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Comparison of three-dimensional surface-imaging systems☆

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3D photography;
Soft-tissue simulation

Summary *Background:* In recent decades, three-dimensional (3D) surface-imaging technologies have gained popularity worldwide, but because most published articles that mention them are technical, clinicians often have difficulties gaining a proper understanding of them. This article aims to provide the reader with relevant information on 3D surface-imaging systems. In it, we compare the most recent technologies to reveal their differences.
Methods: We have accessed five international companies with the latest technologies in 3D surface-imaging systems: 3dMD, Axisthree, Canfield, Crisalix and Dimensional Imaging (Di3D; in alphabetical order). We evaluated their technical equipment, independent validation studies and corporate backgrounds.
Results: The fastest capturing devices are the 3dMD and Di3D systems, capable of capturing images within 1.5 and 1 ms, respectively. All companies provide software for tissue modifications. Additionally, 3dMD, Canfield and Di3D can fuse computed tomography (CT)/cone-beam computed tomography (CBCT) images into their 3D surface-imaging data. 3dMD and Di3D provide 4D capture systems, which allow capturing the movement of a 3D surface over time. Crisalix greatly differs from the other four systems as it is purely web based and realised via cloud computing.
Conclusion: 3D surface-imaging systems are becoming important in today's plastic surgical set-ups, taking surgeons to a new level of communication with patients, surgical planning and outcome evaluation. Technologies used in 3D surface-imaging systems and their intended field

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of application vary within the companies evaluated. Potential users should define their requirements and assignment of 3D surface-imaging systems in their clinical as research environment before making the final decision for purchase.

Since the first report of computed tomography (CT)[1] in 1967 and magnetic-resonance imaging (MRI)[2] in 1971, the term 'three-dimensional (3D) imaging' has referred to techniques that can process true internal 3D data by acquiring volumetric pixels (or voxels) of the measured target. In contrast to CT and MRI, an imaging process measuring and analysing surfaces (*x*, *y* and *z* coordinates) in a 3D space is called '3D surface imaging'.[3]

Since the 1940s, 3D surface-imaging technologies have measured the complexities of an object with stereophotogrammetry,[4,5] image-subtraction techniques,[6] moiré topography,[7] liquid-crystal scanning,[8] light-luminance scanning,[9] laser scanning,[10] structured light,[11] stereolithography[12] and video systems.[13–16] These systems provide 3D analysis with promising results,[8,14–16] but most have not been applied in clinical routine due to time-consuming processes, inconsistent image quality and unpredictable costs.

In the last decade, advances in optical systems including structured light[17] and stereophotogrammetry[18] have made 3D surface imaging less time consuming: generating precise 3D surface images, handling vast data formats efficiently and being more accessible to patient protocols.[17,19]

3D surface-imaging technologies offer multiple medical applications. Practical guides have been written for these systems,[3,20] but most departments are uncertain which imaging system best meets their needs. We sought to provide a framework for comparing the technologies currently available on the market, and thereby to help readers evaluate and find the most suitable system for their use.

Material and methods

Hardware and software products of five companies — 3dMD, Axisthree, Canfield, Crisalix and Dimensional Imaging (Di3D) — were selected for comparison on these parameters: price, hardware set-up, technique of realisation, range of coverage, capture speed, processing speed, data file size, geometry representation, error in geometry, maintenance and support, customer training, on-site installation, portability, calibration time and sample density. Information was gathered by on-site demonstrations, personal interviews and trial captures at our institutions (except for Crisalix and Di3D). We performed extensive research of the companies' history and literature review on scientific validation of the products. A table with a glossary of parameters used in this article clarifies the technical terms (http://goo.gl/teFO80).

The basic technologies used by the selected systems fall into two groups: structured light[17] (Axisthree) and stereophotogrammetry[18] (3dMD, Canfield and Di3D). Subsequently, the basic technologies are explained concisely with illustrations.

Structured-light (http://goo.gl/P6rLbK) technology estimates the 3D surface of an object by the deformation of a projected pattern. The simplest set-up includes one projector, which projects a pattern (stripes, grid, dots, etc.) onto the object's surface, and a calibrated camera captures an image of the object overlaid by the pattern from a viewing direction different from the projector, in order to see the deformation of the projected pattern. With the knowledge about the design and geometry of a projected pattern and perception of the deformation by the 3D surface of the object, it is possible to estimate the 3D surface of the object and generate a 3D surface image.[17]

There are three different strategies for stereophotogrammetry: active, passive and hybrid. 'Active stereophotogrammetry' (http://goo.gl/Nj7ZK2) is based on structured light. It projects a pattern onto the surface of an object and uses two (or more) cameras to capture the deformation of the pattern by the objects' surface from different viewpoints. A 3D surface image is generated by a process called triangulation, calculating the 3D coordinate of each 2D point (pixel) visible in both camera views. This is achieved by combining the knowledge about the system (position of camera, distances of cameras, etc.) and the captured 2D images of the cameras with their correspondences (pairs of 2D points/pixels, which occur in both camera views). The projected pattern simplifies the finding of correspondences and no additional lighting is needed for this strategy, resisting the effects of ambient lighting.[19] By contrast, 'passive stereophotogrammetry' (http://goo.gl/X2fa2C) determines 3D surface images only based on the images taken by two (or more) cameras without the projection of a pattern. Due to the missing, projected pattern, the process of finding correspondences between views/images is more difficult and ambiguous. It is important to choose high-quality cameras, to capture surface details and sufficient texture information of the objects of interest including natural patterns, such as pores, freckles, scars and rhytids. The lighting conditions must be carefully controlled, since a strong directional ambient light may cause glare, diminishing the surface details.[19] Lastly, 'hybrid stereophotogrammetry' combines both active and passive, to achieve higher accuracy and quality in 3D surface imaging.

Results

3dMD: technology and products

Since 1997, 3dMD, based in London, UK, and Atlanta, GA, USA, has been developing products for 3D imaging in

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Table 1 Comparison of 3D surface-imaging systems.

Company/ products	3dMDface	3dMDhead	3dMDtrio	3dMDtorso	3dMDbody	Axisthree XS-200	Axisthree XS-400	Canfield VECTRA H1	Canfield VECTRA M3	Canfield VECTRA XT	Canfield VECTRA CR 3D	Crisalix 3D MAMMO simulator	Crisalix 3D FACE simulator	DI3D™
Hardware	2 modular units of 6 medical grade, machine vision cameras, industrial-grade flash system synchronized in a single capture with a PC-controller desktop or PC-controller laptop for portability	5 modular units of 15 medical grade, machine vision cameras, industrial-grade flash system synchronized in a single capture with a PC-controller desktop	3 modular units of 9 medical grade, machine vision cameras, industrial-grade flash system synchronized in a single capture with a PC-controller desktop	4 modular units of 12 machine vision cameras and an industrial-grade flash system synchronized in a single capture with a PC-controller desktop	from 4 to 22 modular units of 12 to 66 machine vision cameras and an industrial-grade flash system synchronized in a single capture with PC-controller desktop (s)	3 imaging heads with cameras, projectors and lenses	4 imaging heads, chassis unit with micro controller, actuation control, automatic Range Finder PC with Intel i3 processor	1 pod with on-board modular, intelligent flash unit laptop	3 pods, floor stand 36 MP color texture, on-board, intelligent flash units PC + 23″ monitor	3 pods, floor stand with motorized lift to adjust for patient height, 36mp color texture, on-board, intelligent flash units PC + 23″ monitor	2 or more pods, floor stand system scalable and customizable PC + 23″ monitor or laptop	none from Crisalix; user needs a pc/laptop and a standard consumer camera (digital camera, webcam, smartphone, etc.)		standard 3D system uses 4 Canon EOS 550D 18 MP, two head studio flash kit for illumination, optional: laptop with pre-installed software
Realization	combined active and passive (hybrid)stereo photogrammetry					structured light		passive stereo photogrammetry				3D reconstruction from 2D image analysis		passive stereo photogrammetry
Coverage	190-degree face and neck capture (ear-to-ear)	Full 360-degree capture of the head, face, and neck	Dual purpose 190-degree face, neck, and décolletage capture and torso capture for augmentation including under the breast	190-degree face neck, , and décolletage capture and torso capture for fuller figured reduction and reconstruction including under the breast	360-degree capture of body from head to toe with multiple anatomical options depending on application	~ 180-degree face capture	~180-degree face/torso capture	capturing volume (mm): 220x130x70 (H---W---D) typical application: 100-degree of left, right or front face	capturing volume (mm): 400x300x250 (H---W---D) typical application: face, neck and décolletage	capturing volume (mm): 600x550x350 (H---W---D) typical application: face, breast, torso, body	depends on number and placement of pods	~180° frontal and top-down views		~180-degrees face capture
Capture Speed	~1.5 ms at highest resolution	~1.5 ms at highest resolution	~1.5 ms at highest resolution	~1.5 ms at highest resolution	~1.5 ms at highest resolution	<= 2 seconds	2 <= seconds	8 ms	3,5 ms	3,5 ms	2 ms	depends on camera of user		length of a flash ~ 1 ms
Processing Speed	<8 seconds	<15 seconds	<10 seconds	<12 seconds	<60 seconds	depends on PC of customer	face: < 1 min torso: < 30 sec.	~20 seconds	~120 seconds	~80 seconds	~120 seonds	<= 5 min		60 seconds
File Size	depends on configuration, 4MB - 26MB	depends on configuration, 15MB - 95MB	depends on configuration, 11MB - 65MB	depends on configuration, 12MB - 70MB	depends on configuration, 5MB - 100MB	3 MB	3 MB	8 MB	8 MB	8 MB	depends on configuration	there are no files (web service)		50 – 60 MB
Geometry representation	a continuous point cloud available as a textured mesh and dense textured point model					a continuous point cloud -> later converted to a mesh		mesh				mesh		a continuous point cloud -> converted to mesh later
Error in Geometry	< 0.2mm	< 0.2mm	< 0.2mm	< 0.3mm	< 0.2mm to 1mm	< 0.5mm	< 0.5mm	> 0.1mm (x,y,z)	> 0.1mm (x,y,z)	> 0.1mm (x,y,z)	> 0.1mm (x,y,z)	2-5 mm		<= 0.2 mm (32,33)
Onsite Installation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	no need (web service)		✓
Portable	✓	✓	✓	✓	✓	✓	no	✓	✓	no	✓	✓		✓
Calibration time	20 seconds	90 seconds	30 seconds	45 seconds	90 seconds	< 5 minutes	< 5 minutes	no calibration	< 3 minutes	no calibration	< 2 minutes	no calibration		5 minutes
Sample density	62 vertices / cm²	62 vertices / cm²	62 vertices / cm²	55 vertices / cm²	8-62 vertices / cm² depending on configuration	each head samples 0.5 million points	3 samples/mm²	1.2 mm geometry resolution (polygon edge length)	1.2 mm geometry resolution (polygon edge length)	1.2 mm geometry resolution (polygon edge length)	1.2 mm geometry resolution (polygon edge length)	not specified		20 samples/mm² to 30 samples/mm²
approx. Price (June 2013)	Each system is custom-configured and upgraded from standard modules to meet the customer's specific imaging workflow requirements. Prices start at 21.000 EUR.					13.000 EUR	27.000 EUR	9.000 EUR	26.000 EUR	37.000 EUR	depends on setup	1590 – 5490 EUR per year		25.000 EUR

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medicine. In 2001, 3dMD introduced its first face and torso capture systems. A modular design was introduced in the following year to increase functionality and flexibility. The dynamic 4D system (3D plus time) was introduced in 2004.

The 3dMD technology (http://3dmd.com/) exploits hybrid stereophotogrammetry (active, http://goo.gl/Nj7ZK2, and passive, http://goo.gl/X2fa2C) with the software algorithms using both projected random patterns and texture of the skin (pores, freckles, etc.) to stereo-triangulate and generate a 3D surface image. System calibration takes up to several minutes depending on the hardware set-up. 3dMD offers six different hardware products (Table 1), each suitable for a specific application: 3dMDface (sample capture: http://goo.gl/56Pzlu), 3dMDhead (sample capture: http://goo.gl/G94fle), 3dMDtorso (sample capture: http://goo.gl/sWawTG), 3dMDbody, 3dMDtrio and 3dMDdynamic 4D systems (http://goo.gl/P3Jl0F). Besides the preconfigured products, they offer custom packages, such as the 3dMDflex (Figure 1) and 3dMDcustom systems. Because of the modular system, its hardware allows relocation of the set-up and enables mobility. The 3dMDdynamic 4D system (Table 2) captures up to 10 min of sequential 3D surface images of 60 frames per second.

3dMD provides a visualisation software, called 3dMDvultus (http://goo.gl/5xJoAX, Table 3), which can fuse the resulting 3D surface image with CT/cone-beam computed tomography (CBCT)/digitised dental study models to visualise 3D volumes, track the patient's history and simulate soft-tissue outcomes (surgical and non-surgical) by employing a biomechanical mass-spring model.[21]

Scientific validation of 3dMD

Maal et al.[22] evaluated treatment outcomes in oral and maxillofacial surgery by comparing the data captured with 3dMD (3dMD LLC, Atlanta, GA, USA) and Maxilim (Medicim NV, Mechelen, Belgium). The intra- and inter-observer error of the reference-based registration method was found to be 1.2 and 1.0 mm, respectively. Aldridge et al.[23] investigated the precision, error and repeatability associated with anthropometric landmark coordinate data. The 3dMDface System data were highly repeatable and precise. A validation of the ability to determine the volume and contour of the breast by Losken et al.[24] found the relative difference between the measured volume and the calculated volume to be about −2% (standard deviation (SD) ± 13–16%). Mean relative difference between the measured and calculated distances between nipple and sternal notch was about −6% (SD ± 6–7%). Lubbers et al. evaluated data acquisition and data of the 3dMD system and found the system to be reliable, with a mean global error of 0.2 mm (range, 0.1–0.5 mm) for mannequin head measurements.[25]

Axisthree: technology and products

'Axisthree' (http://www.axisthree.com/professionals/home) is based in Belfast, Ireland, and was founded in 2002. It focusses on 3D simulation using clinical data to do physics-based tissue-behaviour simulation on models. In 2006, Axisthree created a technology called Colour-Coded Triangulation (CCT™)[26] together with Siemens and opened up its technology to third-party development, which facilitated its reach to various medical 3D-imaging applications.

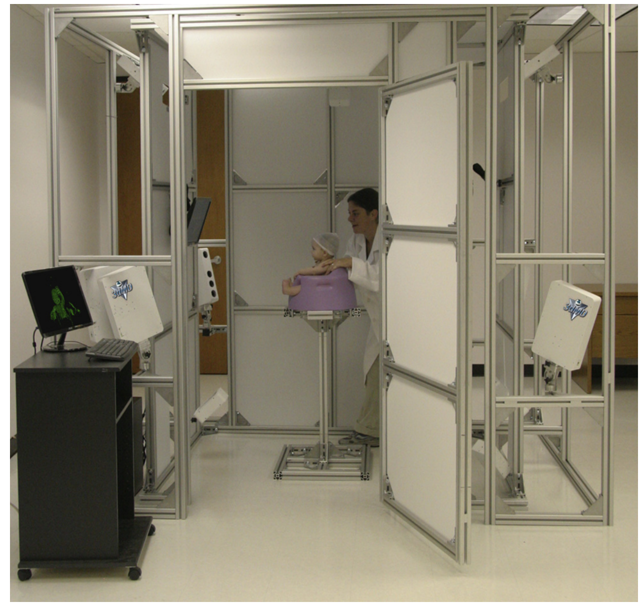

Figure 1 3dMDflex system (Courtesy of 3dMD, Atlanta, Georgia, USA; with permission).

Axisthree uses the principal of structured light to create 3D surface images (http://goo.gl/P6rLbK). System calibration takes <5 min, and it is necessary only when the hardware has been moved. There are two hardware configurations (Table 1): XS-200 for faces (sample capture: http://goo.gl/S4keOT) and XS-400 for torso (Figure 2, sample capture: http://goo.gl/zf609K).

Axisthree's 'Tissue Behaviour Simulation' (TBS; Table 3) allows the simulation of surgical procedures and the evaluation of their outcome. According to the company, TBS generates real-time highly accurate simulations of soft-tissue modelling.

Scientific validation of axisthree

Currently, there are no peer-reviewed papers about this system.

Canfield: technology and products

'Canfield' Scientific, Inc. (http://www.canfieldsci.com/), based in Fairfield, NJ, USA, was founded in 1988. Initially, it developed specialised 2D photographic systems, especially off-the-shelf customised solutions. Its best-known software application is Mirror® Medical Imaging Software, for simulating procedures in 2D images. In 2005, Canfield introduced its first 3D surface-imaging system.

Canfield exploits the principle of passive stereophotogrammetry, where the texture of the skin is used to determine the geometry and generate a 3D surface image (http://goo.gl/X2fa2C). Canfield supplies four hardware options (Table 1): VECTRA H1 (http://goo.gl/X4ezUW),

Table 2 Comparison of 4D capturing systems.

Companies/products	3dMDdynamic	DI4D™
Hardware	2 modular units of 6 medical grade (2 viewpoints), or three modular units of 9 medical grade (3 viewpoints), high frame rate machine vision cameras, with a PC-controller workstation	Standard system 4 monochrome and 2 colour cameras (Basler avA1600-65 km/kc 1200 × 1600 pixel @ 60 fps cameras), two Kino-Flo Diva Lite 400 s for illumination, one or more PCs with appropriate NVidia graphics cards
Realisation	Combined white light active and passive (hybrid) stereophotogrammetry, tracking the deformation of the entire surface frame by frame	Passive stereophotogrammetry and per-pixel optical flow
Coverage	190-degree face capture (ear-to-ear/2 viewpoints). 3 modular units increase performance space.	∼180 degrees
Capture speed	60 3D sequential frames per second for up to a 10 min capture cycle at highest resolution	One frame ∼2 ms, standard systems 60 frames per seconds, specialist systems up to 500 frames per second
Processing speed	Varies based on capture duration and PC processing power. Approximately 10 seconds per 3dMD image per processor thread.	2 pod data using NVidia CUDA acceleration is approx 30 seconds per frame including optical flow tracking to previous and subsequent frame
File size	Varies based on capture duration and system configuration. Depending on configuration, a single 3D capture within the continuous 4D sequence ranges from 4 MB—95 MB.	2 pod 4D data fully processed at 100% scale is approximately 70 MB per frame
Geometry representation	A continuous point cloud per frame, available as a textured mesh per frame for processing, dense surface tracking allows thousands of individual surface points to be tracked in six degrees of freedom (x,y,z within yaw, pitch, role of the subject)	A continuous point cloud per frame, converted to a mesh per frame for viewing/export, mesh tracking converts to a consistent mesh topology per frame with dynamic normal maps and texture maps
Error in geometry	<0.2 mm RMS or better within depth of field	n/a
Onsite installation	✓	✓
Portable	✓	✓ (setup in approx. 2.5 h)
Calibration time	100 s	5 min, should be done for every capture session
Sample density	62 vertices/cm^2	1200 × 1600 processed at 100% scale: approx 20 samples per mm^2
Approx. price (Jan. 2013)	Price on application	95.000 EUR

VECTRA M3 (http://goo.gl/4xn4zi), VECTRA XT (Figure 3) and VECTRA-CR. VECTRA H1 captures 100° of frontal faces (http://goo.gl/u8R258). VECTRA M3 captures face, neck and décolletage (http://goo.gl/UZQeAX). VECTRA XT captures face, breast and body (http://goo.gl/3LXPfm). VECTRA-CR 3D is a portable, customised and versatile 3D system for clinical research (CR).

The Canfield Sculptor™ software (Table 3) performs tissue simulations with 3D surface images. Breast Sculptor™ provides automatic breast measurements and simulates breast augmentation outcomes. Face Sculptor™ can simulate multiple surgical and non-surgical facial procedures.

Scientific Validation of Canfield de Menezes[27] tested the accuracy and reproducibility of the Canfield VECTRA-CR system and stated that random errors were always <1 mm. Rosati et al.[28] evaluated the integration of the dental virtual model into soft-tissue facial morphologies created with VECTRA-CR and found that the greatest mean relative error of measurements was <1.2%. Quan et al. measured the 'bottoming-out' phenomenon after breast reduction with VECTRA-CR,[29] documented the migration of breast tissue from the upper pole to the lower pole of the breast by 6% ($P < 0.05$) and concluded that the 3D surface-imaging system is a useful tool to monitor postoperative changes in breast morphology objectively. A scientific validation of the current passive stereophotogrammetry-based VECTRA system is not yet available.

Crisalix: technology and products

Crisalix (http://www.crisalix.com) is based in Bern, Switzerland, and was founded in 2009. It is the first web-based 3D simulator for plastic surgery and aesthetic procedures. Unlike the other companies, Crisalix does not offer any hardware. The program creates 3D surface images from three 2D images taken with a consumer camera,

Table 3 Comparison of functions of software.

Companies	3dMD	Axisthree	Canfield	Crisalix	Di3D
CT/CBCT Fusion	3dMDvultus and third-party software (e.g. Dolphin, Materialise CMF, Materialise Simplant OMS, Maxilim, OnyxCeph3D)	No	Third-party software (e.g. Dolphin)	No	Third-party software (e.g. Dolphin, Maxilim and Materialise OMS)
Track patients history	✓	✓	✓	Under development	✓
Simulate surgery	✓	✓	✓	✓	Third-party software
Monitor progress, evaluation of outcome	✓	✓	✓	Under development	✓
Real-time 3D volumetric visualisation	✓	✓	✓	✓	✓
Tissue behaviour simulation	✓	✓	✓	✓	Third-party software

physical distance measurements of the patient's anatomy and a set of landmarks. Crisalix offers two products: 3D MAMMO simulator (http://goo.gl/yPjFya) for planning and biomechanical simulations of breast implants and skin elasticity and 3D FACE simulator (Figure 4) for surgical and non-surgical facial procedures. Crisalix does not reveal how fast the 3D surface image is generated or how long the entire process will take, but considering the image acquisition time,[30,31] we estimate ~10–15 min. Since all calculations and simulations are done through cloud computing storing the data in Switzerland, there is no information on data size.

Scientific Validation of Crisalix de Heras Ciechomski et al. evaluated the accuracy of the surface reconstruction of the 3D MAMMO simulator on 11 clinical cases against ground truth from 3D laser scans[30] with mean reconstruction errors (root mean square (RMS)) between 2 and 4 mm. Oliveira-Santos et al. assessed the accuracy of the 3D FACE simulator with experiments on synthetic and real faces. The average reconstruction error over the whole data set (338 faces) was below 2 mm.[31] They also qualitatively evaluated the data set of real faces through a visual analysis by two surgeons, and 26 of 28 real faces were categorised as 'good' or 'very good', sufficient for practical use in consulting.

Di3D: technology and products

'Di3D' (http://www.di3d.com), Dimensional Imaging Ltd, is based in Glasgow, Scotland, and was founded in 2002. In

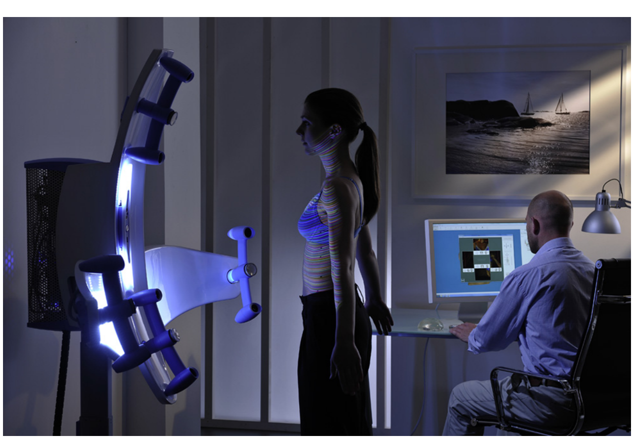

Figure 2 Axisthree XS400 system (Courtesy of Axisthree, Belfast, Ireland; with permission).

Figure 3 Canfield Vectra XT system (Courtesy of Canfield, Fairfield, Neu Jersey, USA; with permission).

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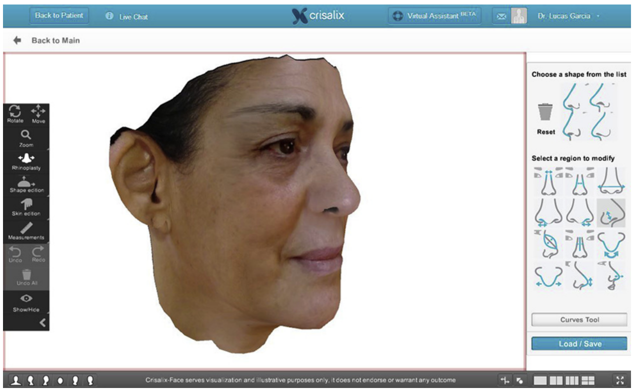

Figure 4 Sample image of Crisalix 3D Face simulator (Courtesy of Crisalix, Bern, Switzerland; with permission).

2010, it launched a 4D system, which captures 3D video sequences of dynamically changing surfaces.

Di3D's technology exploits passive stereophotogrammetry (http://goo.gl/X2fa2C). System calibration takes about 5 min. The standard system is the DI3D™ FCS-100 system (Table 1, Figure 5). They offer custom-capture systems with up to 32 cameras. The DI4D™ — 4D Capture System (Table 2, http://goo.gl/US0JfU) generates a 4D sequence of 3D surface images over time with a temporal resolution of 60 surface images per second.

DI3Dview™ is a 3D analysis, simulation and measurement software (table 3, http://goo.gl/0I76Tl), which can fuse the resulting 3D surface image with CT/CBCT.

Scientific validation of Di3D

Wider at al. assessed for geometric accuracy and found a mean error of 0.057 mm, a repeatability error (variance) of 0.0016 mm and a mean error of 0.6 mm in linear measurements, compared with manual measurements.[32] Khambay et al. assessed the accuracy and reproducibility, which resulted in system error within 0.2 mm.[33] Fourier et al. concluded that the results of accuracy and reliability comparing laser-surface scanning (Minolta Vivid 900), CBCT and 3D stereophotogrammetry (Di3D system) were accurate and reliable for research and clinical use.[34] Catherwood et al.[35] demonstrated accurate and reliable breast assessment with a mean difference between manual and digital curved surface distance measurement of 1.36 mm, with maximum and minimum differences of 3.15 and 0.02 mm, respectively. These validations were done on inanimate objects.

Discussion

For decades, 3D surface scanners have been used by the automotive and aerospace industries, in which the accuracy of measurement is of prime importance.[26] The speed of acquisition was less important because moving subjects are uncommon. In the last 30 years, these scanners have been adapted for medical applications[26] and gained increasing popularity worldwide.[36] Because most articles are technical, clinicians often face difficulties in gaining a full understanding of the technologies of the devices.[37] We have provided clinically relevant technical information to compare these 3D surface-imaging systems.

Figure 5 Di3D FCS-100 system (Courtesy of Dimensional Imaging Ltd., Glasgow, Scotland, UK; with permission).

A major advantage of 3D surface-imaging systems over 2D photographs is the ease of imaging a patient in 3D, compared with traditional multiview photographs.[19] A single 3D camera shot can generate any 2D view without repositioning the patient. Since there is no need for direct contact with the patient, measurement errors caused by modification of soft tissues in direct measurements can be avoided.[20]

3dMD combines active and passive stereophotogrammetry triangulation strategies into its systems called 'hybrid' stereophotogrammetry.[36] The cameras are based on machine vision standards: containing sensors of higher quality and consistency than off-the-shelf single-lens reflex (SLR) cameras. Machine vision cameras are designed for engineering and industrial applications and can be configured to tightly synchronise the capture times of 1.5 ms (1/650th of a second = 0.0015 s)[19] generating high-quality 3D data at 4–100 MB.

Axisthree uses structured light for its 3D surface-imaging systems, a technology with easy implementation and rapid full-field measurement,[38] which evolved from machine vision industries.[39] This technique[26] was further developed by Siemens and introduced into the medical community by Axisthree in 2006.[36] Originally designed for use in engineering, where accuracy of measurement is of prime importance, the data acquisition of this system is around 2 s (three imaging devices, approximately 300 ms per imaging head, e.g., 1/3rd of a second = 0.3 s).[36] As in photography,[40] a maximum capture speed of a 1/500th of a second is recommended for the 3D surface-imaging system to be robust against the patient's motion. Slower capturing might result in inaccuracies in the 3D surface image. A data acquisition of 2 s might lead to noisy or missing raw data geometry. Compensation during 3D reconstruction by filling in gaps can introduce errors when validating the accuracy of the geometry.[19] At this moment, no validation of the structured-light technique used on living subjects is available; however, the company states that long-time experience in gathering tissue-behaviour data from real patients has resulted in a huge knowledge library, which enables it to create a simulation tool that offers high realism and anatomical accuracy.[36]

Canfield and Di3D employ passive stereophotogrammetry, which generates 3D surface images solely on the basis of natural patterns, such as skin pores, freckles, scars and so forth. Therefore, the 3D reconstruction depends on the integrity of the pixels and requires high-resolution cameras. Both Canfield and Di3D use cameras capturing high-quality surface images at 8–60 MB, which include enough surface details for 3D reconstruction. In contrast to active stereophotogrammetry, strong directional ambient light may cause the effects of glare on subject's surface, diminishing the details of the texture.[19] Therefore, lighting must be carefully controlled with standardised flash units to overcome the sensitivity to illumination changes. According to Di3D, criticism[19] of the limited commercial DSLR camera (Canon)[32] sync-speed preset (1/200th of a second) can be overcome. Di3D states that with the cameras set at a shutter speed of 1/50th of a second, F/20 aperture and ISO 100, the synced cameras capture the data within the length of the flash illumination, which lasts 1–1.25 ms (1/1000th of a second = 0.001 s–1/800th s = 0.00125 s). In this way, motion artefacts are avoided.

Crisalix's 3D MAMMO and 3D FACE are web-based simulators.[30,31] Their goal lies not in providing precise 3D models but in facilitating communication between physicians and patients on simulated outcomes of plastic surgery. It requires only a computer and a standard camera. This is an advantage for physicians not having the necessary resources for a 3D surface-imaging hardware system. Crisalix makes no claims about the accuracy of neither the image nor the simulated results.

All systems are challenged in rendering accurate surfaces for hair and shiny areas. Even though the software renders a 3D surface, it is not necessarily an accurate or measurable surface. Depending on the system, the 3D surface-rendering software can (1) generate an inaccurate, general representation of the surface for visualisation purposes; (2) decide not to render a 3D surface without integrity; or (3) modify the rendering algorithms to approach the generation of each surface (soft tissue, hair and shine) differently depending on the surface properties.

Conclusion

Technologies have advanced rapidly in the last decade taking surgeons to a new level of surgical planning, outcome evaluation and communication with patients. Technologies used in 3D surface-imaging systems and their intended field of application vary among the companies evaluated. Users should define their requirements for 3D surface imaging before making the final decision for purchase.

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Conflict of interest

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