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FEATURES SECTION

Current Products and Practices

Applications of 3D imaging in orthodontics: Part I

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Part I of this paper describes the background, general concepts, available techniques and the clinical applications of recording external craniofacial morphology in three dimensions. Part II explores the different 3D techniques of imaging the dental arches, and their possible uses in orthodontic diagnosis and treatment.

Key words: *3D Facial Imaging, Stereophotogrammetry, Facial Assessment, Study Models Archiving, Virtual Orthodontic Patient*

Introduction

Three-dimensional (3D) imaging has evolved greatly in the last two decades and has found applications in orthodontics, as well as in oral and maxillofacial surgery. In 3D medical imaging, a set of anatomical data is collected using diagnostic imaging equipment, processed by a computer and then displayed on a 2D monitor to give the illusion of depth. Depth perception causes the image to appear in 3D.[1]

The applications of 3D imaging in orthodontics include pre- and post-orthodontic assessment of dentoskeletal relationships and facial aesthetics, auditing orthodontic outcomes with regard to soft and hard tissues, 3D treatment planning, and 3D soft and hard tissue prediction (simulation). Three-dimensionally fabricated custom-made archwires, archiving 3D facial, skeletal and dental records for in-treatment planning, research and medico-legal purposes are also among the benefits of using 3D models in orthodontics.

Part I of this paper focuses on the techniques that record the external craniofacial morphology and their applications (i.e. 3D imaging of the face), whereas Part II will evaluate the applications of direct or indirect recording of dental morphology (i.e. 3D imaging of the teeth).

Historical background

From the introduction of the cephalostat, Broadbent stressed the importance of coordinating the lateral and postero anterior cephalometric films to arrive at a distortion-free definition of skeletal craniofacial form.[2] The first reports on implementation of this method were by Singh and Savara[3] on 3D analysis of maxillary growth changes in girls. Computer programs have since been developed to collect three-dimensional coordinates directly from digital cephalogram images, eliminating the need for hand tracing and mouse-based X–Y digitizing tablets.[4,5]

Stereophotogrammetry has evolved from old photogrammetric techniques to provide a more comprehensive and accurate evaluation of the captured subject. This technique uses one or more converging pairs of views to build up a 3D model that can be viewed from any perspective and measured from any direction. The earliest clinical use of stereophotogrammetry was reported by Thalmann-Degan in 1944 (according to Burke and Beard[6]) who recorded change in facial morphology produced by orthodontic treatment. With great advances in computer technology, a new generation of computerized stereophotogrammetric techniques has arisen making the capturing and building procedures quicker, simpler and more accurate.

On the other hand, the first commercial Computerized Tomography (CT) scanner appeared in 1972. Soon after, it was apparent that a stack of CT sectional images could be used to generate 3D information. In the early 1980s, researchers began investigating 3D imaging of craniofacial deformities. The first simulation software was developed for craniofacial surgery in 1986. Shortly after,

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the first textbooks on 3D imaging in medicine appeared with a concentration on the principles and applications of 3D CT- and MRI-based imaging. Three-dimensional imaging has evolved into a discipline of its own, 'dealing with various forms of visualization, manipulation and analysis of multi-dimensional medical structures'.[7]

General 3D concepts

Before exploring the different techniques available, it is necessary to understand some of the principles and terminology in 3D imaging. In two-dimensional (2D) photographs or radiographs, there are two axes (the vertical and the horizontal axes), while the Cartesian coordinates system in 3D images consists of the *x*-axis (or the transverse dimension), *y*-axis (or the vertical dimension), and the *z*-axis (the anteroposterior dimension 'depth axis'). Figure 1 illustrates the right-handed *xyz* coordinate system, which is used in 3D medical imaging. The *x*-, *y*- and *z*-coordinates define a space in which multi-dimensional data are represented and this space is called the 3D space.[7]

3D models are generated in several steps. The first step, 'Modeling', uses mathematics to describe the physical properties of an object. The modeled object can be seen as a 'wireframe' (or a 'polygonal mesh'). The mesh is usually made up of triangles or polygons and it is used as a mode of visualization. A part of the modeling procedure is to add a surface to the object by placing a layer of pixels and this is called 'image' or 'texture mapping' (Figure 2). The second step is to add some shading and lighting, which brings more realism to the 3D object. The final step is called 'rendering', in which the computer converts the anatomical data collected from the patient into a life-like 3D object viewed on the computer screen.[1]

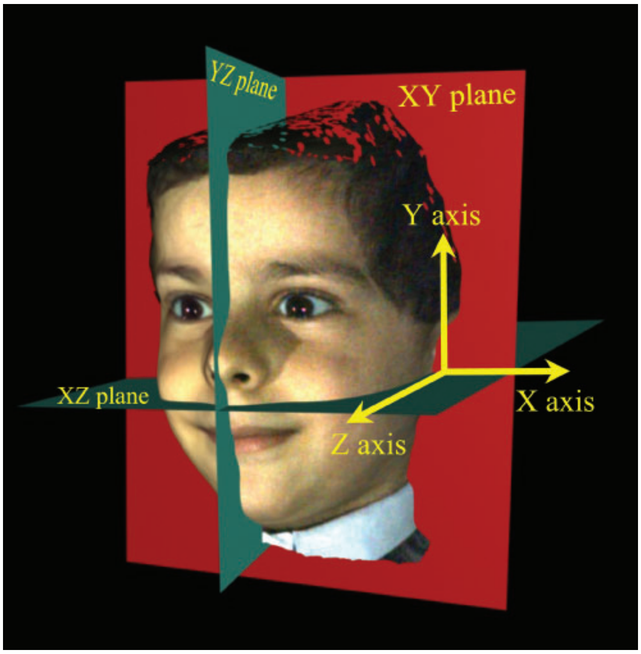

Figure 1 Right-handed *xyz* coordinates system

Udupa and Herman[7] classified 3D imaging approaches into three categories:

- slice imaging, e.g. a set of CT axial data to produce reconstructed 2D images;
- projective imaging, e.g. surface laser scanning to produce what is considered a 2.5-D mode of visualization;
- volume imaging, e.g. holography or 'varifocal mirrors' techniques.

Projective imaging is the most popular 3D imaging approach, but it does not provide a true 3D mode of visualization similar to what is offered by the volume imaging approach.

For measuring scanned objects in 3D, there are two main geometrical strategies: orthogonal measurement and measurement by triangulation.[8] Orthogonal measurement means that the object is sliced into layers. The *x* and *y* dimensions are measured directly on the slice surface, and the *z* dimension is measured by tallying the number of slices in the area of interest. An example of this method is the ordinary CT scan. Measurement by triangulation is analogous to the geometry of mammalian stereoscopic vision.[8] Simply, two images of the object need to be captured from two different views simultaneously or in rapid succession. Stereophotogrammetry depends on this method of measurement, as well as both biplanar and coplanar stereo X-ray systems.

3D imaging of the face

A broader description of these techniques is given elsewhere.[9] The most common ones are highlighted.

3D cephalometry

Despite several improvements in 3D cephalometric research with more advanced armamentarium,[4,10] this technique is time-consuming, exposes the patient to radiation, does not define soft tissues and there are difficulties in relating accurately the same landmarks in the two radiographs, especially in the biplanar technique.[9,11]

3D CT scanning

This technique has gained considerable popularity and applications in the medical field, but with regard to facial imaging, its main disadvantages are considered to be:

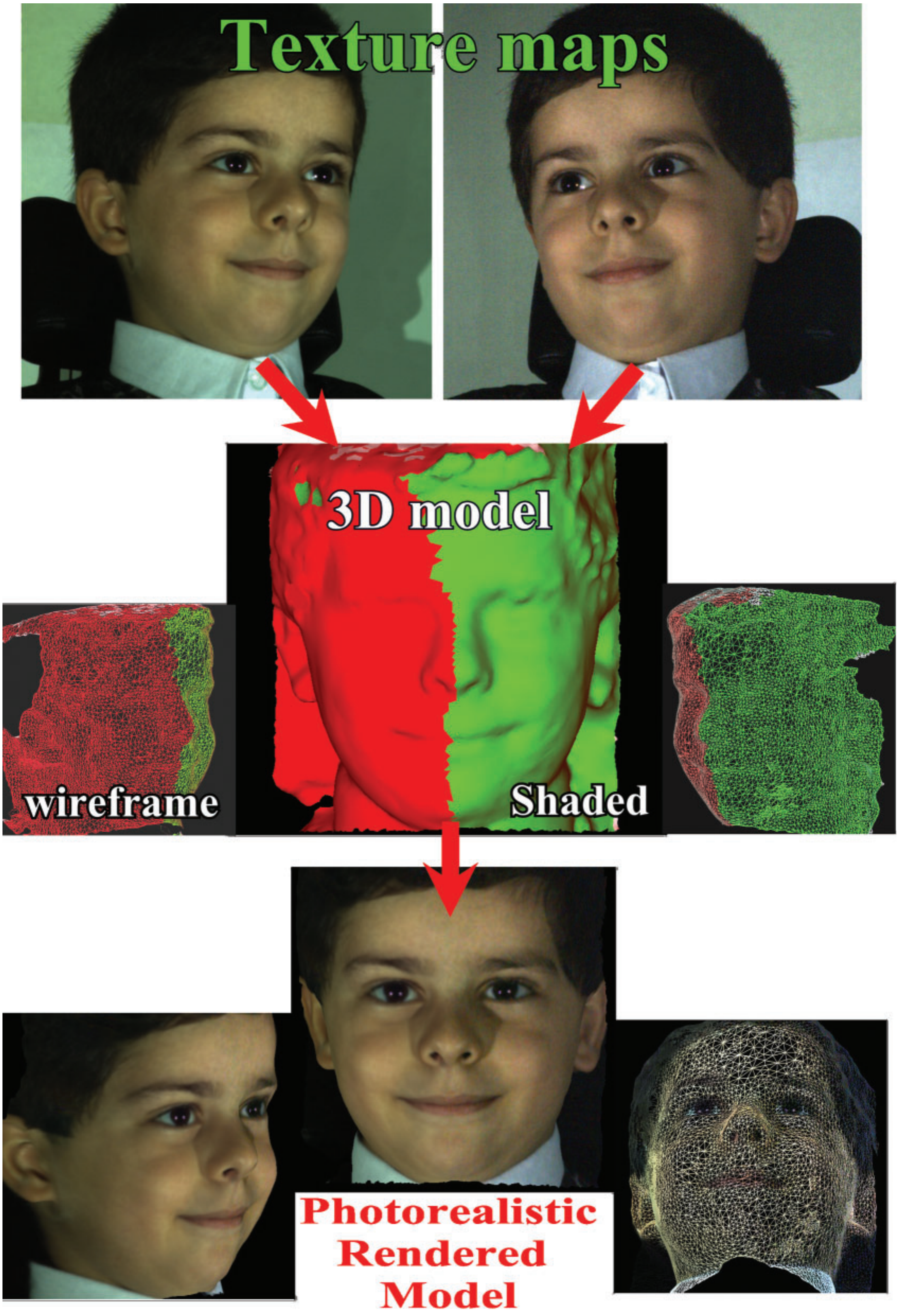

Figure 2 Texture images captured by color cameras are mapped onto the 3D model to produce the 'photorealistic rendered model'. In order to cover the face from ear to ear, two texture maps are captured from two different angles in front of the face. These images are taken simultaneously to prevent any error due to change in facial expression

- patient exposure to a high dose of ionizing radiation;
- limited resolution of facial soft tissues due to slice spacing;
- the possibility of having artifacts created by metal objects inside the mouth.[9]

3D laser scanning

Laser scanning provides a less invasive method of capturing the face for planning or evaluating outcome of orthodontic or orthodontic-orthognathic surgical treatment. However, this technique has several shortcomings for facial scanning. They include:

- the slowness of the method, making distortion of the scanned image likely;
- safety issues related to exposing the eyes to the laser beam, especially in growing children;
- inability to capture the soft tissue surface texture, which results in difficulties in identification of landmarks that are dependent on surface color. Even with the new white-light laser approaches that capture surface texture color, the shortcomings persist.[9]

Vision-based scanning techniques

These techniques are totally non-invasive, non-contact and vision-based imaging systems.

Moiré topography

Moiré topography delivers 3D information based on the contour fringes and fringe intervals. Difficulties are encountered if a surface has sharp features. Better results can be obtained on smoothly contoured faces. However, great care is needed in positioning the head, as a small change in head position produces a large change in fringe pattern. A 3D facial measuring system was proposed by Motoyoshi *et al.*,[12] but this system does not capture the normal facial texture and subsequent landmark identification is difficult.

Structured light techniques

In the structured light technique, the scene is illuminated by a light pattern and only one image is required (compared with two images with stereophotogrammetry). The position of illuminated points in the captured image compared to their position on the light projection plane provides the information needed to extract the 3D coordinates on the imaged object.[13] However, to obtain high-density models, the face needs to be illuminated several times with random patterns of light. This increases the capture time with increased possibility of head movements. In addition, the use of one camera does not provide a 180° (ear to ear) facial model, which necessitates the use of several cameras or rotating the subject around an axis of rotation, which is not practical and has resulted in reduced applicability of this technique.[14]

Techalertpaisarn and Kuroda[15] used two LCD projectors, charge-coupled device (CCD) cameras, and a computer to produce a three-dimensional image of the face that can be edited, shifted or rotated easily in any direction. This system needs at least 2 seconds to capture an image, which may be too long to reliably avoid head movements, especially when dealing with children.

Another variant of this technique was reported by Curry *et al.*[16] Their system consists of two cameras and one projector. A color-coded light pattern is projected onto the face before each image is acquired. The displacement of the pattern enables the software to compute an accurate 3D model. Another image is acquired without any accompanying light pattern, to be used for texture mapping. Three acquisitions are needed (one frontally and two obliquely) to cover the whole face. In a further step, the three stereo-images are ‘stitched’ together using specific software. The produced 3D facial maps are integrated with other 3D skeletal and 3D dental maps.

Stereophotogrammetry

Stereophotogrammetry refers to the special case where two cameras, configured as a stereopair, are used to recover 3D distances of features on the surface of the face by means of triangulation.[9]

The technique has been applied clinically by using a portable stereometric camera optically linked with a simple plotting instrument.[6] The incorporation of recent technology in computer science in the field of stereophotogrammetry has given the ability to process complex algorithms in order to convert simple photographs to three-dimensional measurements of facial changes. Ras *et al.*[17] have demonstrated a stereophotogrammetric system that gives the three-dimensional coordinates of any chosen facial landmark, so linear and angular measurements could be calculated to detect any changes in facial morphology. This system consists of two synchronized semi-metric cameras mounted on a frame with a distance of 50 cm between them and positioned convergently with an angle of 15°.

The C3D® imaging system has been developed as the result of collaboration between Glasgow University Dental School and the Turing Institute. C3D® is based on the use of stereo digital cameras and special textured illumination, with a capture time of 50 milliseconds and it is sufficiently cost effective to be utilized within the daily clinical routine. C3D® captures the natural surface appearance of the patient’s skin and ‘drapes’ this skin texture over the captured 3D model of the face (Figure 3).

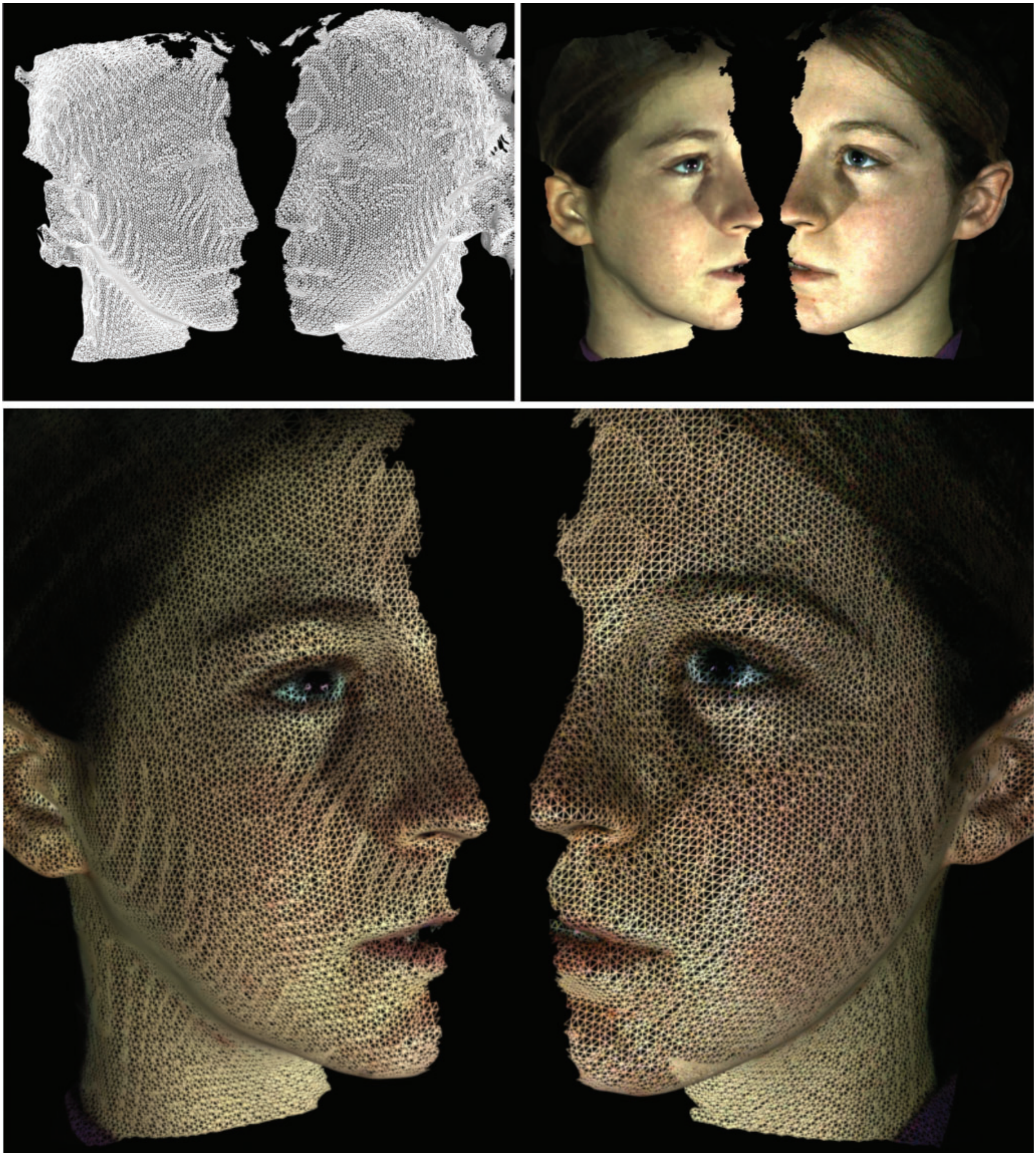

Figure 3 The whole merged 3D face is a composite of two halves, each half representing the image acquisition from each pod. Top left: wireframe range models without any surface texture. Top right: facial texture maps of both sides. Bottom: 3D rendered polygonal meshes with textures enforced

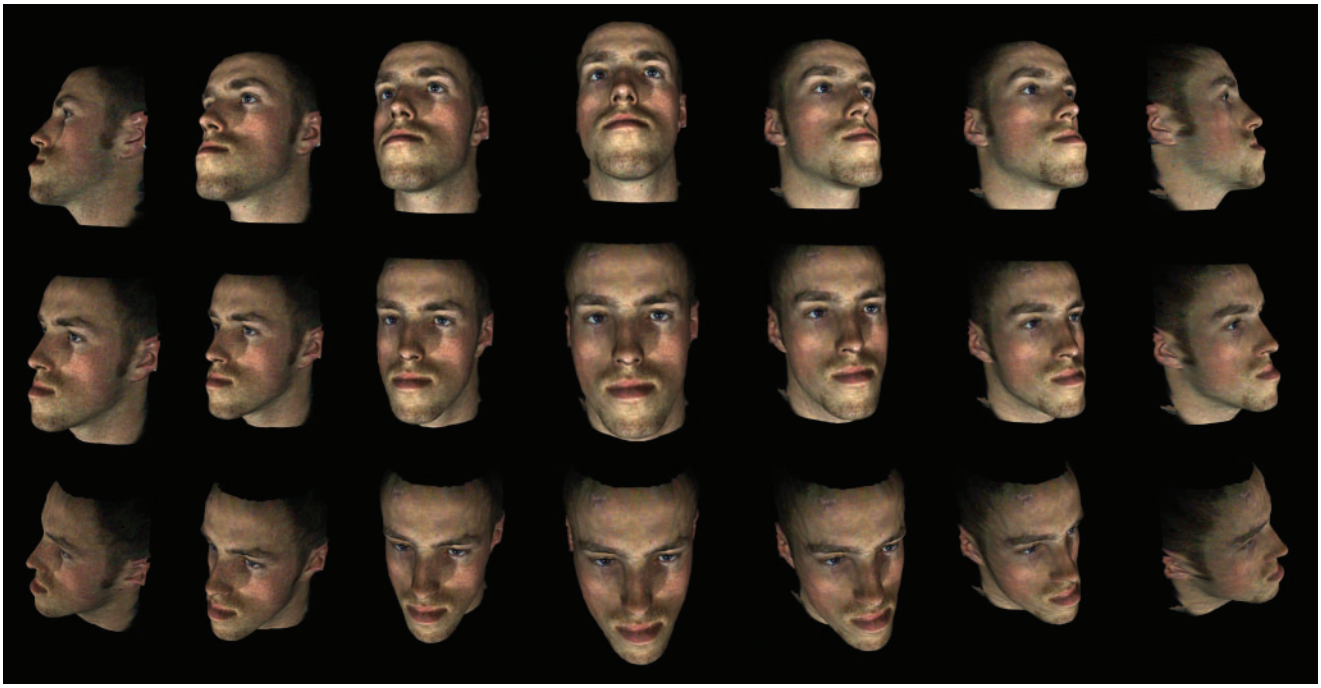

Figure 4 3D imaging of the face enables the orthodontist to evaluate the face from any direction. Here, a skeletal Class III case is displayed in different views, with gradual rotations around the y-axis from $-90°$ to $+90°$ (middle row). $+30°$ and $-30°$ rotations around the x-axis are shown in the upper and lower rows, respectively

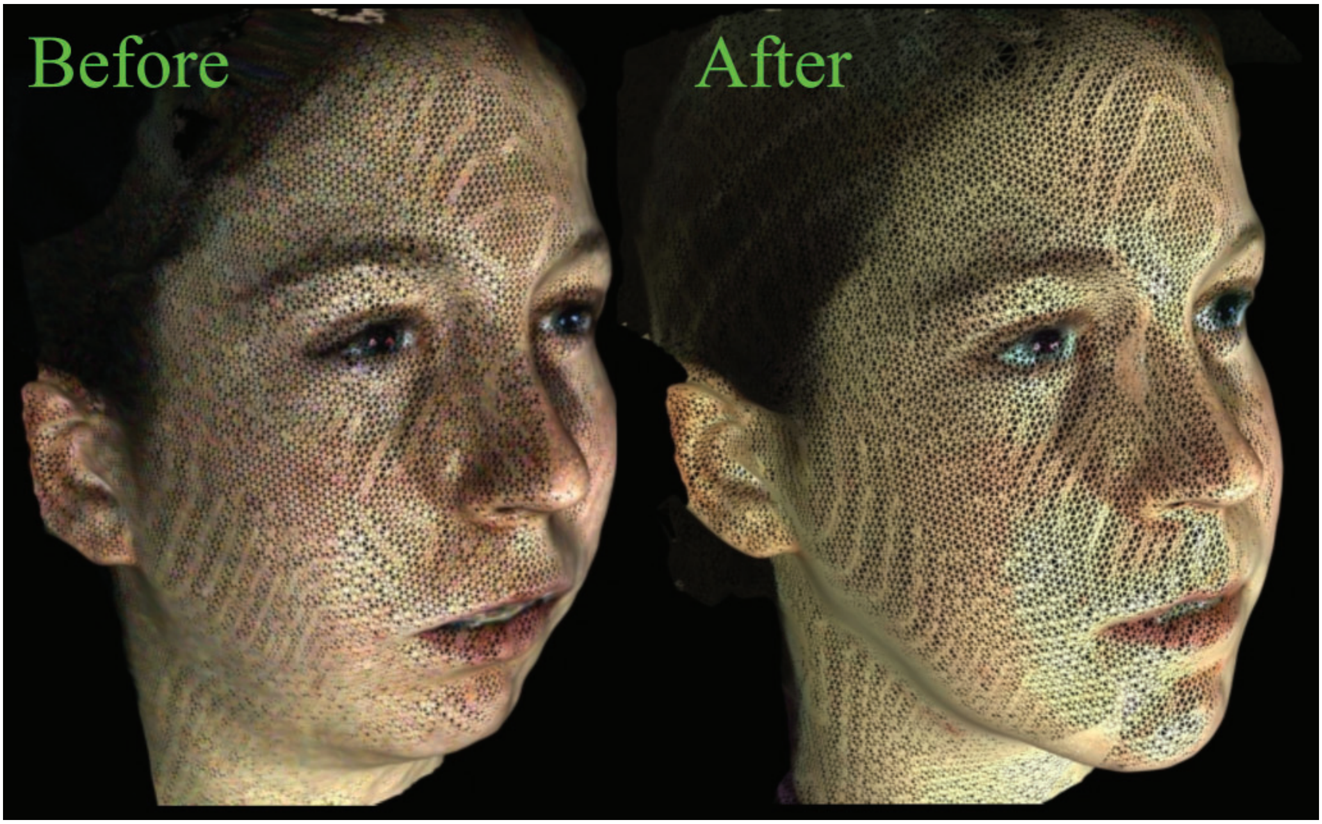

Figure 5 A Skeletal Class II case shown 1 month before and 6 months after orthognathic surgery

So, C3D® affords the clinician a life-like 3D model of the patient's head that can be rotated, enlarged, and measured in three dimensions as required for diagnosis, treatment planning and surgical outcome analysis.[9,11,18] The system has been validated and its accuracy was reported to be within 0.5 mm.[19]

A description of the system and its theoretical technical basis are published elsewhere.[9,20] More information can be obtained from the 3DMATIC website at the Computing Science Department of Glasgow University.[21]

3D Facial Morphometry (3DFM)

Although this is not a 'true' imaging system, it employs two CCD cameras that capture the subject, real time hardware for the recognition of markers and a software for the 3D reconstruction of landmarks' x, y, z, co-ordinates relative to the reference system.[22] Landmarks are located on the face and then covered with 2 mm hemispheric reflective markers. An infrared stroboscope is used to light up the reflective markers. Two-side acquisition is usually needed to capture the whole face.[22]

Placement of landmarks on the face is time- and labor-consuming. Reproducibility of landmark identification is questionable. Change of facial expression between the two acquisition sessions increases the magnitude of error. No life-like models can be produced to show the natural soft-tissue appearance of the face. As a result, this system cannot be used as a 3D treatment-planning tool or as a communication media with orthodontic or orthognathic patients.

Applications of 3D imaging of the face

Assessment of facial deformity, and the outcome of surgical and/or orthodontic correction

For the subjective assessment of deformities, 3D models are very valuable media for locating the source of deformity and its magnitude. Although the nature of patients' facial deformities is usually expressed in three dimensions, diagnosis of these deformities has been made principally using 2D records (photographs and radiographs). Three-dimensional models can be manipulated in any direction, which gives considerable information to the orthodontist without the need for patient recall or being restricted by the time of clinical assessment (Figure 4). Assessment of outcome can also be performed easily by visual comparison of pre- and post-treatment models placed side by side. Figure 5 illustrates an example of an orthognathic patient treated by bi-maxillary surgery, where the face has been scanned using stereophotogrammetry (C3D® system).

For the objective assessment of facial morphology and facial changes following orthodontic and/or surgical interventions, different methods and analyses have been

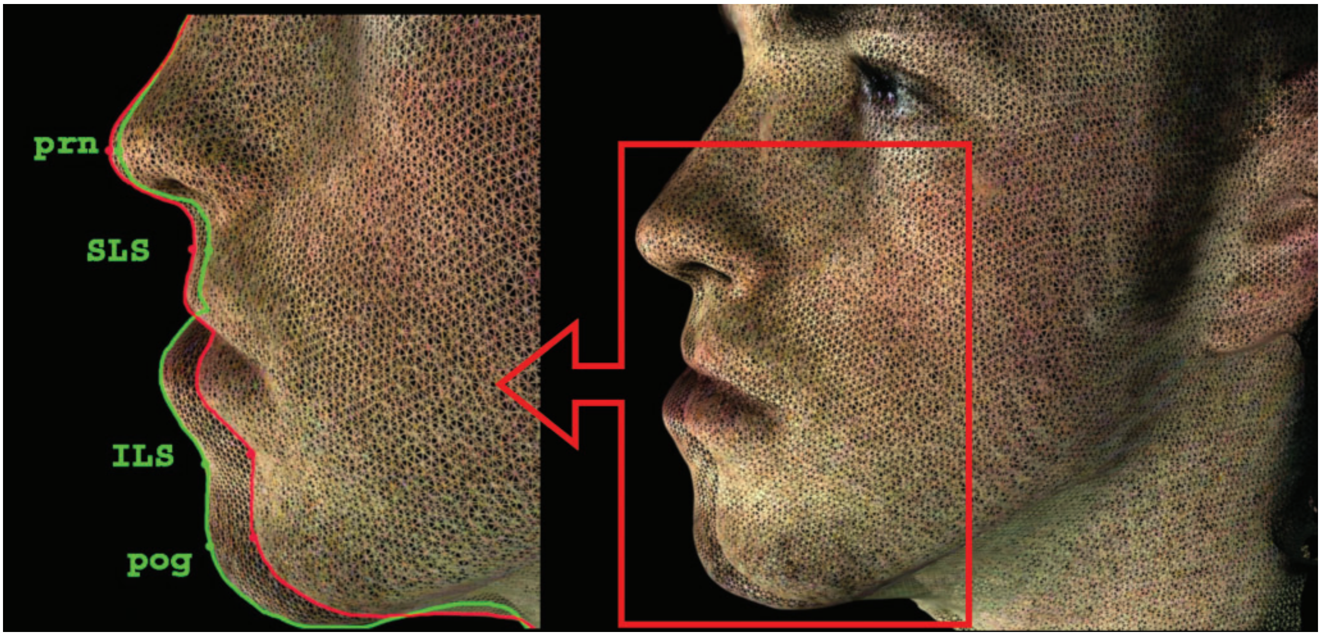

Figure 6 Mathematically superimposed pre- and post-surgical 3D models of a Class III patient. This patient has been treated by bi-maxillary surgery to advance the maxilla and setback the mandible. Seven points across the eyes and the nose are used for the superimposition. Displacements of residual facial soft tissue landmarks can be calculated and an objective assessment of the change can be obtained

proposed.[9,23–25] Figure 6 illustrates an example of a landmark-based superimposition of two 3D models using seven stable and easily identifiable landmarks on the face in order to calculate displacements for other facial landmarks. CT scanning has been used to assess surgical outcome and soft to hard tissue displacement ratios in orthognathic surgery.[26–28] Optical laser scanning has been used to assess facial soft-tissue changes following functional treatment,[29] following extraction and non-extraction orthodontic treatment,[30] following orthognathic surgery,[25] and in cleft lip and palate patients.[31] Stereophotogrammetry has been used to assess the outcome of Twin Block treatment,[32] and the combined orthodontic-surgical corrections of Class II or Class III patients[9] (Figures 4–6). Ferrario *et al*. applied their 3DFM technology in different orthodontic and allied fields.[33]

The results of facial changes have been reported in different ways. Landmarks' displacements,[34] inter-landmark distances and angles,[17] color-millimetric maps[25] and volumetric changes[23,35] have been described. The variety of methods used indicates the wealth of information the 3D images have, as well as reflecting the need to standardize the methods of assessment so consistent evidence is obtained from different research groups.

Communication tool

Instead of discussing treatment objectives and treatment options using X-ray viewers, 2D photographs or composite tracings, life-like 3D models provide a very clear tool for showing areas of deformities, levels of asymmetry and relative relationships between different components of the face, all of which are in an interactive manner on-screen in front of the patient. Patient care is aided by the ability to share patients' 3D records over distance between colleagues. 'Tele-orthodontics' is one of the promising applications of having complete 3D records of patients, especially in cases where inter-disciplinary treatment is required.

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