Stefan Abela

Digital Orthodontics

Providing a Contemporary Treatment Solution

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Cambridge, UK

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A Professional Message from the Author

This is a book that I am hoping will rejuvenate your professional career and boost it to yet an undiscovered level that you couldn't think was possible, igniting an uncountable interest in providing your preferred specialism in a new way.

Presenting all this collated information in the form of a textbook has been daunting, challenging, and extremely time-consuming, and this expression could only be described as an understatement to the dedication put towards delivering a textbook to the highest level possible and on time. However, it has been nothing by my pleasure to deliver it to you.

Writing this book meant endless hours of research, collaboration with other experts in the specialism, and a test of my character. I have completely changed my outlook on the profession, having experienced nothing but support and witnessed a spirit of collaboration and help.

I am also hoping that once you progress through this book, you will discover a keen passion for delivering the highest standards of orthodontics in the most contemporaneous manner possible, a revolutionary method that involves the newest technology available in medicine.

I am sharing this textbook with a newly found vigour, and being my third textbook, you might notice a more mature way of writing. I will let you lead on how you would like to use and interpret this book.

You might own this textbook for knowledge-building, confidence-building, or simply for inspiration to alter your techniques in a way that will ultimately benefit your clients. You might want to embrace the textbook as an eye-opener to the plethora of technologies that are available, and you might not have had the time to reflect on and validate its use in practice.

I am sincerely hoping that if you have found practice challenging at times and have wondered whether you have the energy to sustain it long-term, this textbook will empower you to build that surge, revalidation, and the finding of a new self, as ultimately we do not know what tomorrow holds. Why not build that high-end, tech-based practice that you have always wished for? Why not fall in favour of embracing the new technologies? Why not be convinced about the benefits of different technologies, perhaps the same ones that your younger peers are already convinced of?

I have personally decided to handcraft this textbook as there was none like it, and I genuinely felt you and any other clinician practising orthodontics might benefit from having it in hand, on the shelf, or simply knowing of its existence.

Let's be bold and help push the boundaries of our profession forward!

With inspiration, respect, and a deep sense of partnership,

Stefan Abela.

Preface

This book has been planned and executed with the primary intention of offering the most up-to-date, readily accessible guidance on the techniques, equipment, and concepts needed to provide a fully digitised journey to a modern patient seeking orthodontic treatment. It also describes the clinical procedures, techniques, and how to embrace the new technologies to provide the best clinical delivery. This book outlines the processes of how the key clinical stages can be provided in a digital format to render the patient's experience completely contemporary. These key stages include clinical and radiographic image acquisition, orthodontic appliance design, and fabrication. This book also provides invaluable information on the latest intraoral scanners, software programmes, hardware, materials, lasers, 3D printing, and CAD/CAM technology. The second section describes the future evolution expected within the specialty. This aspect of orthodontics like other specialties has been gaining an unprecedented momentum and will undoubtedly play an ever-increasing important role, if not a completely essential one. This book will be extremely relevant to undergraduate, postgraduate, and practising clinicians alike wanting to acquire more knowledge on how to convert their practice to a digital one.

Cambridge, UK
October 2025

Stefan Abela

Introduction

The era of digital technology complemented with artificial intelligence (AI) has now become a tangible reality and one that will undoubtedly improve the services provided by clinicians and the final outcomes experienced by patients. A fully digital workflow is aimed at expediting the pace of delivery of clinical services whilst simultaneously improving the final outcomes by simplifying the diagnostic processes, treatment planning, and final execution stages of the treatment journey. A fully digitised workflow extends to the very final stages of treatment, which in orthodontics is the provision of retainers for long-term wear.

This digitised workflows permit very standardised protocols of all the treatment stages mentioned above, eliminating any subjective differences in interpretation of treatment delivery, differences in manual dexterity skills, and could enhance the predictability expected by patients.

With all the advantages mentioned herewith, it might be surprising that the uptake of digitised pathways was not as forthcoming as the market might have anticipated. The reasons could be multiple in number and multifactorial in nature. Amongst a plethora of reasons, these include:

- Specific skills that clinicians need to obtain to be able to provide this modern way of practice.
- The obstructive challenge of changing one's ingrained patterns of delivery care.
- The challenging prospect of changing clinical techniques that feel close to second nature, having been implemented for years and known to be successful.
- The costly investment in equipment, including hardware and software components.
- Any additional recurring costs for consumable materials needed with digitised pathways.
- Recurring software fees following the initial installation.
- Additional fees associated with software renewal and/or upgrade of licences.
- The constant upgrading of equipment renders any purchased equipment obsolete after a very short period of time.
- The learning curve associated with software and hardware manipulation.
- Obtaining the physical space to harbour the equipment.

– Justifying the business case to shift from less costly well-known techniques to digital ones that could be more expensive.
– The need to train all members of staff to enable the whole team to deliver the same level of service.

The three main stages of a totally digital workflow include the following:

1. The acquisition of the patients' intraoral digital models with the use of intraoral scanners
2. The manipulation of the files obtained from the first stage using proprietary software, depending on the intended use by the clinical team, including appliance design
3. The transfer of the final digital files to 3D printing equipment to obtain the physical copy of the study and/or working models or the production of the appliance needed

It is almost a given that the use of digital workflows will escalate to unprecedented levels with the passing of time, akin to the use of electric vehicles. An exponential rate of improvements will most probably ensue with a proportionate shift of clinicians resorting to novel methods of providing orthodontics, liberating an infinite desire to improve the technology further and rendering the prices further accessible to the benefit of all the users and recipients.

This book aims to armour clinicians providing orthodontic treatment, with the latest insights into the market's readily available equipment, to describe detailed clinical stages that need to be embraced to provide these modern techniques and any future innovations that the market might provide to render your practice future-proof.

Stefan Abela.

October 2025.

Acknowledgements

It has been utterly touching how the profession and my most esteemed colleagues have come together to help, share, and disseminate our knowledge to benefit the wider scientific community. I would never wish to forget anyone who has been so helpful and contributed immeasurably to this textbook and I hope that I have included the major contributors in this section.

Many thanks first and foremost go to the Chief Editorial Board at Springer International, which actuates book projects of this calibre and enriches the scientific knowledge by continuing to be the main protagonist in the medical publishing sphere.

I would also like to personally thank Dr. Rolf Kühnert from OnyxCeph^{3}™ software, Image Instruments, Chemnitz, Germany, and Prof. Dr. Benedict Wilmes from the University from the department of Orthodontics, Düsseldorf, Germany, for their contributions.

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Dr. Stefan Abela is a specialist and consultant in orthodontics, directing private practices in London and Ely, Cambridgeshire, within the United Kingdom. He obtained his first qualification from the Malta Medical School, University of Malta, Msida, Malta, in 2003. To date, he has obtained numerous postgraduate qualifications from The Royal College of Surgeons of England and The Royal College of Surgeons of Edinburgh. He has been actively involved in the UK's national education and training programme for postgraduate trainees and has been a former Consultant at Guy's and St Thomas' NHS Foundation Trust, UK and the Head of

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Abbreviations

ABO	American Board of Orthodontics
AI	Artificial intelligence
ANN	Artificial neural network
A-P	Antero-posterior
BPR	Buccal power ridges
BSSO	Bilateral sagittal split osteotomy
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CBCT	Cone-beam computed tomography
CNCM	Computer numerical control machine
CNN	Convolutional neural network
DICOM	Digital Imaging and Communications in Medicine
DLP	Digital light processing
FDM	Fused deposition modelling
FFF	Fused filament fabrication
GCF	Gingival crevicular fluid
IBT	Indirect bonding tray
ICP	Intercuspal position
IDS	Invisalign Doctor Site
IMF	Intermaxillary fixation
IOSim	Invisalign® Outcome Simulator
IOFTN	Index of orthognathic functional treatment need
IOTN	Index of Treatment Need
IPR	Interproximal reduction
LL	Lower left
LR	Lower right
LRT	Lingual root torque
MM	Millimetre
OB	Overbite
OBJ	Object file format
OJ	Overjet
OMI	Orthodontic mini-implant
PC	Polycarbonate
PET	Polyethylene terephthalate

PETG	Polyethylene terephthalate glycol
PI	Plaque Index
PP	Polypropylene
PPP	PolyJet photopolymer
PVS	Polyvinyl siloxane
RCT	Randomised controlled trial
SLA	Stereolithography
SLS	Selective laser sintering
SM	Study model
SMP	Shape memory polymers
STL	Standard triangle language
TMJD	Temporomandibular joint dysfunction
TPU	Thermoplastic polyurethane
UL	Upper left
UR	Upper right
WM	Working model
VCC	Virtual C-Chain
VPC	Virtual Power Chain

Basic Clinical Concepts

1

1.1 Introduction

The specialism of orthodontics has been a platform onto which the introduction of a plethora of new technologies that benefit the end users, the clinicians, and the patients making use of the new applications, has proved to be ideal.

These technologies can be simplified by the description of the stages of application at a clinical level:

1. The acquisition of the initial and/or final records in a fully digital format.
2. The digital manipulation of the obtained records using the appropriate software programmes.
3. The final rendition of the software interpretation into the device or appliance required for clinical use.

Figure 1.1 illustrates a fully digitised workflow in a typical practice setting.

This chapter aims at simplifying the stages of a fully digitised orthodontic pathway based on the stage of application as mentioned above and in an alternative, more useable general format, they could also be classified as follows:

1. Pre-treatment phase.
2. Planning phase.
3. Delivery phase.

This chapter also aims at describing the hardware and software requirements needed to provide a fully digitised pathway.

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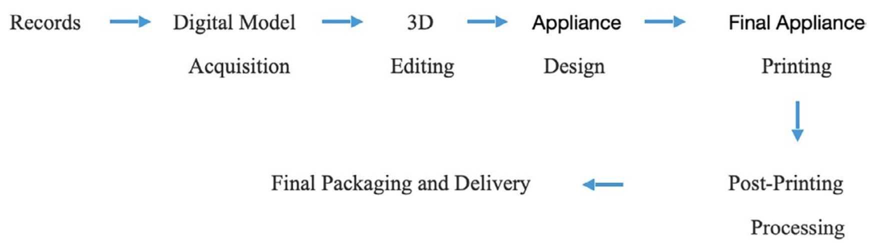

Fig. 1.1 A fully digitised workflow

1.2 Digital Records Acquisition

The first stage of any orthodontic treatment is the acquisition of up-to-date records. This consists of three parts:

1. Digital Dental Study Models.
2. Digital Radiographs.
3. Digital Extra and Intraoral Photographs.

1.2.1 Digital Dental Study Models

The acquisition of dental study models in a digital format is one of the initial steps in providing orthodontic treatment. Over the past decade, the scanning technology has been continuously updated and has now been fine-tuned more than ever. The subtle differences between the different intraoral scanners are now down to speed and type of image capture more than precision and usability.

Conventionally, this stage has been carried out using alginate impressions or polyvinyl siloxane (PVS), however, to some patients this procedure remains uncomfortable and for working models they may result in deficiencies in capturing parts of the teeth surface that may eventually compromise the fit of the manufactured appliance.

Other patients might be more sensitive and more susceptible to heightened gagging experience rendering intraoral scanners an extremely useful tool in modern practice [1].

Additional advantages of digital study models over conventional impressions include:

- Faster turnaround of dental study model manufacturing [2].
- Ease of digital relaying of records between different sites and/or suppliers [3].
- More ecologically friendly due to reduced material use and transportation.
- Better clinician-to-patient communication due to better visualisation of the intraoral findings [4].
- Better patient involvement for planning purposes [5].

– Better clinician-to-dental technician communication [6, 7].
– Easier digital manipulation of the digital study models for planning purposes [8].
– Direct digital measurements of specific points of interest [9, 10].
– Could be obtained by auxiliary members of staff within the dental team and less reliant on skills, material knowledge and qualifications [11].
– Less storage facilities needed with digital scans in comparison to plaster study models [12–14].
– No possibility of irreversible damage to the study models [15].
– Possibility of rescanning or altering a field of interest [16].

The disadvantages of obtaining digital study models are fewer, principally being:

– Acquiring the skill to obtain complete dental arches [17].
– Costs to purchase the equipment and maintenance [18].
– Slower acquisition than conventional impression-taking [19].
– Difficulty with obtaining subgingival prepared margins for prosthetic rehabilitation [4, 20].
– Oral fluids might be more impactful as a hindrance in image capture especially in interdental regions or subgingival areas [20].

Digital dental study models can be obtained using intraoral or extraoral scanners.

1.2.2 Intraoral Scanners

The advent of intraoral scanners together with computer-aided design and manufacturing (CAD/CAM) led to a numerous array of intraoral scanners being available on the market. This vast number of makes and models of intraoral scanners vary mostly in price, aesthetics, portability, and mode of action.

All intraoral scanners employ either of these four technologies for image capture:

1. triangulation,
2. confocal imaging,
3. accordion fringe interferometry (AFI) or,
4. active-wave-front sampling using 3D in-motion video [21].

The latest leading intraoral scanners and the latest versions could be listed in alphabetic order as follows:

- Aoralscan 3 by SHINING 3D, Hangzhou, China.
- CEREC Primescan by Dentsply Sirona, Charlotte, NC, USA.
- i900 by Medit Corp., Seoul, South Korea.
- Lumina by iTero, Aligntech Inc., San Jose, CA, USA.
- TRIOS 5 by 3Shape, Copenhagen, Denmark.

Other scanners could be listed alphabetically as follows:

3Disc Ovo by 3DISC, Herndon, VA, USA.
Alliedstar AS 200E, by Alliedstar Medical Equipment Co., Ltd., Pudong, Shanghai, China.
Carestream CS3800 by Carestream, Rochester, NY, USA.
Helios by Eighteenth, Safari Medical Technology Co., Ltd., Changzhou, Jiangsu, China.
Launch DL-300 by Guangdong Launca Medical Device Technology Co., Ltd., Dongguan, China.
PANDA Smart by Freqty Technology, Chengdu, Sichuan, China.
Planmeca Emerald S, by Planmeca Group, Helsinki, Finland.
RAYiOS2 by Ray Medical, Seoul, South Korea.
3DS 3.0 by Runyes Medical Instrument Co., Ltd., Ningbo, Zhejiang, China.
Virtue Vivo by Straumann Group, Basel, Switzerland.
Vivascan by Ivoclar, Schaan, Liechtenstein.

The commonalities between the different types can be found in the image generation with the following image formats being the most commonly used formats:

1. STL (Standard Tessellation Language).
2. PLY (Polygon File Format).
3. OBJ (Object File Format).

1.2.2.1 STL

STL or Standard Tessellation Language remains the most commonly used image format following intraoral scanning.

Originally developed by Charles Hull, it is now over 30 years in use and remains the most versatile format in digital orthodontics.

For simplification purposes, the digital images obtained are composed of 3D coordinates represented as a mesh of triangles. STL files are virtually compatible with most existing CAD/CAM systems and thus as explained earlier, defined the most versatile of all formats.

The main advantages of STL are:

(a) Ease-of-use with most computer-aided design and 3D printers.
(b) Open-source code.
(c) Universally-accepted format.

The main disadvantages of STL are:

(a) Allows 3D printing in one colour due to a monochrome storage possibility.
(b) Limited level of accessible data from files following storage leading to possible resolution loss.

The images obtained postscanning can require large storage capacities, consequentially leading to the need of compression and decompression for storage or transmission purposes. This is inevitably associated with resolution loss and the operator has to be mindful that the images still need to represent enough accuracy needed for their intended use. A specific study looking at compressed and decompressed STL images of arches in mixed and secondary dentition showed no dimensional distortions of the 3D models [22].

The accuracy of digital files are judged on precision and trueness [23], with the former defined as the closeness of repeated measurements of the same two points in different time points, whilst the latter is defined as the closeness between the dimension of two scanned points and the dimensions in real life [24].

1.2.2.2 PLY

PLY, or Polygon File Format, like STL is a commonly used 3D model format in digital orthodontics.

The main advantages of PLY are:

(a) Can be stored in multicolour.
(b) No loss of detail following storage.
(c) Can be used with cases involving a multidisciplinary approach especially when aesthetic dentistry is need as it allows differentiation between the different oral tissues.

The main disadvantages of PLY are:

(a) Not as widely used by CAD software as STL.
(b) Not all intraoral scanners have the capability to export in PLY format.
(c) Might need large storage capabilities.

1.2.2.3 OBJ

OBJ, or Object File Format, is a 3D format similar to STL and PLY, widely used in digital orthodontics albeit the least one.

OBJ format allows a more complicated capture of the oral tissue surfaces including the orientation and relative position of the different structures. This provides a more detailed imagery which could be useful in aesthetic dentistry but not as well used in orthodontics.

The main advantages of OBJ are:

(a) More detailed capture of oral tissue surfaces.
(b) File format storage in multicolour.
(c) Can be the format of choice for different specialisms within dentistry.

The main disadvantages of OBJ are:

(a) Might require large storage capabilities.
(b) Not all intraoral scanners have the capacity to export files in OBJ format.

1.2.3 Extraoral Dental Scanners

Extraoral dental scanners allow the possibility to provide a completely digital solution to an orthodontic treatment pathway and overcomes the initial investment in equipment needed by the clinician. With extraoral scanners, the clinician has the possibility of taking conventional impressions and allows the laboratory to process these using a desktop scanner.

There are two types of extraoral scanners:

1. Direct extraoral scanners.
2. Indirect extraoral scanners.

1.2.3.1 Direct Extraoral Dental Scanners

Direct extraoral scanners, as the name implies, allows the direct scanning of an impression without the need of pouring them into plaster casts.

The elimination of this manufacturing stage is not only time-saving but it also eliminates any sources of error that commonly get introduced with conventional impressions.

There are three types of direct extraoral scanners:

1. Mechanical scanners using touch probes [25].
2. Laser scanners.
3. White light scanners [26].

White light scanners have accuracy superiority over the laser scanners and do not physically contact the impression unlike mechanical scanners.

1.2.3.2 Indirect Extraoral Dental Scanners

Indirect scanners, also referred to as desktop scanners, are an alternative to provide a digital workflow without the need to place the initial investment in purchasing intraoral scanners.

1.2.4 CBCT Scanners

Using CBCT scanners is another indirect workflow that uses the patients' cone beam computed tomography (CBCT) scans to extract the required data to generate digital models [27].

CBCT scanners can also have the facility to scan traditional impressions and produce a digital copy. By accessing the software and placing the maxillary arch impression on the scanning platform, followed by the mandibular arch and the bite registration, the accompanying software can then produce the 3D images of the study models from the impressions [28].

1.2.5 Digital Radiographs

Digital radiographs have been in use for some time in both 2D and 3D formats. This is equally valid for the routine orthodontic radiographs requested; orthopantomogram (OPG), lateral cephalogram (Lat Ceph), and periapical radiographs (PAs) and for CBCTs.

Routinely 2D radiographs are the investigation of choice with singular periapical radiographs requested in selectable cases rather than full-mouth periodicals and 3D radiographs in order to adhere to the As Low as Reasonably Achievable (ALARA) principle [29].

1.2.6 Digital Extraoral and Intraoral Photographs

Whilst 2D photographs have been in use in a digital format for a long time, 3D extra- and intraoral photographs have been gaining increasing popularity and together with facial scanners and CBCTs they represent the future of dental records with optimal accuracy rates [30].

The applications and advantages of 3D photography can be made very obvious when evaluating facial structures including soft tissues in patients with craniofacial deformities. The latter group would include patients diagnosed with cleft lip and palate, facial asymmetries with a skeletal aetiology and patients who underwent orthognathic surgery [31].

The limitations of CBCTs to contrast the hard and soft tissues of the facial structures render them inadequate to replicate the profile of an individualâ€™s facial soft tissues [32].

1.2.6.1 Digital Extraoral Photographs/Facial Scanners

3D Facial Scanners

3D extraoral scanning also referred to as facial scanners can be obtained via the following types of methods:

- Light scanners; two types
  - Structured light scanners (SL).
  - Infrared structured light (ISL).
- Laser scanners (LS).
- Photogrammetry and Stereophotogrammetry.

Light Scanners

Light scanners which can be structured or based on an infrared system, project light patterns over a subject which are in turn captured by a camera system which forms part of the set-up. The triangulated pattern of captured light patterns is interpreted by the software to provide a 3D facial mesh.

Figure 1.2 illustrates this method of light scanning.

Laser Scanners

A facial scanning system based on the laser method is heavily dependent on a set-up which is very similar to the one described above for light scanners. A camera detects and captures all the laser projections from different angles and with the aid of the computer software, a 3D facial mesh can be reconstructed for the user.

Figure 1.3 illustrates this method of laser facial scanning.

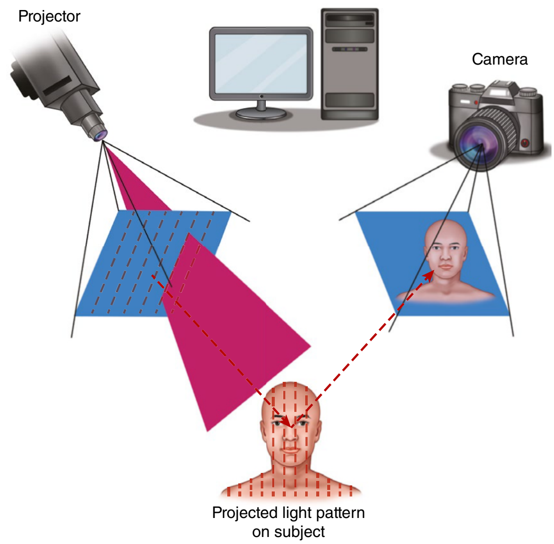

Fig. 1.2 Structured light scanning utilising a projector, a camera, and a computer system to deliver a 3D facial mesh

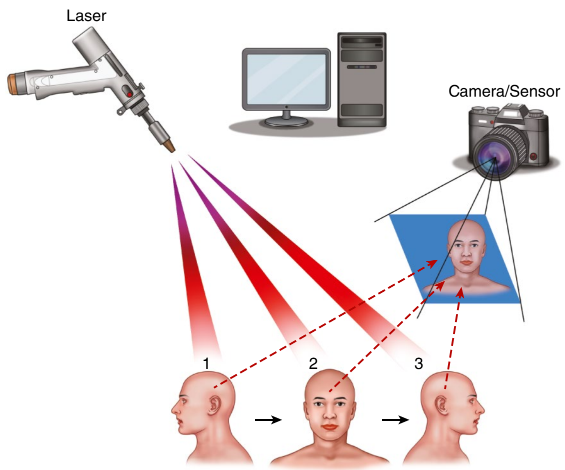

Fig. 1.3 Laser scanners record the subject in multiple positions by taking scans of multiple positions. These scans are then picked up by a camera and computed into one image by a computer algorithm

Photogrammetry

Photogrammetry and stereophotogrammetry are technologies based on mapping techniques of a surface of interest using digital photography with the latter involving the mapping processing to be done from two different planes. It is also dependent on a computer software to configure the numerous images and combine them to produce a satisfactory 3D facial scan. Figure 1.4 illustrates the combination of photogrammetry and stereophotogrammetry.

The accuracy of facial scanners have been shown to have a very acceptable industry-set standard of 2.0 mm with the type of scanner chosen bearing an influence on the accuracy outcome [33–35]. Mobile-friendly facial scanners were also proven to show an acceptable standard albeit not as precise as the professional systems [36]. Two commonly used systems: Bellus3D® Face Camera Pro (Bellus3D) (Bellus3D Inc., Los Gatos, California, USA), and the 3dMDface system (3dMD) (3dMD Inc., Atlanta, Georgia, USA) were studied and compared with one another and specifically for accuracy and precision. The trueness of the images was acceptable and the precision of the photographs were very reputable with extremely high inter observer agreeability [37].

Other well-known systems include the Morpheus 3D® scanner (Morpheus Co., Seoul, Korea). A study carried out on children using this specific 3D photogrammetry device found that the reported accuracy was slightly less when compared to 3D facial captures in adults [38, 39]. Most systems such as Metismile, Shining 3D, Hangzhou, China, Artec 3D Senningerberg, Luxembourg, allow superimposition of intraoral tissues with the aid of softwares such as Exocad GmbH Darmstadt, Germany, Dentalwings Inc., MontrÃ©al, Canada and Geomagic Inc., North Carolina, USA. Other 3D facial scanners available in the market are Face Hunter, Zirkoknzahn® GmbH, Gais, Bolzano, Italy, Snap® DOF Inc., Santa Clara, California, USA,

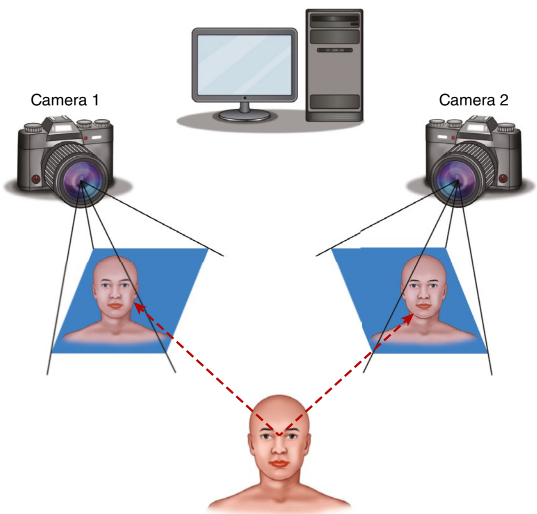

Fig. 1.4 A photogrammetry and stereophotogrammetry set-ups requiring mapping of a subject from different angles and planes in the case of stereophotogrammetry