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Comparison of three-dimensional surface-imaging systems☆

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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