# Three-dimensional diagnosis and visualization supports in orthodontics based on Reverse Engineering and Solid Free-form Fabrication techniques

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## 1. Introduction

Diagnosis means the art or act of identifying a disease from its signs and symptoms (Merriam Webster Dictionary, 2009). The maxillofacial region, extending from the base of the skull to the hyoid bone, is one of the most anatomically complex regions of the body. This area contains elements and organs belonging to a number of different systems that can be affected by a variety of local and systemic pathologic processes. Diagnostic imaging has assumed a central role in the evaluation of this region. New trends in dentistry include digital and three-dimensional (3D) imaging. The ultimate reward of the technologic imaging advancements is the digital representation of the patient's anatomy, as it exists in nature (anatomic truth). Oral and maxillofacial radiology provides the dentist with diverse diagnostic equipments. Current and evolving methods include computed tomography (CT), tomosynthesis (Badea et al., 2001), tuned-aperture CT (TACT) (Webber et al., 1997), localized, or "cone-beam", CT (Heiken at al., 1993) and magnetic resonance imaging (MRI) (Olt & Jakob, 2004). Although oral and maxillofacial radiology is nowadays widely accepted as a routine technique for dental examinations, the equipments are rather expensive and, furthermore, the radiation dose required to enhance both contrast and spatial resolution can be unacceptably high. A solution to this problem is partially given by the use of maxillofacial dedicated cone-beam CT equipments, which can provide images of sufficient quality for the specific diagnostic needs at significantly reduced absorbed radiation dose (Mah et al., 2003). Much effort has focused recently on computerized diagnosis in dentistry (Beers et al., 2003; Cousley at al., 2003). The study and monitoring of facial appearance is particularly important in the field of dentistry and reconstructive maxillofacial surgery. Usually, most of the 3D systems for dental applications found in literature rely on obtaining an intermediate solid model of the jaw (cast or teeth imprints) and then capturing the 3D information from that model (Williams et al., 2004; Alcaniz et al., 1998). User interaction is needed in such systems to determine the coordinates of specific reference points on a dental cast. Other systems for dentistry are under development in order to replace traditional approaches in diagnosis, treatment planning, surgical simulations and prosthetic replacements (Yamani et al., 2000; Halazonetis, 2001). Moreover, there is another class of machine technology, called Solid Free-form Fabrication (SFF), originally developed for industry that is getting a great amount of attention in the medical sector during the last few years (Sykes et al., 2004; Wohlers, 2004). SFF manufactured anatomical models find applications particularly in oral, maxillofacial and neurological surgery. In dentistry SFF can be used mainly for assisting diagnosis, planning treatment and manufacturing implants. The effectiveness of models manufactured by SFF has been demonstrated in various surgical procedures (Erben et al., 2002). In the following study, the reader is presented with an overview of the state of the art of 3D diagnostic tools in orthodontics, 3D capturing techniques and models manufacturing by SFF, emphasizing their use in orthodontics. Moreover some clinical cases, treated using the above-mentioned technologies, are presented and discussed.

## 2. 3D tools in orthodontics

The discipline of orthodontics is concerned with the face and the ability of the clinician to modify its growth. Orthodontists achieve their goals by manipulating the craniofacial skeleton, with particular emphasis on modifying the dentoalveolar region, the temporomandibular joint and the sutures. This article trace the way in which three-dimensional (3D) tools in orthodontics has developed their usefulness today, and the way in which they may develop in the future.

### 2.1 Radiographic tools

The cephalogram is the standard used by orthodontists to assess skeletal, dental, and soft tissue relationships. This approach, however, is based on two-dimensional (2D) views used to analyze 3D objects. Cephalometry was defined by Moyers (Moyers et al., 1988) as a radiographic technique for abstracting the human head into a measurable geometric scheme. Cephalometric radiography is used to describe the morphology and growth of the craniofacial skeleton, predict growth, plan treatment, and evaluate treatment results. Most of these tasks require the identification of specific landmarks and the calculation of various angular and linear variables. Two types of errors occur with this approach: errors of projection and errors of identification (Baumrind et al., 1971). Errors of projection are caused because the images are a 2D representation of a 3D object. X-ray beams are nonparallel and originated from a small source, leading to radiographs that are imperfect enlargements affected by the distances between the focus, the object, and the film (Adams, 1940; Bjork & Solow, 1962). Errors of identification are the errors of identifying specific landmarks on the images and are considered by many investigators as the major sources of error in cephalometrics (Hixon, 1956; Mitgaard et al., 1974). Despite several improvements in 3D cephalometric research (Swennen & Schutyser, 2006) this technique still remains time-consuming, exposes the patient to radiation and does not define the soft tissues. Current and evolving diagnosis tools include computed tomography (CT), tomosynthesis (Badea et al.,

2001) , tuned-aperture CT (TACT) (Webber et al., 1997), localized, or “cone-beam”, CT (Heiken et al., 1993) and magnetic resonance imaging (MRI) (Olt et al., 2004). From the first commercial Computerized Tomography (CT) scanner appeared in 1972, in the early 1980s researchers began investigating 3D imaging of craniofacial deformities. Shortly after, the first textbooks on 3D imaging in medicine appeared and were based on the principles and applications of 3D CT and MRI-based imaging. 3D imaging has evolved into a discipline “dealing with various form of visualization, manipulation and analysis of multi-dimensional medical structures” (Ududpa & Herman, 1991) and new trends in dentistry include digital imaging and 3D imaging of the maxillofacial regions. Since the 1980s, the quality and speed of CT imaging has changed dramatically. Nowadays with improved techniques and imaging programs it is possible to produce images, which can be rotated and cut at any level. The last generation dental CT scanner are now available for clinical practice and uses the principle of tomosynthesis or cone-beamed CT, so called because of the shape of the x-ray beam, as for example the NewTom QR 9000 Volume Scanner (QR Srl, Verona, Italy) (Mozzo et al., 1998). It uses a cone-shaped x-ray beam that is large enough to encompass the region of interest. This type of beam uses the x-rays very efficiently, thus reducing the absorbed dose to the patient. This type of beam also allows for the acquisition of the image data in one revolution of the x-ray source and detector without the need for patient movement. These attributes make this system more efficient than others, and thus it can be applied for specific purposes in the maxillofacial region. As for regards the MRI, it is good for 3D imaging of soft tissues but the accuracy of the data is not sufficient for specific procedures such as for example the precision milling of prostheses, as it does not properly differentiate between air and bone. However, for soft tissues it is excellent, and can be useful in imaging of temporomandibular joints. It is also useful in the management of tumours of the head and neck region and for imaging the brain for neurological problems.

### 2.2 3D capturing techniques

Optical surface scanning was first tested in 1981 to produce a non-invasive 3D image of the face. The system was modified, improved, and re-tested (Arridge et al., 1985; Moss et al., 1987; Aung et al. 1995). Since that time, the system has also been developed to scan models of the teeth. In 1996, the hand-held scanner was designed to make the system mobile (McCallum et al., 1996). This can be used for scanning many parts of the body. The recent introduction of a probe that records the 3D co-ordinates of any point means that many of the hard tissue points used by Farkas (1994) can now be recorded. Over the years, the value of the 3D system in the diagnosis and management of patients has been demonstrated. 3D material has been obtained on various types of craniofacial anomalies such as cleft palate, hemifacial microsomia, and cherubism (Moss & James, 1984; McCance et al., 1997).

Technologies used for the measurement of the surface of objects with micro to macro sizes can be divided fundamentally into two groups: systems based on laser scanning and systems based on white light projection. The used equipment is different, however they are based on the same principle: triangulation.

Laser scanning systems employs lasers to project a spot, a line, multiple lines, or patterns onto a surface, whereas a light sensor, usually a camera, acquires the scene. The three elements laser, light sensor and object surface form a triangle. When the geometrical disposition of the laser and the light sensor are known, the distance of the object surface to the laser scanning device can be easily determined by triangulation. To measure surface areas the laser spot, line, multiple lines or pattern have to move over the area (i.e. scan the surface). For this process, different methods can be used, e.g. mirrors systems, electro-mechanical systems, hand operated systems.

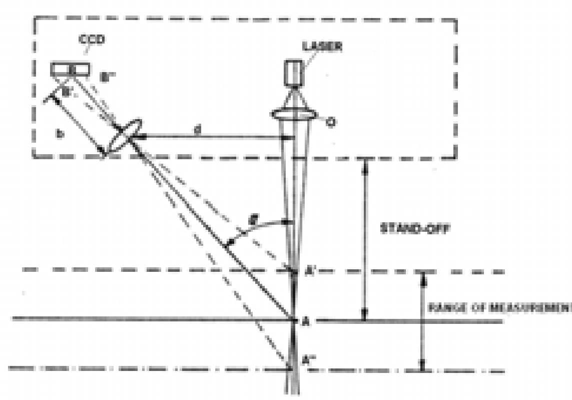



Fig. 1. The concept of laser triangulation

3D measurement systems based on white light employ projectors instead of laser light sources, to project light patterns onto the surface. The measurement principle remains the same: triangulation. A triangle is formed by projector, camera and object. In this case, to cover entire surface parts, surface areas are illuminated by the employed projector. Special codes are used to determine the origin of the light source, e.g. binary codes and colour codes. The two different technologies result in different surface scanning devices with diverse characteristics. Some examples are laser profilers mounted on CMM, portable coded light projection surface digitizer, portable laser scanners and hand held surface digitizers. Medical sciences are also interested in the 3D scanning technologies because of their high accuracy, fast acquisition and non-contact characteristics. A good example of the advantages of optical 3D measurement technologies in the medical field can be found in orthodontics. In fact, the 3D measurement of dental casts brings many advantages and new opportunities. Several 3D scanners specially designed for these applications are available on the market and are later on described in detail. They allow a precise, full automatic and fast 3D scanning of full dental casts, dies/stumps, inlay preparations, bridge preparations, bites/antagonists, wax-ups and superstructures. The acquired data can be useful for many reasons, as for example: 3D databases of dental casts accessible in a local area network reduce storage costs and give easy and instantaneous access to a patient's teeth profile (Gracco et al., 2005), 3D software solutions allow a simplified design of caps, crowns, inlays and bridges from the scanned data (Raffaeli et al., 2005). Reverse engineering systems in orthodontics are generally used for computer aided dental restoration and diagnosis and treatment planning.

### 2.2.1 Computer aided dental restoration

An accurate measurement of 3D models of the teeth is the basis of the entire process. As for regards the clinical requirements, the non-contact optical method is obviously the ideal approach. In the CEREC system (Otto et al., 2002; Luthardt et al., 2002), a probe was designed in order to acquire the optical impression of the selected tooth. However, it can only detect the depth of the cavity and not the complete 3D shape of the tooth. Other CAD/CAM systems available on the market, as for example IVB 3D Jena (http://www.ivb-jena.de) and 3Shape (http://www.3shape.com), tended to rely on in vitro shape measurement, mostly using a laser scanning technique to measure the shape of the model rather than the original tooth. The above because laser scanning is actually a point-wise method in principle, which allows only one height data point to be measured or recorded at a single instant. The use of a particular mechanical positioning setup, though, makes the point-wise scanning a rapid process of possibly within a fraction of a second, and it brings certain restrictions in the meantime that prohibits its direct application in an intra-oral environment. Fig. 2 shows the example of the 3D dental scanner 3Shape D-200 (3Shape A/S, Denmark), some sample data of 3D scans, as well as an example of digital design of dental restorations.

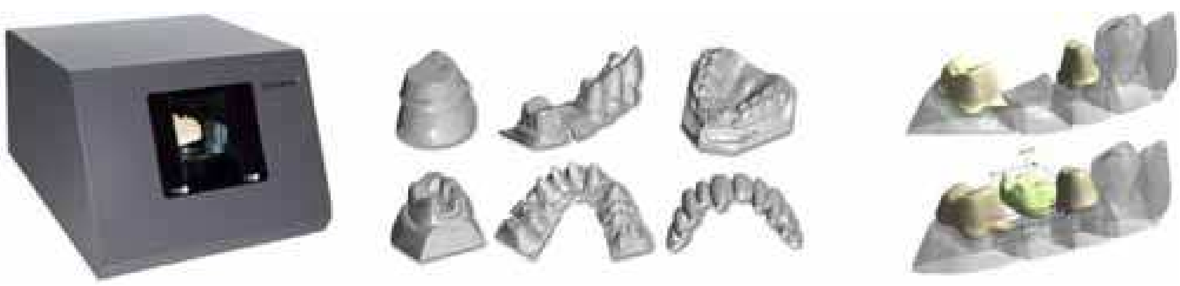


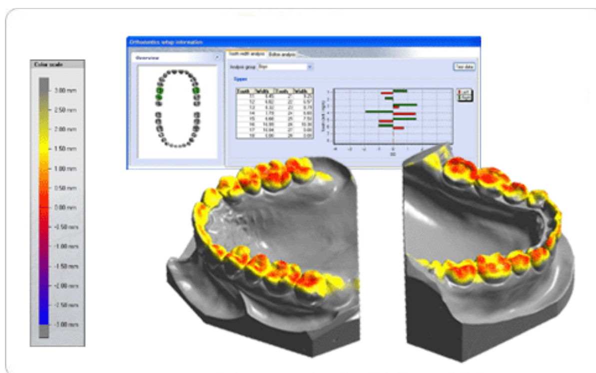
Fig. 2. 3Shape D-200 Dental 3D Scanner (left); sample measured data (center); 3Shape DentalDesigner software examples (right)

#### 2.2.2 Diagnosis and treatment planning

Hard and software solutions are well-suited for orthodontic applications in which fast and accurate 3D scanning of full dental casts are essential. 3D orthodontics software currently under development includes functions as: storage, research and analysis (http://www.3shape.com) and for the orthodontic treatment planning and the correct placement of appliances (http://orthocad.com). As for regards the first aspects, 3D databases accessible in a local area network (LAN) reduce storage costs and give easy and instantaneous access to the patient's teeth profile. Moreover, scanning and software solution are often integrated with such 3D databases. In fact are often available software packages for the analysis of the patient's dentition in order to assess the efficiency of an orthodontic treatment. In such an application, an intuitive interface allows the user to set references points on the scanned casts in order to measure paths, angles and available space for orthodontics treatments. Different measurement tools are available, user is allowed to pick point on the cast 3D model or on 2D cross sections and measure distances. This also allows for easy comparisons among 2D cross sections. Moreover, analysis algorithms allow the user to measure the teeth size and position amid compare this data with statistics of population's standard mouth anatomy. Graphic reports allow the practitioner to compare two dental casts in order to analyze growth and dental treatment efficiency. In Fig. 3 are shown some functions of the software 3Shape Orthoanalyzer (3Shape A/S, Denmark).
As for regards the orthodontic treatment planning and the correct placement of appliances, the systems available on the market allow the orthodontist to make accurate measurements

for the treatment planning while at the same time eliminating plaster model storage and retrieval issues. Moreover, allow practitioners to simulate treatment strategies and select and execute the most appropriate treatment plan that includes precise positioning of orthodontic brackets as shown in Fig. 4.

*(a)*



*(b)*

Fig. 3. Specific functions of the software package 3Shape Orthoanalyzer for storage (a), research and analysis (b) purposes in orthodontics

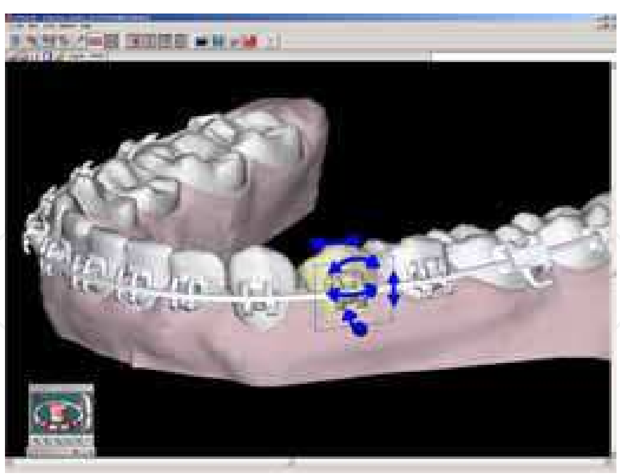


Fig. 4. Specific functions of the software Orthocad (Cadent Inc., USA) that uses computers to make an indirect bonding set-up for bracket placement

Lingual orthodontic treatment is an alternative to the traditional vestibular treatment, and is designed to satisfy those patients who wish to have their teeth aligned but do not want

labial brackets. Due to the difficulties in positioning, indirect bonding techniques have been developed to transfer brackets location from a physical model by bonding trays. A solution based on a new three-dimensional CAD system, called CADental, has been proposed to virtually design trays both for the requirements of lingual and vestibular appliances. It has been implemented using a geometrical modelling kernel, within a low-cost commercial CAD system (Rhinoceros 3.0, by Rhino3D). It allows the positioning of the brackets and the definition of a suitable bonding tray in a very short time, verifying, at the same time, the accuracy of the result in order to avoid errors and iterations.
The CADental software tool has been developed for an easy interfacing with 3D shape acquisition systems used to scan impressions and plaster casts, and with the rapid prototyping machines used to build physical models and trays (Fig. 5). During the implementation stage particular attention was dedicated to the development of a user-friendly interface suitable to non-expert users of 3D CAD modelling systems. The functionalities have been strongly automated and the user interface has been based on semantic entities linked to the operator's traditional way of working.

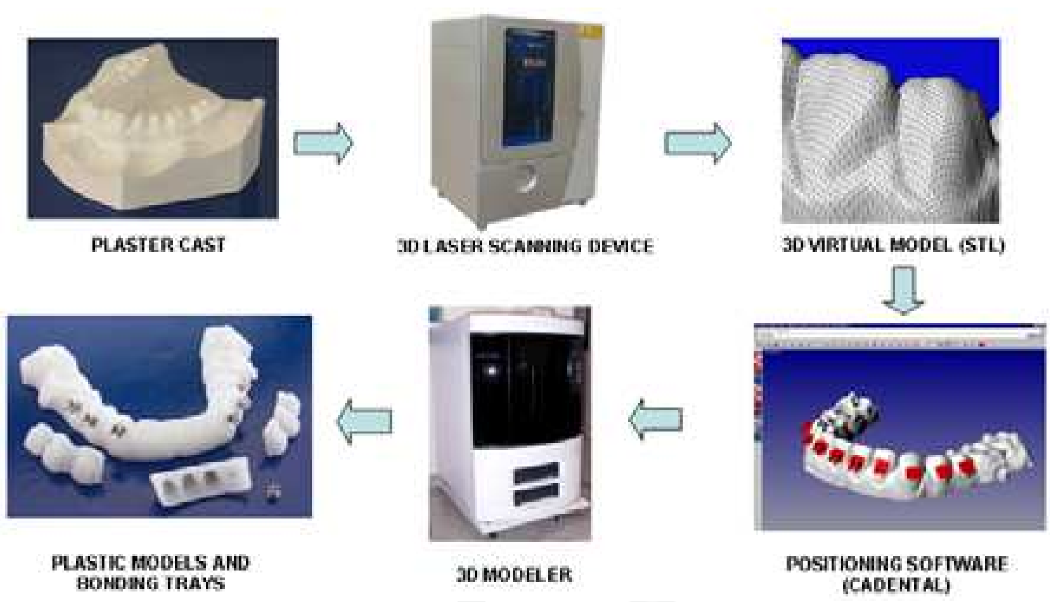



Fig. 5. Plaster casts or impressions scanning to obtain 3D virtual models. CADental software allows the manufacturing of the Tweed support, analyse and measure models, positioning of the brackets, creations of virtual set-ups and bonding trays. Models and trays can be manufactured in medical Acrylonitrile Butadiene Styrene (ABS) plastic

A successful large scale operation to mass produce a customized device brings together the best of reverse engineering hardware and software. Case in point, the company, Align Technology of California, manufactures clear, molded, removable thermoplastic shells called aligners to do the work of permanent metal braces (Melkos, 2005). The process is based on a series of scans collected during the layer-by-layer destruction of the study model poured from an actual patient dental impression. Surface data from the scanning process are analysed and processed to create the sequence of progressive orthodontic arrangements that will achieve the end goal of straightening or repositioning the teeth. The data are sent to a stereolithography machine to produce all the models required for the complete set. Then a thermoformed shell is made for each step in the treatment and the set is shipped back to the local dentist. Patients wear the removable device for only two weeks before moving to the next. This reverse engineering technology not only allows custom manufacture of the aligners at various stages of treatment but makes a simulation of the orthodontic correction process possible, using the patient's own data set. Optical modelling processing finds and application also in order to reduce the stress caused to patients by conventional methods of modelling using CT or MRI for extraoral defects and body areas. In fact the selected body part could be digitized using optical 3-coordinate measuring technology, providing an extensive data record. With such a technology, the patient's physical and psychological stress may be reduced. Diverse application were found in literature and describes for example a technique for optical modelling of facial prosthesis (Runte et al., 2002; Cheah et al., 2003), ocular prosthesis (Reitemeier et al., 2004) and ear prosthesis (Ciocca et al., 2004).

### 2.3 Solid Free-form Fabrication (SFF) techniques

SFF technologies, originally developed for industry, have been receiving a great amount of attention in the medical sector in the last few years. Medical SFF is defined as the manufacture of dimensionally accurate physical models of human anatomy derived from medical image data using a variety of SFF technologies. SFF-manufactured anatomical models find applications particularly in oral (Lee et al., 2006), maxillofacial (Winder et al., 2005) , neurological surgery (Muller et al., 2003; Mazzoli et al., in press) and orthopaedics (Minns et al., 2003). In medicine, they are mainly used for assisting diagnosis, planning treatment, and manufacturing implants (Petzold et al., 1999). SFF models' effectiveness has been shown in various surgical procedures (Erben et al., 2002). Patients find the medical models helpful for informed consent. Medical modeling is an intuitive, user-friendly technology that facilitates diagnosis and surgical planning, allowing surgeons to rehearse procedures readily and, moreover, improves communication between doctors and patients. Furthermore, SFF-manufactured models can be used in the reconstruction of post-traumatic defects, tumoral resections, and other complex craniofacial defects. SFF technologies can be of benefit in the pre-operating estimation of the quantitative surgical outcome, in the reduction of the operating time and in the production of more predictable results. Currently, the SFF techniques used in medical applications are 3D printing (3D-P), stereolithography (SLA), selective laser sintering (SLS), fused deposition modeling (FDM), laminated object manufacturing (LOM) (Berry et al., 1997; Leong et al., 2003; Liu et al., 2006) and electron beam melting (EBM) (Mazzoli et al., in press). Each of these different techniques builds up a model, layer by layer, using different processes and materials. 3D-P creates models by spraying liquid binder through ink-jet printer nozzles on to a layer of metallic or ceramic precursor powder. SLA by tracing a lower power ultraviolet laser across a vat filled with resin. SLS by a heat fusible power by tracing a modulated laser beam across a bin covered with the powder. FDM by heating thermoplastic material, extruded through a nozzle positioned over a computer controlled x–y table. LOM by a heat-activated, adhesive coated paper, tracing a focused laser beam to cut a profile on sheets positioned on a computer controlled x–y table. EBM consists of a layer-based direct manufacturing process of complex parts by melting metal powder with an accelerated electron beam. As for the materials 3D-P uses a wide selection of powder materials, SLS fine thermoplastic powder, SLA UV-sensitive resins, LOM thin sheets of material such as paper, FDM thermoplastic filaments and EBM fine metallic powder.

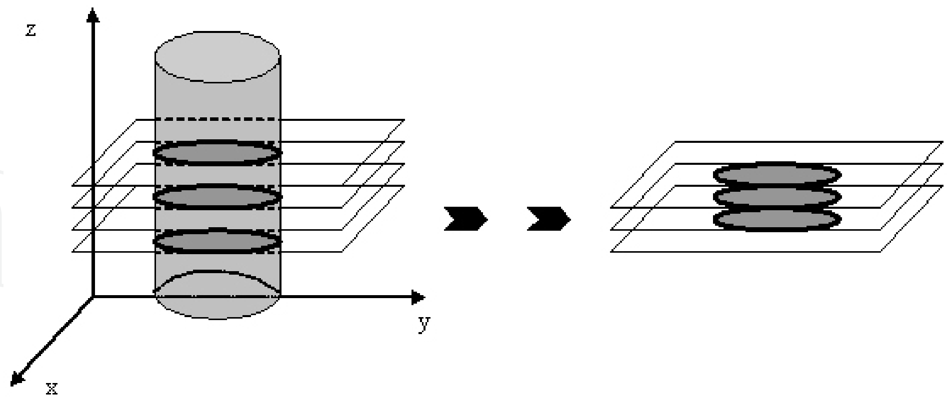



Fig. 6. The concept of layered manufacturing

The dimensional accuracy is a major concern for the clinical application of 3D medical models and was previously studied and assessed, under specific conditions, by some of the authors (Mazzoli et al., 2007). Techniques were developed to represent the data in 3D on a 2D screen. Given the visualization provided by sophisticated software packages, the fabrication of physical models may seem superfluous. However, even if the display of a 3D volume on a 2D screen provides useful information to the clinicians, as later on discussed in the presentation of some clinical cases treated at the Department of Orthodontics of the University of Ferrara, it does not provide with a complete understating of the patient's anatomy. In short, there are several visualization issues that are being addressed but not yet resolved by virtual models. For the above mentioned reason the construction of physical model is often necessary. An anatomical model can be manufactured using SFF techniques by the following steps:

1. acquisition: patient scans with X-ray CT or MRI imaging;
2. design: segmentation to delineate and extract the surface as triangles or polygons (creation of the 3D CAD solid model of the anatomy);
3. converting: convert the CAD model to STL format;
4. pre-process: slice the STL file into thin cross-sectional layers (generated by a dedicated software);
5. building process: construct the model one layer atop another by a selected SFF process;
6. post-process: clean and finish the model.

Specific scanning protocols are required to generate precise anatomical physical models. The type of scanner will need to be determined in order to check that the image reconstruction software can translate the data and also the kind of scan (i.e. axial or helical). The recommended slice thickness is 1.0 mm or less. The scan spacing: should be 0.5 mm or at least one-half the smallest dimension of interest. The resolution should be 512 x 512 or higher. The Field of View (FOV) should be chosen so that object imaged should fill the field of view without extending beyond it. The position of the long axis of the object to be scanned should be parallel to the bore of the scanner. Generally, scans should start just off the object and finish off the other side of the object (so that the entire object is imaged). Objects to be scanned should not be taped down or placed on similarly dense objects that will show up in the scan. If significant variations in material densities exist within the object to be scanned, distortion can be experienced (artifacts). In the case of metal artifacts, the distortion can be severe. The scan protocol can and should be adjusted to take into account the presence of artifacts. Moreover, the scan protocol should take in account any gantry tilt angle. It is advisable to avoid gantry tilt when acquiring a CT data set, otherwise, sophisticated mathematical algorithms are required to successfully correct the data. From the image data, the reconstruction software is then used to extract part contours and/or surfaces (segmentation), as the case may be. Segmentation may be carried out by image tresholding, manual editing or autocontouring to extract volumes of interest. One of the simplest methods of tissue segmentation applied to the images is CT number tresholding. A CT number range is identified by either region of interest (ROI) pixel measurements or pixel intensity profiles, which is representative of the anatomy to be modelled. As a matter of fact thresholding is the first action performed to create a segmentation mask on a set of digital images. The ROI can be selected by defining a range of grey values. The boundaries of that range are the lower and upper threshold value. All pixels with a grey value in that range will be highlighted in a mask. The selection of a proper threshold value is the major source of errors in this stage. In fact, low threshold value will yield too big models, while too high threshold value will cause fine structures not to be reproduced. This makes it impossible to find a “correct” threshold value. A solution for the threshold problem is to work with local thresholds for different regions of the model. Final delineation of the anatomy of interest may requires 2D or 3D image editing to remove any unwanted details. A number of software packages are available for data conditioning and image processing for the SFF of anatomical models, including MIMICS by Materialise NV (http://www.materialise.com), BioBuild by Anatomics Pty Ltd (http://www.anatomics.com/about/index.html), 3D Doctor by Able software Corporation Ltd (http://www.ablesw.com/) and Analyze by Mayo Clinic (http://www.mayo.edu/bir/Software/Analyze/Analyze.html). The clinical cases presented in this study were modelled using the software MIMICS that provides a comprehensive range of data interpretation and image processing to interface with SFF technology. As previously mentioned the SFF techniques currently used in medical applications are 3D printing (3D-P), stereolithography (SLA), selective laser sintering (SLS), fused deposition modeling (FDM), laminated object manufacturing (LOM) and electron beam melting (EBM). The above-mentioned techniques will be afterward described in detail.

#### 2.3.1 3D Printing (3D-P)

3D-P uses a technology similar to the ink-jet printing. As shown in Fig. 7, parts are built upon a platform situated in a bin full of powder material. An ink-jet printing head selectively "prints" binder to fuse the powder together in the desired areas. Unbound powder remains to support the part. The platform is lowered, more powder added and levelled, and the process repeated. When finished, the green part is sintered and then removed from the unbound powder. No external supports are required during fabrication since the powder supports overhangs. 3D-P advantages include speedy fabrication and low material costs. Limitations on resolution, surface finish, part fragility and available materials are its disadvantages. The problem of the accuracy of the final parts is due to the stairstepping effect in the X-Y plane, because of the print-head raster-scanning on the layers. Moreover, 3D-P parts have a ribbed and little rough appearance due to layering beads of plastic and are not suitable for extensive functional testing.

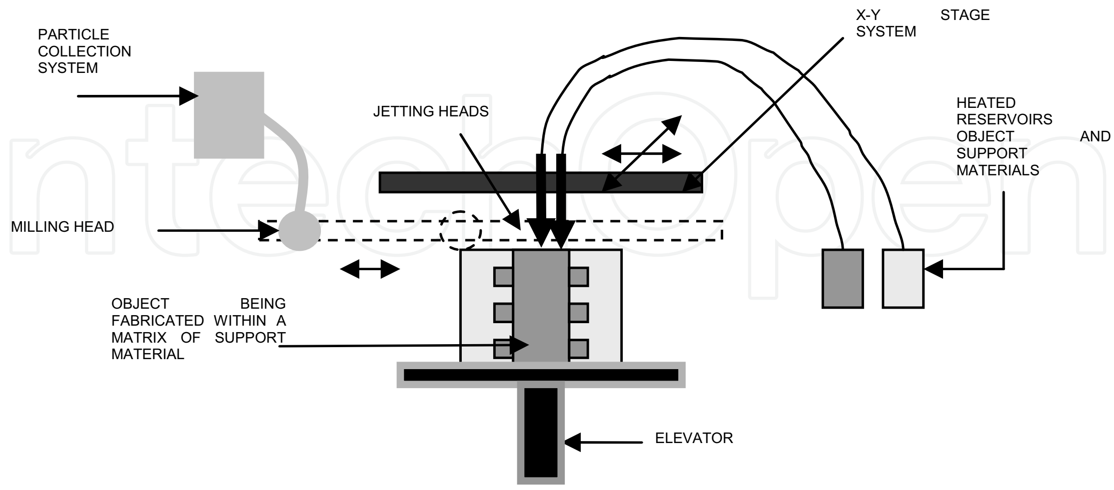



Fig. 7. Schematic of 3D-P

### 2.3.2 Stereolithography (SLA)

Patented in 1986, stereolithography started the SFF revolution. The technique builds three-dimensional models from liquid photosensitive polymers that solidify when exposed to ultraviolet light. As shown in Fig. 7, the model is built upon a platform situated just below the surface in a vat of liquid epoxy or acrylate resin. A low-power highly focused UV laser traces out the first layer, solidifying the model's cross section while leaving excess areas liquid. The movement of the laser light on the surface of the resin is controlled by a movable mirror, using the data from the CAD system. Next, an elevator incrementally lowers the platform into the liquid polymer. A sweeper re-coats the solidified layer with liquid, and the laser traces the second layer atop the first. This process is repeated until the prototype is complete. Afterwards, the solid part is removed from the vat and rinsed clean of excess liquid. This part is called "green part". Supports are broken off and the model is then placed in an ultraviolet oven for complete curing. In Fig. 8 is represented the schematic diagram of SLA.

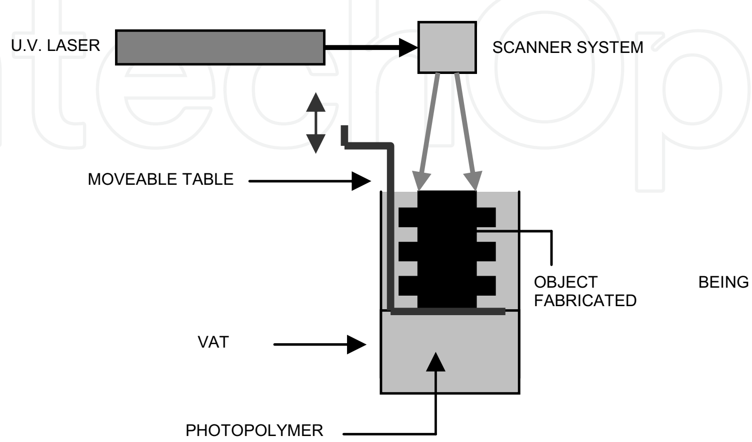



Fig. 8. Schematic of SLA

SLA can produce surgical templates out of sterilizable USP Class VI resin. Advantages of SLA process include high part-building accuracy, smooth surface finish, fine building details and high mechanical strength. Moreover, selectively colour-changing materials for biomedical applications are available, providing superior visualization by highlighting selected features in different colour. Disadvantages of this process include expensive equipment and material cost, wet materials handling and post-processing of the manufactured parts.

### 2.3.3 Selective Laser Sintering (SLS)

Developed by Carl Deckard for his master's thesis at the University of Texas, selective laser sintering was patented in 1989. The process is somewhat similar to SLA in principle as can be seen from the figure below. In this case, however, a laser beam is traced over the surface of a tightly compacted powder made of thermoplastic material. The powder is spread by a roller over the surface of a build cylinder. A piston moves down one object layer thickness to accommodate the layer of powder. Excess powder in each layer helps to support the part during the build. Heat from the laser melts the powder where it strikes under guidance of the scanner system. The CO2 laser used provides a concentrated infrared heating beam. The entire fabrication chamber is sealed and maintained at a temperature just below the melting point of the plastic powder. Thus, heat from the laser need only to elevate the temperature slightly to cause sintering, greatly speeding the process. A nitrogen atmosphere is also maintained in the fabrication chamber in order to prevent the possibility of explosion in the handling of large quantities of powder. After the object is fully formed, the piston is raised to elevate the object. Excess powder is simply brushed away and final manual finishing may be carried out. No supports are required with this method since overhangs and undercuts are supported by the solid powder bed. This saves some finishing time compared to SLA. However, surface finishes are not as good and this may increase the time. No final curing is required as in SLA, but since the objects are sintered they are porous. Depending on the application, it may be necessary to infiltrate the object with another material to improve mechanical characteristics. Much progress has been made over the years in improving surface finish and porosity. The method has also been extended to provide direct fabrication of metal and ceramic objects and tools.

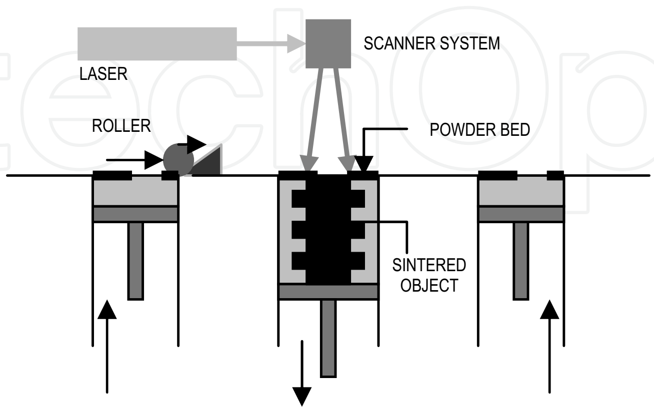



Fig. 9. Schematic of SLS

Advantages of SLS include high part accuracy, material versatility, easy post-processing and no support needed. Disadvantages include that SLS manufactured parts have little rough grainy and porous surface finish which is not as smooth as SLA but acceptable for most of applications but parts can be easily primed and finished to smooth level. The larger shrink rates of SLS increase the tendency for the prototype to warp, bow or curl subject to the part geometry. SLS features detail is not as crispy and sharp as produced by SLA.

### 2.3.4 Fused Deposition Modelling (FDM)

In this technique, filaments of heated thermoplastic are extruded from a tip that moves in the x-y plane as described in the figure above. The controlled extrusion head deposits very thin beads of material onto the build platform to form the first layer. The platform is maintained at a lower temperature, so that the thermoplastic quickly hardens. After the platform lowers, the extrusion head deposits a second layer upon the first. Supports are built along the way, fastened to the part either with a second, weaker material or with a perforated junction. FDM method produces models that are physically robust. Wax can be used as the material, but generally models are made of ABS plastic. Just out of the machine, models may have a fairly rough surface finish, but they can easily be cleaned up. Because of the use of a single well-defined thread to build the model, this is the only one of the processes where it is relatively easy to change colour; in fact the ABS fibre is available in a range of bright primary colours. Alternatively, models can be painted. Moreover, FDM provides a high level of visualization by highlighting selected features in a different colour. FDM can produce models out of medical grade ABS, which is sterilizable and translucent and meets all FDA USP Class VI requirements for temporary use inside the body.

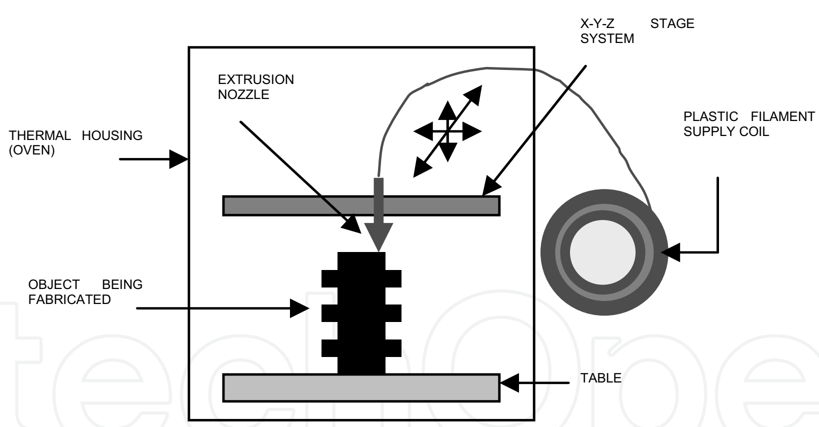



Fig. 10. Schematic of FDM

Advantages in using FDM include the speed and safety of the machine. The machine does not use any toxic materials, so it can be installed in an office environment. The build time for the machine is faster than the SLA. There is no part clean-up needed for a part made by FDM. Disadvantages include that surface finish of the parts is inferior to those produced using SLA or SLS, due to the resolution of the process which is dictated by the filament thickness. Accuracy is relatively low and is difficult to build parts with complicated details; poor strength in vertical direction and slowness for building a mass part.

### 2.3.5 Laminated Object Manufacturing (LOM)

In this technique, developed by Helisys of Torrance, CA, layers of adhesive-coated sheet material are bonded together to form a prototype. The original material consists of paper laminated with heat-activated glue and rolled up on spools. As shown in the figure below, a feeder/collector mechanism advances the sheet over the build platform, where a base has been constructed from paper and double-sided foam tape. Next, a heated roller applies pressure to bond the paper to the base. A focused laser cuts the outline of the first layer into the paper and then cross-hatches the excess area (the negative space in the prototype). Cross-hatching breaks up the extra material, making it easier to remove during post-processing. During the build, the excess material provides excellent support for overhangs and thin-walled sections. After the first layer is cut, the platform lowers out of the way and fresh material is advanced. The platform rises to slightly below the previous height, the roller bonds the second layer to the first, and the laser cuts the second layer. This process is repeated as needed to build the part, which will have a wood-like texture. Because the models are made of paper, they must be sealed and finished with paint or varnish to prevent moisture damage, but because the raw material (paper) is cheap, LOM is particularly suitable for large models given that the manufacturing speed is very fast. Disadvantages include that it is hard to make hollow parts due to the difficulty in removing the core and there are serious problems with undercuts and re-entrant features. Other problems are the great amount of scrap so that the machine must be constantly manned and parts need to be hand finished. Moreover, given that the laser cuts through the material, there is a fire hazard which means that the machines need to be fitted with inert gas extinguishers. The drops of molten material, which form during the cutting process, need to be removed also.

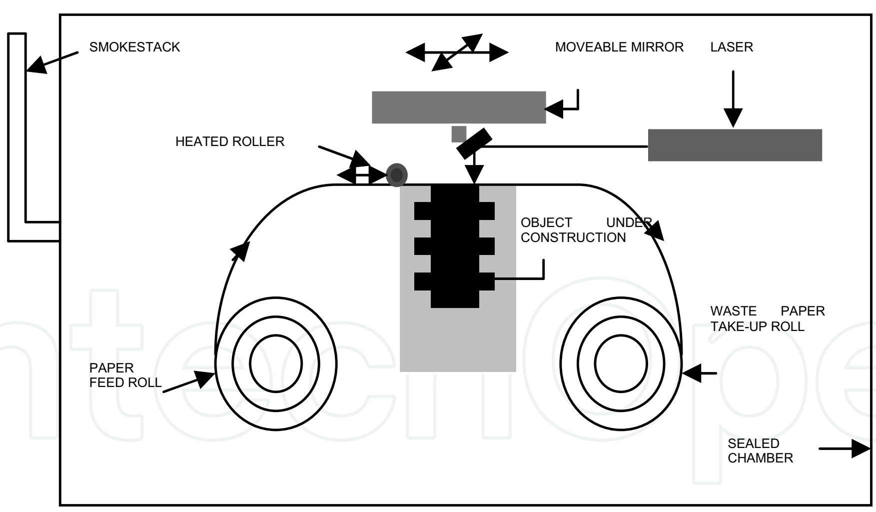



Fig. 11. Schematic of LOM

### 2.3.6 Electron Beam Melting (EBM)

Electron beam melting (EBM) is a type of rapid prototyping for metal parts. It is often classified as a rapid manufacturing method. The technology manufactures parts by melting metal powder layer per layer with an electron beam in a high vacuum. Unlike some metal sintering techniques, the parts are fully solid, void-free, and extremely strong. EBM is also referred to as Electron Beam Machining. High speed electrons (.5-.8 times the speed of light) are bombarded on the surface of the work material generating enough heat to melt the surface of the part and cause the material to locally vaporize.

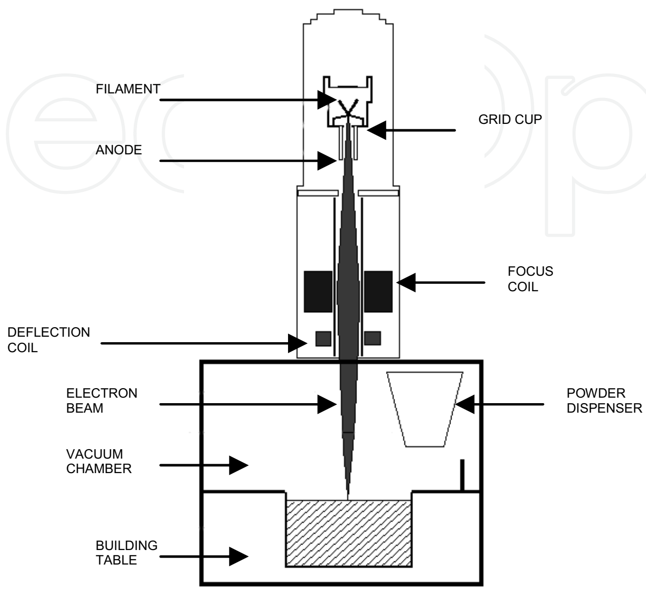



Fig. 12. Schematic of EBM

EBM does require a vacuum, meaning that the workpiece is limited in size to the vacuum used. The surface finish on the part is much better than that of other manufacturing processes. Only shoot-peening process to control residual stresses by compressing surfaces and polishing to reduce roughness may be needed as secondary finishing operations. EBM can be used on metals, non-metals, ceramics, and composites.
Some of its benefits include: ability to achieve a high energy level in a narrow beam, vacuum melt quality can yield high strength properties of the material, vacuum environment eliminates impurities such as oxides and nitrides and permits welding in refractory metals and combinations of dissimilar metals. Some apparent disadvantages of electron beam technology are: requires vacuum which adds another system on the machine which cost money and must be maintained, electron beam technology produces gamma rays while in operation and requires electrically conductive materials.
In the following section some clinical cases, treated with the aid of RE and SFF processes, will be presented and discussed.

## 3. Application of RE and SFF in clinical cases

Several clinical cases in the field of orthodontics, supported by the use of RE and SFF techniques, are provided in this section. In fact, the quality of service, in terms of improvement in patient satisfaction, is an increasingly important objective in all medical fields, and is especially imperative in orthodontics due to the high numbers of patients treated. All the cases are related to patients clinically treated at the Department of Orthodontics of the University of Ferrara (Italy).

### 3.1 Application of RE techniques

#### 3.1.1 Evaluation of the post-extractive facial edema

A RE-based approach was also used in the evaluation of the post-extractive facial edema, after the unilateral extraction of completely impacted mandibular third molars on 40 patients. Range camera Comet Vario Zoom (Steinbichler Optotechnik GmbH, Germany) together with the processing software PolyWorks (InnovMetric Software Inc., Canada) were used to carry out computerized analysis of the 3D images obtained in this morpho-volumetric study of post-extractive edematous swelling as shown in Fig. 13. The acquired data and analysis revealed no statistically significant gender-related difference in edemal volume at any post-operative stage analyzed. Both male and female patients, however, showed a significant increase in volume (mean volume: 28,766.96 $mm^3$) two days after surgery. Furthermore, on the seventh day after surgery, the edematous swelling was reduced to levels similar to those recorded immediately following extraction in both males and females.

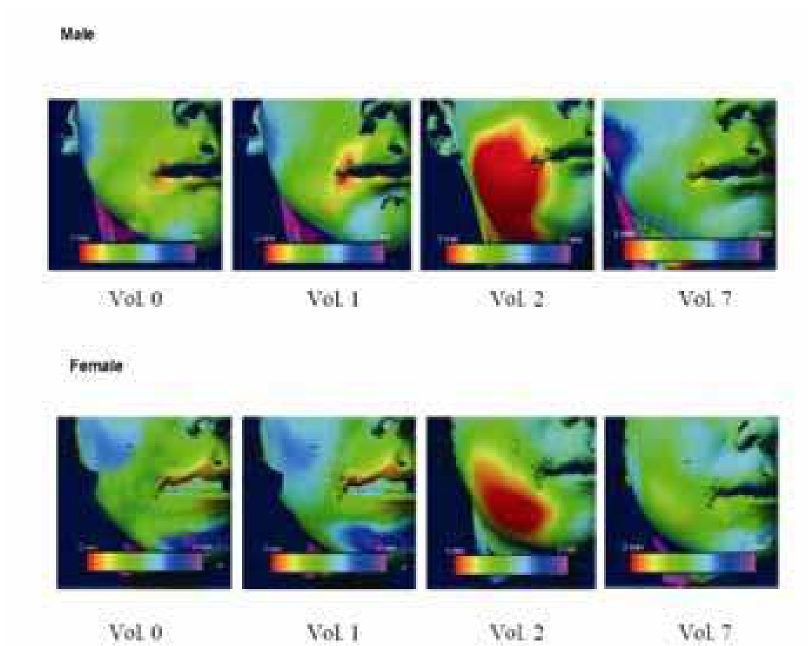



Fig. 13. Intermediate colours indicate the edematous distance and volumes

#### 3.1.2 Evaluation of palatal morphologic and volumetric changes after the use of a rapid palatal expander (RPE)

RE systems and software were employed to evaluate the palatal morphologic and volumetric changes after the use of a RPE appliance in four children patients (aged 7-8 years) in mixed dentition with a posterior crossbite, a skeletal Class II malocclusion and with narrow maxillary arches (Mazzoli et al., 2008). The patients were treated using the Haas RPE in order to solve the maxillary contraction. For each patient three measurements were done: pre-treatment ($T_1$), after expansion therapy ($T_2$), and six months after the removal of the expander ($T_3$) without no contention. Traditionally, treatment stability was evaluated with calipers and compasses, which register just linear measurements and depend on the ability of the operator without providing precise 3D measurements.

In the above cited study a Roland Picza system (Roland DG Mid Europe Srl, Acquaviva Picena, Italy) was used to scan casts with a resolution of up to 0.05 mm and a scanning step up to 0.02 mm. The obtained data were managed using the software Rapidform (INUS Technology Inc., Korea), an advanced 3D scan data processing software, and Rhinoceros (McNeel, Seattle), a modeling software for designers. The base palatal volume was delimited by the gingival margins and by a vertical plane connecting the distal aspect of the last permanent molars. All tests confirmed the hypothesis that the measurements at T2 and T3 were significantly different from those at the start of the treatment supporting the effectiveness of the RME treatment. In Fig. 14 are showed the cross-sectional superposition of the recordings at T1, T2 and T3 reporting the variations in palatal transverse diameters between the above selected couples of teeth in one clinical case.

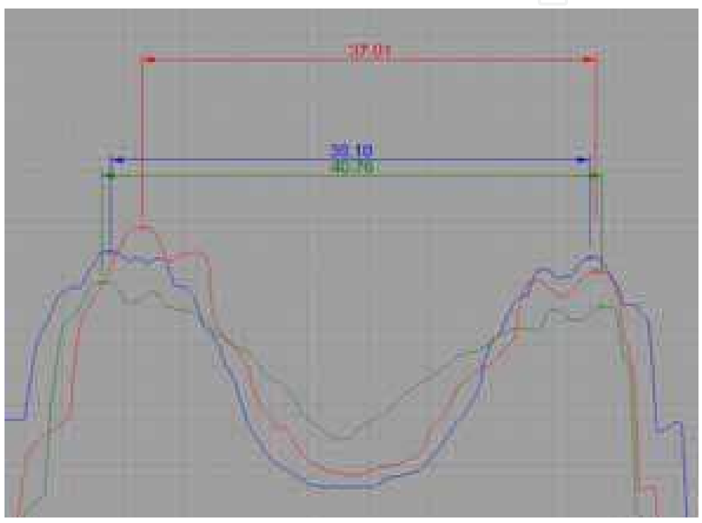


Fig. 14. Cross-sectional superposition of the recordings at T1 (red), T2 (green) and T3 (blue) reporting the variations in palatal transverse diameters between the outer side cusps of the first primary molars (54-64)

### 3.1.3 Evaluation of 3D Technologies in Dentistry

A study has specifically aimed to evaluate Reverse Engineering (RE) and Rapid Prototyping (RP) in order to define an ideal chain of advanced technological solutions to support the critical processes of orthodontic activity (Gracco et al., 2008). Information technology can provide a meaningful contribution to bettering treatment processes, and we maintain that systems such as CAD, CAM and CAE, although initially conceived for industrial purposes, should be evaluated, studied and customized with a view to use in medicine. Advantages to using such systems to carry out many of the stages in orthodontic processes currently performed by hand, such as the design and manufacture of corrective appliances and the production of virtual models of the dental arches, and also to determine the feasibility of their use in the planning and simulation of corrective and implantological treatment and in the design and manufacture of fixed and mobile prostheses. Two types of test were employed to study the acquisition systems, the first aimed at evaluating the system usability and the time required for scanning, and the second designed to compare the resolution and accuracy of the systems. To the former end a standard procedure of measurement which could be employed with both specific and general purpose systems, all used in conjunction with a suitable automatic positioning device, was established. The resolution and accuracy of the various acquisition systems were compared via the acquisition of a single view of a significant portion of the same plaster model. The CAD system was employed to measure the dimensional and morphological parameters directly using the triangulated point cloud, without further elaboration. The dimensional reference data were calculated from a measurement carried out by a coordinate measurement machine with contact sensors. This comparative study analyzed rapid prototyping systems and defined suitable methodologies of evaluating the fundamental components of an RE/RP manufacturing for application in the orthodontic field. The preliminary results demonstrate that replication of a plaster model is plagued by problems linked to the size of detail to be reproduced, which is similar to or finer than the fabrication layer of the various additive technologies studied, and therefore results in poor quality reproduction of tooth morphology.

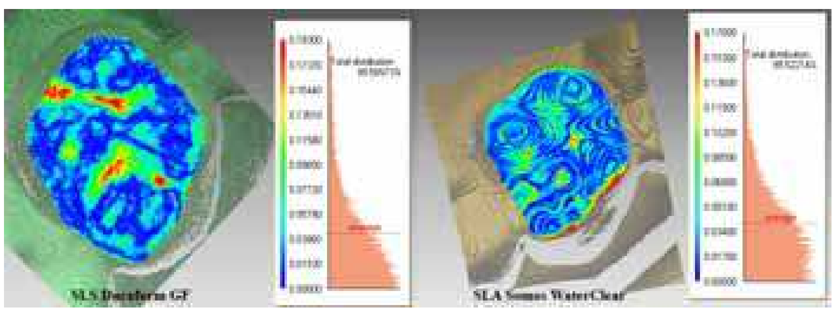



Fig. 15. Colour map of morphological analysis on tooth top: errors are due to surfaces grooves and fabrication layers

### 3.2 Application of 3D anatomical modelling and SFF techniques
#### 3.2.1 Implant-prosthetic rehabilitation

46-year- old Caucasian female (S.F.) showing a partial edentulism referred to the left side of the lower half-arch and a lack of the upper maxillary dental elements, with the exception of the 1.7 and 1.8, due to a pre-existing trauma. Both the edentulous areas showed a high degree of bone resorption with a considerable height and thickness reduction of the alveolar ridge. Such a decrease of available bone tissue made the implant-prosthetic planning phase rather problematic and needed to be widened by CT surveys. In particular, the closeness of the inferior alveolar nerve was critical in the selection of the more suitable dental implants in terms of typology and size. For the above reason 3D renderings, using the software MIMICS, of the two maxillary arches was implemented highlighting the left portion of the inferior alveolar nerve as shown in Fig. 16.

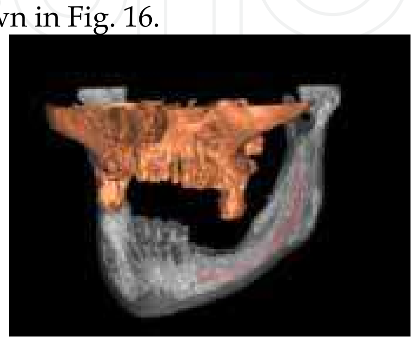
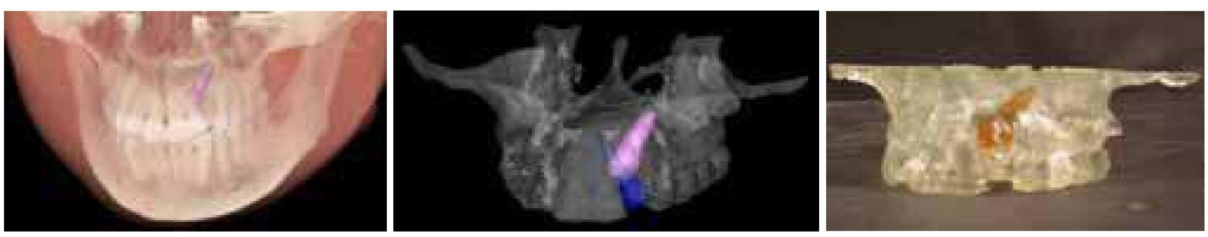


Fig. 16. 3D rendering of the maxillary arch. Highlighted in red the left portion of the inferior alveolar nerve

### 3.2.2 Impacted dental elements

23-year-old Caucasian female (P.S.) showing a total bone impaction of the elements 1.3 and 2.3. Conventional diagnostic tools used in dentistry (inspection and percussion) and radiographic tools (orthopanoramic and TeleRx) were not useful in order to precisely recognize the position of the impacted elements. In particular, it was not possible to identify the anteroposterior spatial relation of the impacted teeth. The 3D rendering and physical model of the maxillary arch irrefutably highlighted the palatal impaction of both the elements.
16-year-old Caucasian female (B.E.) showing a limited bone impaction of the element 2.2 and total impaction of the 2.3. In order to perform the surgical planning for the extraction of the element 2.3, later on an initial phase of alignment and levelling out of the upper maxillary arch, the critical aspect regarded the high level of contiguity between the impacted elements. The 3D rendering and SLA physical model of the maxillary arch (showed in Fig. 17) removed any doubt regarding the hypothetical root resorption relatively to the element 2.2 and simplified the treatment planning for the extrusion of the ectopic element 2.3.



*(a)* *(b)* *(c)*

Fig. 17. (a) volumetric rendering, (b) detail and (c) SLA model of the maxillary arch confirmed the hypothetical root resorption relatively to the element 2.2 and simplified the treatment planning for the extrusion of the ectopic element 2.3

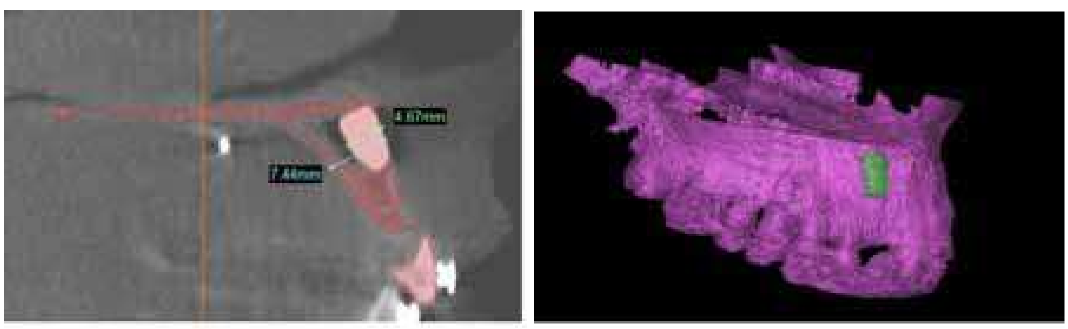
9-year-old Caucasian female (V.C.) showing a supernumerary tooth totally impacted (mesiodens) between the elements 1.1 e 2.1. The 3D rendering and physical model of the maxillary arch was manufactured in order to facilitate the oral surgery. In fact, the conventional radiographic tools were not helpful in the definition of the vestibular or palatine position of the mesiodens.
16-year-old Caucasian male (M.A.) showing a partial impaction of the 1.3, agenesis of the 1.5 and total impaction of the 1.7. Previous orthodontic treatments enabled the incomplete extrusion of the element 1.3 followed by a freezing of the same because of an infraocclusion of the tooth. The 3D rendering and the SLA model highlighted the impaction of the 1.3 on the vestibular cortical portion of the maxillary arch.

### 3.2.3 Joint-related diseases

16-year-old Caucasian female (S.M.) showing a dental class 1 with contracted arches, lower-front dental overcrowding and deep bite. From the objective examination of the stomathognatic apparatus the presence of left- hand joint-related sounds were noticed. The patient reported about the lack of pain and functional limitations. The 3D model of the mandible, manufactured in polyamide by SLS, showed an abnormal shape of the left-condyle: hypoplasic and flat.

### 3.2.4 Evaluation of the position of foreign bodies

18-year-old Caucasian female (P.D.) showing a radiopaque foreign body in the median area between the apices of the elements 1.2 e 2.1. Later on a trauma the patient refers about the lost out the 1.1 and immediately implanted. A second trauma caused the definitive avulsion of the element. Firstly, the patient was orthodontically treated in order to gain space and then was examined by a CT survey. The 3D rendering and SLA model of the upper maxilla allowed an accurate identification of the position and size of the foreign body as shown in Fig. 16. It was recognized as a rectangular block (4.67 × 8.03 × 3.77 mm), positioned in the vestibule, that determined an inflammatory resorption of the cortical portion of the vestibule itself. Later on the acquisition of the above described information, the avulsion was planned and executed and the foreign body was removed. It was determined to be gutta-percha. Contextually, autologous bone grafting was performed in order to fill the gap. An implant-prosthetic rehabilitation will be performed on the patient.



*(a)* *(b)*

Fig. 18. 2D evaluation (a) and 3D rendering (b) of an upper maxilla showing the presence of a radiopaque foreign body

### 3.2.5 Upper airways span monitoring

30 pediatric patients were selected and are currently under treatment by RPE (Rapid Palatal Expander), an orthopaedic appliance that widens the upper jaw by separating the midpalatal suture. The patients were monitored by cone-beam CT (CBCT) before the positioning of the RPE. The only one of them that has already completed the therapeutic treatment was subjected to another CBCT scan after the removal of the RPE. Contextually, the volume of the upper airways was modelled before and after the treatment and the volume augmentation was evaluated as shown in Fig. 19. In this case the estimated augmentation of the volume of the upper airways is equal to the 26.44%.

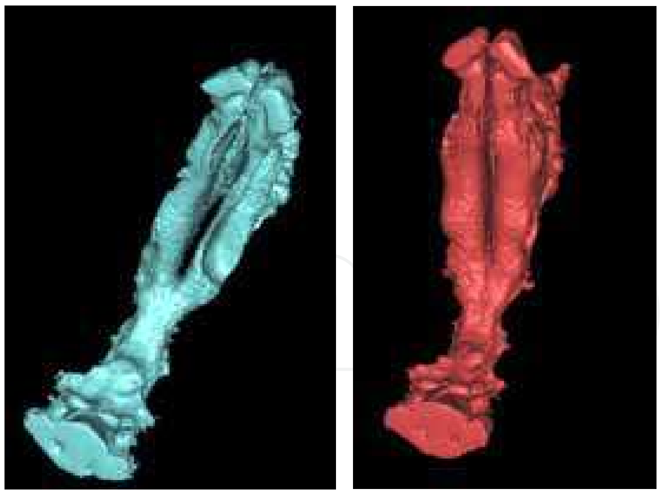


Fig. 19. 3D rendering of the upper airways relative to a RPE treated patient. Before (left) and after (right) the treatment is noticeable the augmentation of the volume of the upper airways.

## 4. Conclusions

Reverse Engineering and Solid Free-form Fabrication techniques have been substantially applied in medicine, however, their application in dentistry, and particularly in orthodontics, is not much widespread. This paper has discussed RE and SFF techniques and their usability in orthodontics. After presentation of RE and SFF technologies, the current and potential use in dental application are discussed showing some treated clinical cases. It is clear that the use of RE techniques and SFF models in dentistry will be expanded in the future with the ongoing research based on the development of new materials and technologies. A number of application examples are discussed, which demonstrate that RE and SFF techniques are playing a more and more important role in dental application.

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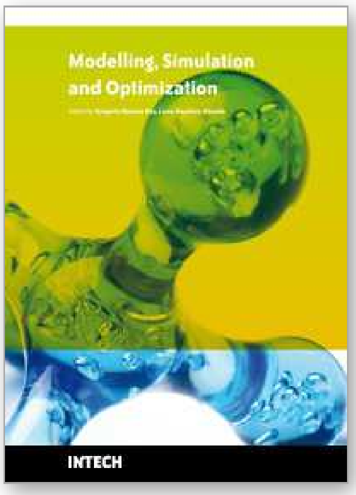


**Modelling Simulation and Optimization**

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Computer-Aided Design and system analysis aim to find mathematical models that allow emulating the behaviour of components and facilities. The high competitiveness in industry, the little time available for product development and the high cost in terms of time and money of producing the initial prototypes means that the computer-aided design and analysis of products are taking on major importance. On the other hand, in most areas of engineering the components of a system are interconnected and belong to different domains of physics (mechanics, electrics, hydraulics, thermal...). When developing a complete multidisciplinary system, it needs to integrate a design procedure to ensure that it will be successfully achieved. Engineering systems require an analysis of their dynamic behaviour (evolution over time or path of their different variables). The purpose of modelling and simulating dynamic systems is to generate a set of algebraic and differential equations or a mathematical model. In order to perform rapid product optimisation iterations, the models must be formulated and evaluated in the most efficient way. Automated environments contribute to this. One of the pioneers of simulation technology in medicine defines simulation as a technique, not a technology, that replaces real experiences with guided experiences reproducing important aspects of the real world in a fully interactive fashion [iii]. In the following chapters the reader will be introduced to the world of simulation in topics of current interest such as medicine, military purposes and their use in industry for diverse applications that range from the use of networks to combining thermal, chemical or electrical aspects, among others. We hope that after reading the different sections of this book we will have succeeded in bringing across what the scientific community is doing in the field of simulation and that it will be to your interest and liking. Lastly, we would like to thank all the authors for their excellent contributions in the different areas of simulation.

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