Title:
Alignment of Dental Depth Images from an Intraoral Scanner

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Introduction:
Owing to the increased demand for biocompatibility and esthetically pleasing dental restorations, all-ceramic restorations such as glass-boned porcelain and phase-stabilized zirconia have been introduced in restorative dentistry [5], [20]. The development of all-ceramic restoration has allowed wider expanded application in dental CAD/CAM. It is because of the manufacturing of all-ceramic restoration requiring a 3D dental model for machining operations. Today, various digitizing systems have been proposed to obtain 3D dental models. More recently, there are two methods to digitize a 3D model. First one is performing directly in the patient's mouth (intraoral) and second one is performing indirectly after taking an impression and fabricating master cast (extraoral) [6], [13].

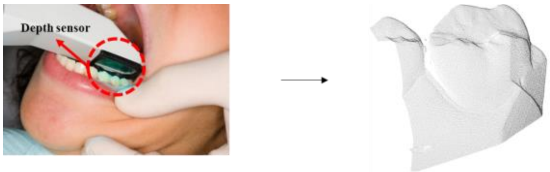

Fig. 1: Dental depth image acquisition by intraoral scanner

One of the probably most well-known digitizing systems is an extraoral system using plaster model. However, A 3D dental model obtained from intraoral scanner can be used as an alternative to conventional plaster casts. Intraoral digitization allows the dental-care provider to obtain directly the data from the patient's teeth (Fig. 1). This method creates 3D models in real-time by registration of each depth image [6]. Thus, it is not necessary to take an impression and fabricating plaster model. Further, this method shows real-time intermediate results of 3D Model during measurement. Also, it can be stored easily, and transmitted digitally [11]. An intraoral scanning technology that provides ease of measurement has more attractive than conventional dental impression system.
However, despite the aforementioned advantages, the most critical issue in dental scanning system is accuracy of the final dental restoration [15]. The accuracy of 3D dental model is a major factor for dental restorations, which has an influence on the fit of fixed restorations. Because the final product of the manufacturing procedure is intended to replace a person's missing tooth structure, the required accuracy level (50 ㎛) should be ensured throughout all steps of manufacturing [16]. Thus, recent studies in intraoral dentistry fields are consist of various digitization techniques for proper accuracy.

Related works:
One of the probably most well-known examples registration point cloud data is Kinectfusion [8]. Kinectfusion uses the Microsoft Kinect device for real-time 3D reconstruction. Kinectfusion uses a Z-

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buffer ICP algorithm for fast registration, but it is relatively not accurate [1]. This method focuses on reconstruction speed, cannot provide the accuracy level which is required in dentistry. Furthermore, it may cause accumulative errors which are fatal to a final dental restoration. Besl and Mckay propose an ICP (*Iterative closest point*) algorithm for registration which requires the specification of an appropriate procedure to find the closest point on a geometric entity to a given point [2]. But single ICP method in intraoral scanning may cause computation time loss. Because each dental depth image is consisted of many points, and dental image shapes are consisted of complex curves. Kim and Chang propose a simultaneous registration of multiple depth images using Global hessian matrix to appropriate each depth images [3]. It works stable, and lead to superior results in previous tests, but it is relatively slow to use in dentistry. T. Weber et al. proposes an automatic registration of unordered point clouds using feature characteristic [21]. It works relatively fast, and lead to superior results in previous tests. But this method, which considers a shape of all dental depth images, may not be suitable for patients with a similar tooth shape in the mouth.

Main Idea:

Before presenting the methodology in detail, it is necessary to regard an intraoral scanning characteristic. An intraoral scanning method uses a hand-held scanner for real-time 3D reconstruction and capture a dental depth images from a part of patient's tooth. Each dental depth images are captured by swing a handheld scanner to left and right sides of the tooth (Fig. 2). A registration method of intraoral scanning uses sequential processing because it focuses on real-time reconstruction which is required fast computation speed [11]. Each depth images are aligned with other depth image which is their previous sequence. However, this method does not help in terms of accuracy. Because of the complicated shape of the teeth, there is no guarantee that the first and second depth images are good correspondence. Therefore, the proposed procedure in this paper is based on the above considerations.

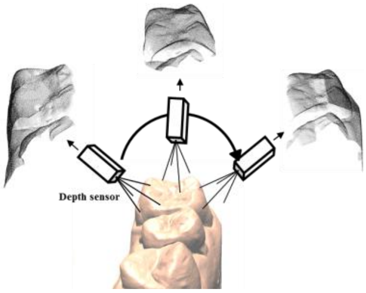

Fig. 2: Acquisition of Dental depth images from a different direction.

This paper proposes an automated alignment procedure of dental depth images captured by intraoral scanners. The proposed procedure identifies an acquired order from initial scanning data and attempts to compute the registration sequence for aligning all dental depth images into a completed model. A core part of the proposed procedure is an algorithm that computes the similarity of each dental depth images, considering only the adjacent dental depth images. The algorithm was designed carefully by considering two major technological requirements of the problem: accuracy and efficiency. To satisfy the accuracy requirement, the proposed algorithm uses the concept of feature vector based on fast point feature histogram (FPFH) to compute the similarity index of each dental depth images. After similarity index computed, all depth images are represented by connected, edge-weighted undirected graph. In this paper, we call it pairwise-chain. In pairwise-chain, the edge is weighted by the similarity index (Fig. 4). After all edges are weighted, the Minimum Spanning Tree (MST) of pairwise-chain is computed (Fig. 4(b)). In this paper, using Kruskal's algorithm for solving MST [9]. The result of MST represents the most consistently solution of all possible depth image pair registration combinations. From consistently solution result, registration sequence is reconstructed, considering the acquired order. The proposed procedure in this paper, nonadjacent edges are eliminated by axis aligned bounding box (AABB) detection, it is very efficient (Fig. 3). The input element of proposed procedure is a rough-aligned dental depth images from an intraoral scanning method and the output element is dental depth images which is precisely aligned.

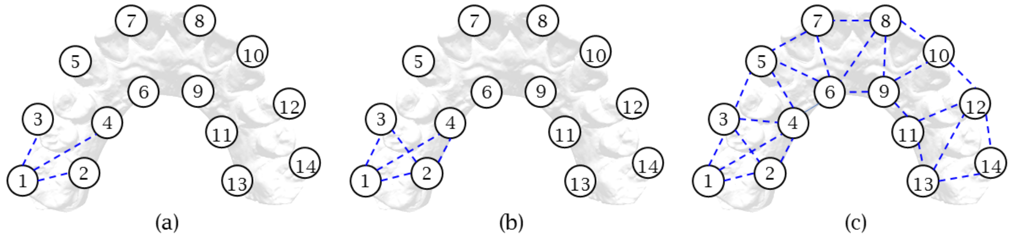

Fig. 3: Pairwise chain, from left to right; (a) Create pairwise chain of depth image #1 based on AABB overlapped neighborhoods; (b) Create pairwise chain of depth image #2 based on AABB overlapped neighborhoods; (c) Complete-pairwise chain.

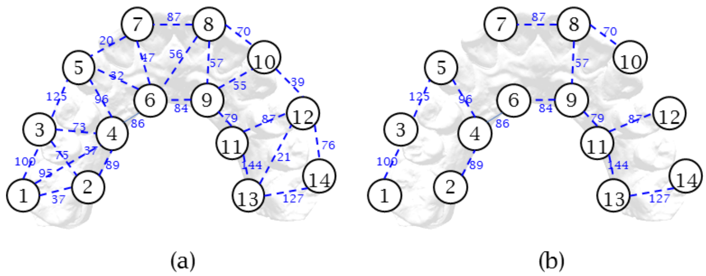

Fig. 4: (a) Pairwise chain graph, Weighted by Similar FPFH Descriptor; (b) Pairwise chain, after MST.

The data used in the experiment consisted of 1,021 dental depth images of mandibular teeth. Each image consists of 80,000 to 140,000 vertices, and it is an experimental data set that have been scanned from the right third molar to the left third molar. The proposed algorithm was implemented in C++ language and test runs were made on a personal computer with a i5-2500 processor with 8 GB memory with geforce gtx 760ti(6gb) and a Windows 7 operating system. The cloud to mesh(C2M) signed distance and its distribution from *CloudCompare* software is used to measure the accuracy of registration.

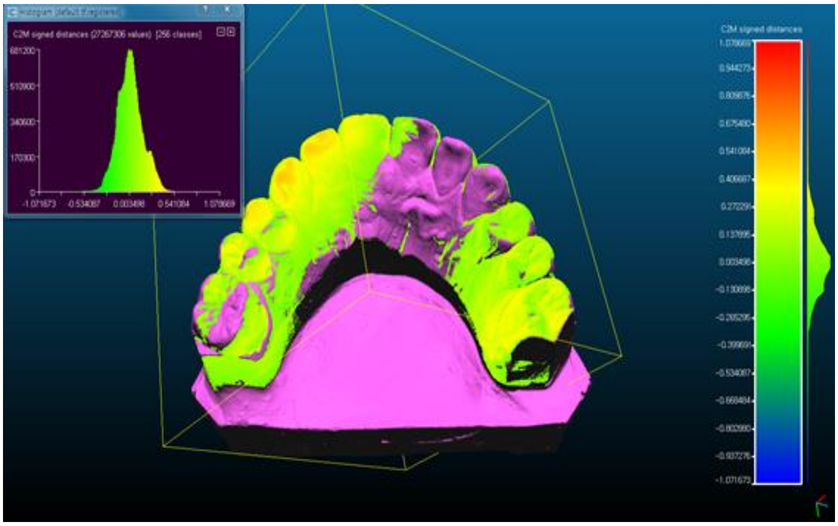

Fig. 5: Cloud to mesh(C2M) signed distance and its distribution : intraoral scanning (Kinectfusion).

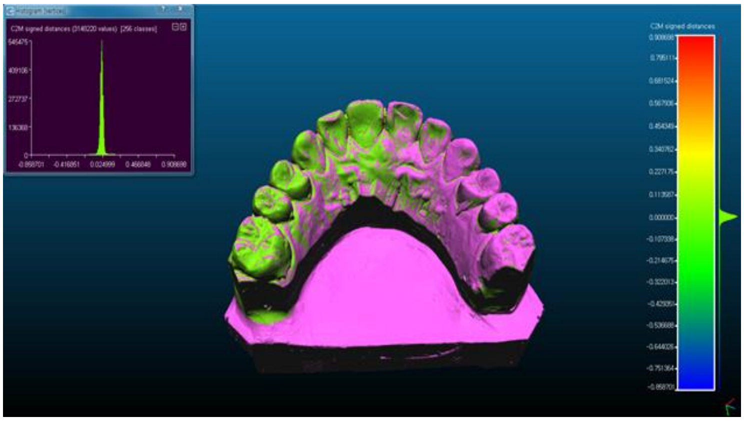

Fig. 6: C2M signed distance and its distribution : The Chang's method [3].

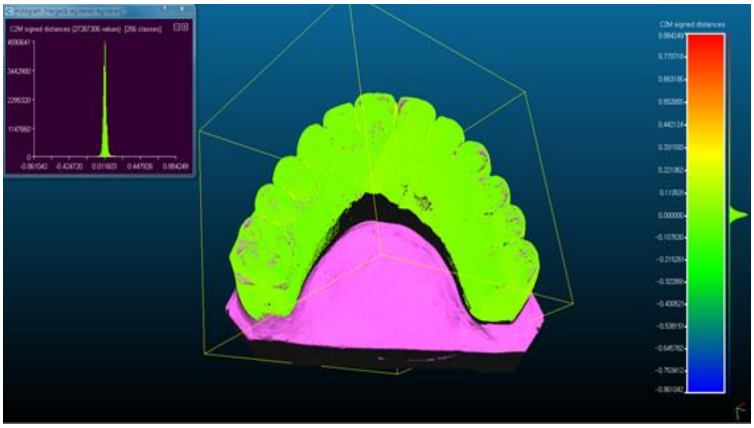

Fig. 7: C2M signed distance and its distribution : The Proposed method.

Method	*Mean dist (μm)*	*Runtime (s)*
KinectFusion	91.00 (0.1)	Real-time
Chang's method	3.36 (0.05)	552
Proposed method	5.19 (0.05)	30

Tab. 1: Result of tests.

Conclusions:

This paper proposes an automated alignment procedure of dental depth images captured by intraoral scanners. A core part of the proposed procedure is an algorithm that computes the similarity of each dental depth images, considering only the adjacent dental depth images. The algorithm was designed carefully by considering two major technological requirements of the problem: accuracy and efficiency. To satisfy the accuracy requirement, the proposed algorithm consists of three steps: (1) find a nearby dental depth image by AABB detection, (2) compute a FPFH descriptor between adjacent dental depth images, (3) make a pairwise-chain, (4) solve a pairwise-chain using MST, and (5) reconstruct a registration sequence. The proposed method provides better result than conventional approach and satisfied a required level of result in dentistry. For the implementation of the proposed algorithm, a detailed description of the algorithm is provided and several illustrations are provided to prove the usefulness of the algorithm. Although the main application of the proposed algorithm is dental depth images from an intraoral scanner, the proposed algorithm can be applied to other small objects.

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