The Iterative closest points (ICP) algorithm can then be used. Unfortunately, there is almost no overlapping region between the maxilla and the mandible. Thus, this method occludes them initially by matching the "identifiable geometric features or patterns" of the upper and the lower, which is the natural arch form for the coarse registration. Our occlusion algorithm is then applied for fine registration to occlude the maxilla and the mandible at the centric occlusion condition.

5.3 5-axis Milling of Plaster Model

This paper describes a method to construct virtual plaster model for general and orthodontic dentistry. Once the digital plaster model is created, an analysis software module can be used for treatment diagnosis and planning. The only requirement of input is the scanned data of teeth. Therefore, not only from the plaster model or the impression scan, the method is also readily applicable to intra-oral scanned data. Moreover, if necessary, the physical plaster model can be fabricated by 5-axis machining or 3D printing techniques. In Fig.10, we show a physical Tweed model produced by 5-axis milling. Instead of plaster which is easy to break, we use synthetic wood material which is unbreakable and dimensionally more stable than the RP material.

(a) (b)

Fig. 10: The physical orthodontic model product by machining.

6. CONCLUSION

This paper proposes a new procedure for virtual plaster model reconstruction. The automatic occlusion algorithm is applied to register the maxilla and the mandible at the center occlusion condition. Moreover, the user can build the model base automatically by setting the parameters of the profile. A blending surface algorithm is used to construct a connected surface smoothly. For bite registration and occlusion, an automatic occlusion algorithm is also developed that simulates the physical collision and stabilization between the maxilla and the mandible. In addition, this paper also presents several measuring tools that can assist dentists in treatment diagnosis and planning. In the end, the physical plaster model can be generated by 5-axis machining.

7. REFERENCES

[1] Goshtasby, A.; Nambala, S.; DeRijk, W. G.; Campbell, S.-D.: A System for Digital Reconstruction of Gypsum Dental Casts, IEEE Transactions on Medical Imaging, 16(5), 1997, 664-674.

[2] Andreetto, M.; Brusco, N.: Automatic 3D Modeling of Palatal Plaster Casts, IEEE Proceedings of the Fourth International Conference on 3-D Digital Imaging and Modeling, 2003.

[3] Brusco, N.; Andreetto, M.: Metrological Analysis of a Procedure for The Automatic 3D Modeling of Dental Plaster Casts, Proceedings of the 2nd international symposium on 3D Data Processing, Visualization and Transmission, 2004.

[4] Hirogaki, Y.; Sohmura, T.; Satoh, H.; Takahashi, J.; Takada, K.: Complete 3-D Reconstruction of Dental Cast ShapeUsing Perceptual Grouping, IEEE Transactions on Medical Imaging, 20(10), 2001.

[5] Brusco, N.; Andreetto, M.; Lucchese, L.; Carmignato, S.; Cortelazzo, G. M.: Metrological Validation for 3D Modeling of Dental Plaster Casts, Medical Engineering & Physics, 29, 2007, 954-966.

[6] Hiew, L. T.; Ong, S.-H.; Foong, K. W. C.: Optimal Occlusion of Teeth, IEEE Control, Automation, Robotics and Vision, 2006.

[7] DeLong, R.; Ko, C. C.; Anderon, G. C.; Hodges, J. S.; Dpuglas, W, H.: Comparing Maximum Intercuspal Contacts of Virtual Dental Patients and Mounted Dental Casts, The Journal of Prosthetic Dentistry, 88, 2002, 622-630.

[8] Kamegawa, M.; Nakamura, M.; Tsutsumi, A.: 3D Morphological Measurements of Dental Casts with Occlusal Relationship using Mircofocus X-ray CT, Dental Material Journal, 27, 2008, 549-554.

[9] Terzopoulos, D.; Platt, J.; Barr, A.; Fleischer, K.: Elastically Deformable Models. Computer Graphics, 21(4), 1987, 205–214.

[10] Terzopoulos, D.; Waters, K.: Physically-Based Facial Modeling, Analysis and Animation, Journal of Visualization and Computer Animation, 1(2), 1990, 73–80.

[11] Lee, Y.; Terzopoulos, D.; Waltes, K.: Realistic Modeling for Facial Animation, Proceedings of the 22nd Annual Conference on Computer Graphics and Interactive Techniques, 1995, 55–62.

[12] Chen, Y.; Lin, S.; Zhong, H.; Xu, Y. Q.; Guo, B.; Shum, H. Y.: Realistic Rendering and Animation of Knitwear, IEEE Transactions on Visualization and Computer Graphics, 9(1), 2003, 43–55.

[13] Eberhardt, B.; Weber, A.; Strasser, W.: A Fast, Flexible Particle-System Model for Cloth Draping, IEEE Computer Graphics and Application, 16(5), 1996, 52–59.

[14] Liu, A.; Tendick, F.; Cleary, K.; Kaufmann, C.: A Survey of Surgical Simulation Applications Technology and Education, MIT Press Journals, 12(6), 2003, 599-614.

[15] OrthoCAD, http://www.orthocad.com/, http://www.cadent.biz/orthodontics.html

[16] emodel, http://www.dentalemodels.com/emodel_services/emodel_by_geodigm.html http://www.dentalemodels.com/emodel_services/eplan_main.html

[17] DigiModel, http://www.orthoproofusa.com/

[18] Orapix, http://www.orapix.com/
[19] Besl, P. J.; McKay, N. D.: A Method for Registration of 3D Shapes, IEEE Transactions on Pattern Analysis and Machine Intelligence, 14(2), 1992, 239-256.
[20] Asada, M.; Ichikawa, I.; Tsuji, S.: Determining Surface Orientation by Projecting a Stripe Pattern, IEEE Transactions on Pattern Analysis and Machine Intelligence, 10(5), 1988, 749-754.
[21] Sansoni, G.; Carocci, M.; Rodella, R.: Calibration 3-Dvision Based on a Combination of Gray-Code and Phase Shift Light Projection: Analysis and Compensation of The Systematic Error, Applied Optical, 38, 1999.
[22] Gottschalk, S.; Lin, M. C.: Manocha D.; Obbtree : A Hierarchical Structure for Rapid Interference Detection, SIGGRAPH, 96, 1996, 171-180.
[23] Piegl, L.; Tiller W.; the NURBS Book, Springer-Verlag, 1997.
[24] Hudson, T.; Lin, M.; Cohen, J.; Gottschalk, S.; Manocha, D; V-COLLIDE: Accelerated Collision Detection for VRML, In Proc. of VRML'97.