
ELSEVIER
Volume 34, issue 4, October 2013
ISSN NO 0141-9382
Displays
Contains Special Issue Articles – Innovative Progress in Materials for Display Technologies
Guest Editors: Shinji Morozumi and Pen-Cheng Wang

Displays 34 (2013) 270–275

Contents lists available at ScienceDirect

Displays

journal homepage: www.elsevier.com/locate/displa

Review

3D whole body scanners revisited

H.A.M. Daanen [a,b,c,*], F.B. Ter Haar [a]

[a] TNO, PO Box 23, 3769ZG Soesterberg, The Netherlands
[b] Amsterdam Fashion Institute, CREATE-IT Applied Research, Amsterdam University of Applied Sciences, The Netherlands
[c] MOVE Research Institute Amsterdam, Faculty of Human Movement Sciences, VU University Amsterdam, The Netherlands

ARTICLE INFO

Article history:
Received 13 June 2013
Received in revised form 26 July 2013
Accepted 21 August 2013
Available online 28 August 2013

Keywords:
Whole-body-scanners
Anthropometry
Garments

ABSTRACT

An overview of whole body scanners in 1998 (H.A.M. Daanen, G.J. Van De Water. Whole body scanners, Displays 19 (1998) 111–120) shortly after they emerged to the market revealed that the systems were bulky, slow, expensive and low in resolution. This update shows that new developments in sensing and processing technology, in particular in structured light scanners, have produced a new generation of easy to transport, fast, inexpensive, accurate and high resolution scanners. The systems are now moving to the consumer market with high impact for the garment industry. Since the internet sales of garments is rapidly increasing, information on body dimensions become essential to guarantee a good fit, and 3D scanners are expected to play a major role.

Contents

1. Introduction

At the end of the previous century the first 3D whole body scanners emerged to the market [1]. These systems were generally rather bulky, expensive (several hundred thousands of dollars for laser based systems) and had resolution in the order of a few mm. In particular the development of megapixel CCD-chips contributed to higher resolution and improved accuracy of 3D scan images. The technology has improved over the last decade and this article aims to give an overview of existing systems and new directions of development, in particular for the clothing industry.

2. 3D scanning systems

The basic technologies available in 1998 were laser scanning, patterned light projection and stereophotogrammetry. New techniques that came to the market are based on millimeter waves and infrared waves.

* Corresponding author at: TNO, PO Box 23, 3769ZG Soesterberg, The Netherlands. Tel.: +31 888665948.
E-mail address: hein.daanen@tno.nl (H.A.M. Daanen).

0141-9382/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.displa.2013.08.011

Table 1 gives an overview of identified 3D whole body scanning systems that are currently on the market.

2.1. Laser line systems

In 1998 Cyberware and Vitronic were the leading manufacturers of laser based systems [1]. A laser line is projected on the body from different sides and viewed by camera's under a fixed angle. In the last decade these companies improved the systems resulting in the Cyberware WBX and Vitronic Smart XXL as top models. Both systems have improved resolution and reduced costs.

The Cyberware WBX is a reliable system for instance used for the movie industry. The previous version was used for the 3D scanning survey CAESAR in the USA, Canada and Italy and provided accurate data [2].

The Vitronic Smart XXL was derived from the Vitronic Pro and is now much more easy to transport with four pods only. A less expensive version is the Smart LC with only 3 pods. These systems are often used in the garment industry; Human solutions (www.humansolutions.com) provides dedicated software to process scans. In the Dutch armed forces, the Vitronic Smart LC is used to scan every recruit, derive the essential body dimensions and print a form with recommended NATO-sizes of combat gear. The system started in 2003 and correctness of prediction gradually improved over time (see Fig 1).

2.2. Structured light systems

While laser systems typically sweep only one laser line over the surface, a structured light system projects an entire pattern. The advantage of a single line is that the sensor can easily detect it and very accurately compute how the projected 2D line is deformed on the 3D surface. The sequential 3D lines then form the complete 3D image. In fact the laser line in a laser system could also be considered a structured light pattern, but it has a strong time component because of its line sweep and therefore considered as a different class of systems.

A structured light systems projects a full structured light pattern into the scene and from the sensed deformed pattern a full 3D image is calculated. This pattern can consist of dots, bars, or any other light pattern. The advantage of a structured light scanner is its speed. Typically structured light scanner produce 3D images at 10–30 frames per second. That is why structure light scanners can also be used as a hand-held device. In order to avoid interference, the different light projection/camera systems in a structured light scanner often do not operate simultaneously but in series. Still, structured light scanning is so fast, that it can be used for 4D scanning; i.e. real time 3D scanning at 200 Hz. This offers nice opportunities to couple movement registration to 3D shape analysis [3].

Because the sensed light pattern is more difficult to convert into an accurate 3D image than a laser line, the accuracy and resolution of these scanners are less. Of course, in a static setup the 3D images of the structured light system can be combined to reduce the level of noise.

The structured light scanner consists of a pattern projector, a camera with a filter to sense the pattern, and often an extra camera to record the true color of the scene or object. The projected light pattern can consist of multiple colors, but bright white, red, or near-infrared is most commonly used.

Space Vision in Japan offers a structured laser light 3D scanning system that is transportable.

The China based company Artec (www.artec3d.com) offers pods that can be combined in a 3D scanner setup and the software recalculates the acquired images to a single 3D scan image. The Artec L™ and Artec Eva™ (the hand-held version) use patterns of bright white light. The software is intuitive and easy to use. Automatically the scans are aligned and the aligned scans are merged in a single file with one command.

The Belgian company 4D-Dynamics offers a range of patterned light projection scanners. Four to eight pods can be combined to acquire a full body scanner.

The introduction of the Kinect™ camera, an add-on for Microsofts X-box™ a few years ago led to a new impulse for 3D scanners. Kinect™ is also a structured light scanner, but uses a pattern of near-infrared which is invisible for the human eye, but not for its sensor. It has an additional RGB (color)-camera to record the color that can be mapped on the 3D image. The technique is inexpensive but the software was initially not open source. Now developer resources are openly available (http://www.microsoft.com/en-us/kinectforwindows/Develop/developerdownloads.asp).

The main disadvantage of the Kinect system is the depth map resolution of only 640 * 480 pixels, but the main advantage is the price and that it works under difficult light conditions. The SoftKinectic DepthSense 311 (www.softkinetic.com) has the same scope as the Microsoft Kinect and it mainly used for gesture analysis. The handheld Mantis Vision F5 (www.mantis-vision.com) has similar properties as the Artec Eva™ but uses a near-infrared pattern instead.

TC^2 and Sizestream employ the sensors for their whole body scanner systems, that operate with good accuracy and are low cost. Artec systems (www.artec3d.com) offer a combined Kinect™ camera and software package for 3D body scanning that is easy to use for 700 US$. One of the least expensive systems is the software package Kscan3D for 299 US$ (www.kscan3d.com) that allows the generation of 3D images using the Kinect™.

The first publications on using the Kinect™ as a 3D whole body scanner started in 2011 and several publications show that system works properly [4–6]. The resolution is up to about 5 mm using 4 Kinect™ systems [6].

A nice and simple application for the Apple iPhone is also available that records images while flashing light from four different directions on the face (www.trimensional.com). Then the application processes the image into a 3D face. However, the author is unaware of any attempt to verify the accuracy of the image; it is merely a gadget and, as far as known, not used in professional applications.

2.3. Multi-view camera system

A 3D image can also be acquired from two or more cameras. A stereo-camera records two images at the same time from a different viewpoint. From the content in the two images the depth to the body can be calculated and converted into a dense 3D image in real-time [7]. Experiments with multiple single cameras around a person is usually limited to the extraction of a the pose and not to extract a dense 3D body surface [8]. The advantage of a stereo-camera systems is that no laser line or light pattern is transmitted, which means that sunlight cannot interfere with the pattern. On the other hand, the line or patterns enables a 3D image with higher resolution and accuracy.

2.4. Millimeter waves

A distinction can be made between active and passive millimeter wave scanners. Active scanners use the reflection patterns of millimeter waves projected on the body, while passive scanners process the millimeter waves that are emitted by the human skin.

Millimeter waves offer the advantage that they pass through most clothing ensembles but not the skin. Thus the shape of the body can be captured without undressing. This offers an advantage

Table 1
Application software.

Scanner	Cyberware	4ddynamics	4ddynamics	Vitronics	Vitronics	TC²	SizeStream	SpaceVision	3dMDbody
Type	WBX	Mephisto EX-pro or CX-pro	Gotcha	Vitus Smart LC	Vitus Smart XXL	KX-16	3D body scanner	Cartesia	Flex8
City	Monterey, CA	Antwerp	Antwerp	Wiesbaden	Wiesbaden	Cary, NC	Cary, NC	Tokyo	Atlanta, Georgia
Country	USA	Belgium	Belgium	Germany	Germany	USA	USA	Japan	USA
Web	www.cyberware.com	www.4ddynamics.com	www.4ddynamics.com	www.vitronic.de	www.vitronic.de	www.tc2.com	www.sizestream.com	www.space-vision.jp	www.3dmd.com
Price indication (US$)	240,000	60,000–120000	10,000	37,000	65,000	10,000	15,000	20,000	190000
Technique	Laser line	Structured light projection	Structured light projection	Laser line	Laser line	Infrared	Infrared	Laser structured light	Stereophotogrammetry
Scanner space ($w * d * h$) (cm)	261 * 235 * 290	300 * 300 * 160	NA	220 * 220 * 260	210 * 210 * 290	114 * 168 * 200	107 * 165 * 216	198 * 229 * 240	440 * 346 * 225
Scanned volume ($w * d * h$) (cm)	130 * 50 * 200	100 * 100 * 200	NA	90 * 90 * 2100	120 * 120 * 2100	90 * 70 * 210	95 * 70 * 215	70 * 60 * 200	79 * 76 * 213
Scan heads	4	4–8	4–8	3	4	16	14	9	9
Point-point distance	<2 mm	<1 mm	<1 mm	$7/cm^3$	$27/cm^3$	1 mm	1 mm	3 mm	<1 mm
Scan duration (s)	17	2	1	12	12	3	6	2	0.002
Output format	.ply	.ply	.ply	ASCII/.obj/.stl	ASCII/.obj/.stl	Derived body dimensions	Derived body dimensions	.obj	TSB/OBJ/STL/WRL/PLY
Color	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes
Moving components	Yes	No	No	No	No	No	No	No	No
Application software	Converters	No	No	(www.)human solutions(.com)	(www.)human solutions(.com)	Clothing related	Clothing related	no	various
Remarks						PC included			4D scanning possible

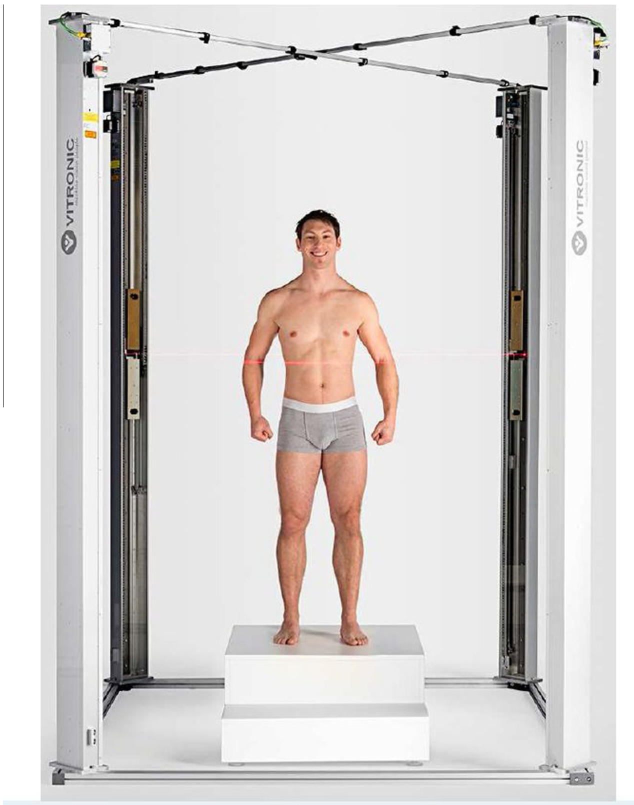

Fig. 1. Vitronic Smart XXL laser based scanner.

in time and effort, but may introduce an ethical problem because the private parts of the subjects can be seen.

Millimeter wave scanners are currently employed at airports for the detection of metal parts under garments (see http://en.wikipedia.org/wiki/Millimeter_wave_scanner) and offer an alternative for low radiation X-ray scanners.

The US based company Intellifit has sold about 10–20 Millimeter Wave Holographic scanners. The scanner is manufactured with the purpose of body scanning in the apparel industry. Although there is no source stating the frequency of the Intellifit scanner, it is likely that the scanner is based on 30 GHz active imaging. Unfortunately, it is not possible to give an exact figure for the accuracy and the precision of the Intellifit scanner but the current precision appears inadequate for made-to-measure clothing. Using interference patterns of different millimeter waves may improve the resolution.

Intellifit uses a cylindrical scanning arm with an millimeter wave emitter and 196 small antennas in a linear array that send millimeter waves and receive the body reflected signal. Many persons can be scanned in a very short time, which offers an advantage over the optical and laser scanners that require undressing. The scanner may be useful in gathering information about a large group of people in short time when the precision requirements are not very high (see Fig. 2).

3. Software

Not only hardware, but also software has developed over the last 15 years. Three main issues are important: easy optimization and repair of the scanned images, databases to browse in this information and dedicated application software. The World Engineering Anthropometry Resource (WEAR – www.wearanthro.org) has produced several tools to store, process and analyze the 3D scans.

Fig. 2. Intellifit scanning booth.

3.1. Optimization and repair of scanned images

It is essential that the captured 3D image of a subject is an exact copy of the original. Therefore, the importance is stressed to evaluate 3D scanners using calibrated objects in order to know the potential and limitation of the systems [9]. For 3D scanning the absolute position of the object in the 3D scanning space is not important; therefore absolute accuracy is not an issue. However, the size and shape of the digital copy should be identical to the original object.

A major challenge is to minimize occluded area in a body scan. Occlusion can be due to the fact that the projected light is not visible on the body or due to the fact that the light cannot be seen by the camera's. In both cases, data will be missing in the scan. One way to minimize the occluded area is to have as much projector and camera systems available as possible. The downside is of course the cost, but a trend is visible that the systems have an increasing number of scanning pods over time, due to the decreased costs of electronic components. However, missing data will always be present (e.g., in the axilla region) and holes have to be filled in order to generate meshes that can be used for milling (.stl format). The poisson surface reconstruction [10] is a tool that uses the initial surface points and creates a new closed surface without holes for a 3D object. The work of Allen et al. [11] presented the use of a scalable human body model to fill the holes in a human body scan in a more realistic manner (see Fig. 3). Once completely filled, the 3D models can be printed in a 3D printer. The use of full size 3D-prints of human bodies for garment applications will probably be limited (to for instance the movie industry) because of its costs. However, 3D prints on a scale of about 20 cm length may be very useful for testing the appearance of garments for instance in educational settings.

3.2. Databases of 3D scans

Probably the first database of 3D scans was Nefertiti [12]. It enabled the search of similar shapes in the CAESAR-database.

3D body scans contain a tremendous amount of data. If we assume a body surface area of 2 m^2 and a resolution of 1 mm, a scan will contain 2 million 3D coordinates. Even though computers are able to store increasingly large amount of data, it is essential for fast processing to store the data as efficient as possible. The best way to derive the most important information from 3D body scans is Principal Component Analysis (PCA) [13]. The most important components are related to height, weight and relative arm/leg length. With only 50 parameters of each scan, the general outline

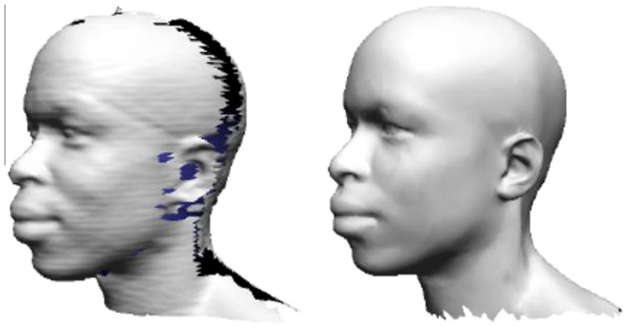

Fig. 3. Correction of holes in 3D scans using a model [11].

of the 3D body scan can be reconstructed, so that it can be used for further processing.

3.3. Dedicated application software for the garment industry

Many applications exist of 3D whole body scanning, in the medical field, anthropometry, design and so on [14] and the number of applications has increased over the last decade. The clothing industry is one of the largest markets and therefore discussed in more detail.

Now, with Kinect™ based 3D body scanning systems priced at 400 US$ or less, 3D whole body scanners are entering the homes. People can make a low cost 3D copy of their body.

This development parallels the shift from physical garment sales in retail shops to internet sales of garments. In retail shops, the best fitting size was determined by trying on different sizes until the best one was found. Unfortunately, this fitting process is impossible with internet sales, and an important issue arises how to select a good fitting garment using the internet. Low cost 3D scanners at home or at strategic locations in villages and cities may offer an opportunity to solve this problem.

However, there are some competing techniques that may be even simpler that may threaten the penetration of 3D scanners to the market for virtual fit of garments.

3.3.1. Competing techniques for fit of garments

The first option is that users of the internet submit some basic data like stature, weight, age and collar size to get fitting garments. This information may not seem sufficient for good fit, but it is recently shown that this works rather well, in particular when subjective information (like 'I have long/normal/short arms') is added [15].

A second option is that the end user uses a digital manikin on the internet to make a copy of him/herself (see for instance http://www.myvirtualmodel.com/). Not only body dimensions, but also hair and skin color can be visualized for instance. The advantage is that clothing of interest can be shown on the digital body. However, it should be realized that these tools often do not provide for accurate fit.

A third option is the use of digital photos that are uploaded to the internet and used to derive body dimensions. Generally, the frontal and sagittal image are used, e.g. [16]. Some examples that are professionally developed in terms of interface are Poikos (www.poikos.com) and UPCload (www.upcload.com). For garment sizing, parameters like chest, hip and waist circumference are important. Estimation of hip circumference from hip width and hip depth yields an error of about 4 cm, which is about one size step [17]. Therefore, it can be expected that these tools may give a good indication, but are probably not accurate.

Considering the ease of use of the techniques above, but the lack of high accuracy, some companies started to use the tools not for sales, but as a way to direct the customer to the best fitting size in the shop. Hointer (www.hointer.com) uses a smart phone to scan a garment in the shop, which is then delivered automatically to the fitting room within 30 s. If it does not fit, the code can be changed and another size will be delivered to the fitting room, thus reducing the time for refitting.

3.3.2. 3D scanner data for garment sizing

All methods described in Section 3.3.1 are easy to use, but lack the accuracy that is required for tight fitting garments. 3D whole body scanners can supply the necessary information and the systems are rapidly decreasing in price. TC^2 and Sizestream supply their scanners with software that enables the generation of garment dimensions from 3D body scans. Thus, made-to-measure garments can be made from the printed patterns. Several large companies that produce cutting machines (Gerber and Lectra) invest in new software that is getting increasingly better [18] to generate clothing patterns from 3D virtual models (these models can often be generated on the basis of imported 3D scans). Sayem et al. [18] identified nine software packages that establish the link between 3D scans and 2D garment patterns. Hin and Krul evaluated two software packages that calculated 1D body dimensions from 3D scans, the Human Solutions and TC^2 package, and concluded that both packages performed about equally well but that the computer generated body dimensions differed considerably from the manually derived body dimensions using ISO 20685 [19]. An important reason for the observed difference is that palpation of bony parts is necessary for manual measurements and that a scanner cannot do this. As a result the chest, waist and hip circumference will be measured at different heights. The absolute circumference differences may be as high as several cm.

4. Conclusion

In conclusion, we observe an increase in resolution of 3D body scanners over the last 15 years with a parallel cost reduction. 3D body scanners now are entering the consumer markets. Dedicated software has become available to repair incomplete scans, allow for efficient storage and deduct the essential body dimensions. For the garment industry, 3D body scanners may offer an opportunity to boost sales over the internet because the body dimensions have sufficient accuracy to make made-to-measure garments or select the best fitting size from a range of pre-manufactured sizes. Using 2D images for body dimension assessment is getting increasingly popular, but the available information is generally insufficient to supply the correct size of tight fitting garments.

Acknowledgements

This work is supported by the project 'Virtual expectations, physical experience' of RAAK (Regional Attention and Action for Knowledge circulation) that is managed by the Foundation Innovation Alliance with funding from the ministry of Education, Culture and Science (OCW).

The support of the members of WEAR (world engineering anthropometry resource) (www.wear-anthro.org) is greatly acknowledged, as well as the support of Thierry Mentzel, M.Sc.

References

[1] H.A.M. Daanen, G.J. Van De Water, Whole body scanners, Displays 19 (1998) 111–120.
[2] K.M. Robinette, H.A.M. Daanen, Precision of the CAESAR scan-extracted measurements, Appl. Ergon. 37 (2006) 259–265.

[3] M. Mochimaru, M. Kouchi, 4D measurement and analysis of plantar deformation during walking and running, Footwear Sci. 3 (2011) S109–S112.
[4] S. Song, S. Yu, W. Xu, Study on 3D body scanning, reconstruction and measurement techniques based on kinect, J. Tianjin Polytech. Univ. 31 (2012). 34–37+41.
[5] J. Tong, J. Zhou, L. Liu, Z. Pan, H. Yan, Scanning 3D full human bodies using kinects, IEEE Trans. Visual. Comput. Graphics 18 (2012) 643–650.
[6] R. Wang, J. Choi, G. Medioni, Accurate full body scanning from a single fixed 3D camera, in: Proc. – Jt. 3DIM/3DPVT Conf.: 3D Imaging, Model., Process., Vis. Transm., 3DIMPVT, 2012, pp. 432–439.
[7] W. Van der Mark, G. Burghouts, E. Den Dekker, T. Ten Kate, J. Schavemaker, 3-D Scene Reconstruction with a Handheld Stereo Camera, COGnitive systems with Interactive Sensors (COGIS), Stanford University, California, USA, 2007.
[8] M. Hofmann, D.M. Gavrila, Multi-view 3D human pose estimation combining single-frame recovery, temporal integration and model adaptation, in: IEEE Comput. Soc. Conf. Comput. Vis. Pattern Recogn. Workshops, CVPR Workshops, 2009, pp. 2214–2221.
[9] M. Kouchi, M. Mochimaru, B. Bradtmiller, H. Daanen, P. Li, B. Nacher, et al., A protocol for evaluating the accuracy of 3D body scanners, Work 41 (2012) 4010–4017.
[10] M. Bolitho, M. Kazhdan, R. Burns, H. Hoppe, Parallel poisson surface reconstruction, Lect. Notes Comput. Sci. 5875 (2009) 678–689. LNCS.
[11] B. Allen, B. Curless, Z. Popović, The space of human body shapes: reconstruction and parameterization from range scans, ACM Trans. Graphics 22 (2003) 587–594.
[12] E. Paquet, M. Rioux, Nefertiti: a query by content software for three-dimensional models databases management, Proc Int Conf Rec Adv 3 D Dig Image Model (1997) 345–352.
[13] C. Shu, P. Xi, Z.B. Azouz. Consistent parametrization and principal component analysis of 3D anthropometry data, in: International WEAR conference Banff, 2007. ISBN: 980363 6 1.
[14] P.R.M. Jones, M. Rioux, Three-dimensional surface anthropometry: applications to the human body, Opt. Lasers Eng. 28 (1997) 89–117.
[15] H.A.M. Daanen, M.B. Byvoet, Blouse sizing using self-reported body dimensions, Int. J. Cloth. Sci. Technol. 23 (2011) 341–350.
[16] S. Saito, M. Kouchi, M. Mochimaru, Y. Aoki, Simple system for 3D body shape estimation, in; 1st IEEE Global Conference on Consumer Electronics 2012 (2012) 203–205.
[17] H.A.M. Daanen, A.J. Krul, Reliability of circumference estimation based on depth and width of the hip, Rep. TNO Soesterberg A88 (1997).
[18] A.S.M. Sayem, R. Kennon, N. Clarke, 3D CAD systems for the clothing industry, Int. J. Fash. Des. Technol. Eudc. 3 (2010) 45–53.
[19] A.J.S. Hin, A.J. Krul. Performance of Human Solutions body measure software, Report TNO-DV3 2005 A-009, 2005.