3D Facial Surface Imaging in Dentistry and Beyond

D.J.J. Farnell [1][0000-0003-0662-1927], AI Zhurov[1][0000-0002-5594-0740]], S Evans[1][0000-0002-2657-7436]

[1] School of Dentistry, Cardiff University, Cardiff CF14 4XY, Wales
FarnellD@cardiff.ac.uk
ZhurovAI@cardiff.ac.uk
Evansst@cardiff.ac.uk

Abstract. 3D surface imaging generally is used extensively in computer-aided design and computer-aided manufacturing (CAD/CAM), where the advent of low-cost 3D printers and handheld 3D scanners has brought these technologies into the home. However, 3D surface imaging of the face specifically is a relatively small research field globally; a search of PUBMED (in March 2022) indicated that only 663 papers were published on 3D facial surface imaging in the last year, whereas a similar search on PUBMED using the term MRI yields 45,819 “hits” over the same time period. Despite this disparity, 3D facial surface imaging is a healthy field of research with distinct areas of application. Here we outline methods of 3D surface image capture before describing shape representation and analysis. Applications of 3D facial surface imaging in dentistry and “beyond” are then considered. Finally, future research avenues for the Dental Data Science / 3D Imaging research group at Cardiff University are presented.

Keywords: 3D Facial Surface Imaging, Shape Representation and Analysis, Medicine, Dentistry

Before discussing applications of 3D facial surface imaging, we provide background [1] relating to 3D imaging techniques, as well as shape representation and analysis. 3D surface imaging techniques use light and so are “non-ionising,” which is a strong advantage. By definition though, they cannot yield much information into tissues beneath the skin. 3D laser imaging directs a laser beam across an object (e.g., the face) to produce a 3D shape image. By contrast, stereophotogrammetry takes images of a 3D object from different angles in order to reconstruct it digitally in 3D. It can provide 3D shape information and “textural” (i.e., photographic in this context) data. It can be used to provide “4D” shape information, i.e., changes in shape over time. Problems can occur due to reflections and elements for more complex structures that contain strong curves or holes (e.g., ears or nose). Structured light imaging (see Fig. 1) projects a pattern of light onto an object and then deformations of the resulting pattern reflected from a 3D object are resolved into 3D information. This approach has similar advantages and disadvantages to stereophotogrammetry. However, the practical application of this approach is strongly enhanced by the ability to stitch together individual images from different viewpoints to provide a complete reconstruction of a 3D object.

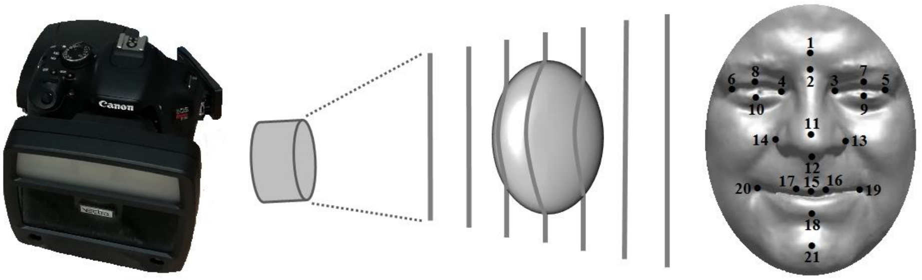

Fig. 1. (left) The Vectra camera, which uses structured light; (middle) simplified schematic of structured light hitting an object; (right) 3D image of the one of the author's face (DJJF) obtained using the Vectra, where 21 biologically relevant landmark points were placed here manually also.

Common shape representations [2] are meshes (3D shapes are represented by connected polygons, normally triangles), graphs, and point clouds (3D shapes are represented by collections of Cartesian coordinates). Manual placement of key landmark points (and as shown in Fig. 1) allows the regular placement of points across a set of images. Semi-landmark methods also position landmarks point regularly on an (often parametric) topological surface [3,4]. Another method used for consistent placement of points is by deforming a template based on the mean shape for each new face [5]. There are other forms of shape description [2], including: volumetric, projections, RGB-D, and multi-view. Procrustes transformations use rotations, translations, and scaling to provide a common centre and length scale for all shapes [3]. Principal components analysis (and variants therein) [3,6-8] and partial least-squares analysis [3,9] are common methods of shape analysis that require "regular" representations of shape as provided by landmarks. Deep Learning methods may also be used for shape analysis (see, e.g., a recent review in Ref. [2]).

3D facial surface imaging has previously been used in orthognathic and in plastic and/or maxillofacial surgery (see, e.g., [10-13]). 3D surface imaging might be used alone or alongside other imaging modalities such as CT and MRI [1], where this evidence can be viewed by the entire clinical team to arrive at a treatment plan; this might also include accurate quantitative measurements of distances or volumes. Statistical modelling [14] and machine or deep learning [15,16] have also been employed using 3D facial surface data to understand and predict outcomes of surgery. However, a recent article [17] argues strongly that 3D surface imaging is not enough for "surgical simulations" and that one should employ a model that also includes the complex (non-linear) mechanisms of soft tissues. Other topics using 3D facial surface imaging that are relevant to evaluating clinical outcomes relate to "4D" videos of the dynamics of 3D facial expressions [18] and 3D facial aesthetics [19-21].

Another very strong area of research relates to the (many) "determinants" of facial shape [22] (i.e., factors such as sex, age, etc.). The difficulty here is in disentangling the effects all of these different "determinants." However, clear patterns do exist in some cases. For example, research into sexual dimorphism in 3D facial shape [22] shows consistently (see Fig. 2) that females tend to have more prominent cheeks and generally rounder faces, whereas males are more likely to have more prominent chins, foreheads, and noses. 3D facial changes with age have also been studied extensively in order understand normal facial development in children [7,9,22] and in identifying typical markers of aging in older people [23]. A fascinating area of research relates to the role of genes on 3D facial shape, e.g., to describe normal 3D facial variation [22,24] and also to understand and identify syndromes affecting facial shape [25,26]. Clearly, there are many ethical issues relating to the investigation of such "determinants" of facial shape. Other areas of application of 3D imaging in dentistry and medicine are connected to CAD/CAM of dental prostheses [27] and face mask design and fit (see, e.g., [28]).

3D facial surface imaging is also useful in areas outside of medicine and dentistry, such as facial identification and/or reconstruction in forensic sciences [29-31]. This research is relevant to archeology, e.g., letting us see the face of a long-dead king based on their human remains [32]. Other very strong areas of research that utilise 3D facial surface imaging are 3D facial expression classification [33-36] and 3D facial recognition [37,38].

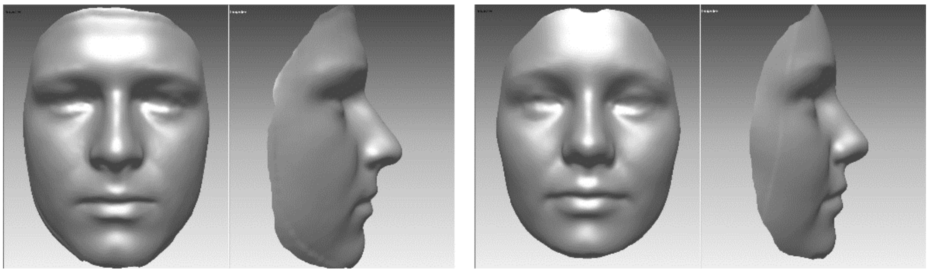

Fig. 2. Average faces (data from Ref. [6,39]) over all male subjects (left) and female subjects (right).

In conclusion, 3D facial surface imaging provides a valuable tool in medicine and dentistry; the Dental Data Science / 3D Imaging research group at Cardiff University will continue to carry out research in these areas. There are also potential applications of 3D facial surface imaging in forensics science and archeology that we might explore in future. Previously, impressions of the dental arch were carried out manually by using an impression material and a plaster cast of dentition is formed in the dental laboratory, which is subsequently used to inform the manufacture of restorations and prostheses. It is common nowadays to use intra-oral 3D surface image capture of dentition directly [40], which is likely to be more acceptable to the patient, quicker, and more reliable; we will carry out research in this area also. Another area that we hope to continue to work on in future relates to paediatric bruising, where previous 3D surface imaging studies have focused primarily on bite marks [41,42]. Clearly this research also has many ethical issues, although we note that 3D surface imaging might provide useful additional evidence in future in deciding whether bruises are from abuse or not and/or also in bruise age estimation [43]. Underpinning all of these practical applications, we will continue to develop and apply mathematical and computational methods of 3D shape representation, analysis, and visualisation [6-9].

References

1. Karatas, O.H., and Toy, E.: Three-dimensional imaging techniques: A literature review. European Journal of Dentistry 8(01), 132–140 (2014).
2. Ahmed, E., Saint, A., Shabayek, A. E. R., Cherenkova, K., Das, R., Gusev, G., and Aouada, D.: A survey on deep learning advances on different 3D data representations. arXiv preprint arXiv:1808.01462 (2018).
3. Zelditch, M.L., Swiderski D.L., and Sheets H.D.: Geometric morphometrics for biologists: a primer. Academic Press (2012).
4. Gunz, P., and Mitteroecker, P.: Semilandmarks: a method for quantifying curves and surfaces. Hystrix, the Italian Journal of Mammalogy 24(1), 103–109 (2013).
5. White, J. D., Ortega-Castrillón, A., Matthews, H., Zaidi, A. A., Ekrami, O., Snyders, J., and Claes, P.: MeshMonk: Open-source large-scale intensive 3D phenotyping. Scientific Reports 9(1), 1–11 (2019).
6. Farnell, D.J.J., Popat, H., and Richmond, S.: Multilevel principal component analysis (mPCA) in shape analysis: A feasibility study in medical and dental imaging, Computer Methods and Programs in Biomedicine 129, 149–159 (2016).
7. Farnell, D.J.J., Richmond, S., Galloway, J., Zhurov, A.I., Pirttiniemi, P., Heikkinen, T., Harila, V., Matthews, H., and Claes, P.: Multilevel Principal Components Analysis of Three-Dimensional Facial Growth in Adolescents. Computer Methods and Programs in Biomedicine 188, 105272 (2019).
8. Galloway, J., Farnell, D.J.J., Richmond, S., and Zhurov, A.I.: Multilevel Analysis of the Influence of Maternal Smoking and Alcohol Consumption on the Facial Shape of English Adolescents. Journal of Imaging 6(5), 34 (2020).
9. Farnell, D.J.J., Richmond, S., Galloway, J., Zhurov, A. I., Pirttiniemi, P., Heikkinen, T., Harila, V., Matthews, H., and Claes, P.: An exploration of adolescent facial shape changes with age via multilevel partial least squares regression. Computer Methods and Programs in Biomedicine 200, 105935 (2021).
10. Lin, H.-H., Lo, L.-J.: Three-dimensional computer-assisted surgical simulation and intraoperative navigation in orthognathic surgery: A literature review. Journal of the Formosan Medical Association 114, 300–307 (2015).
11. Tarassoli, S.P., Shield, M.E., Allen, R.S., Jessop, Z.M., Dobbs, T.D. and Whitaker, I.S.: Facial Reconstruction: A Systematic Review of Current Image Acquisition and Processing Techniques. Frontiers in Surgery 7, 537616 (2020).
12. Tzou, C. H. J., and Frey, M.: Evolution of 3D Surface Imaging Systems in Facial Plastic Surgery. 3-D Imaging Technologies in Facial Plastic Surgery. An Issue of Facial Plastic Surgery Clinics 19(4), 591 (2012).
13. Chang, J.B., Small, K.H., Choi, M. and Karp, N.S.: Three-dimensional surface imaging in plastic surgery: foundation, practical applications, and beyond. Plastic and Reconstructive Surgery 135(5), 1295–1304 (2015).
14. Popat, H., Richmond, S., Marshall, D., and Rosin, P. L.: Three-dimensional assessment of functional change following Class 3 orthognathic correction–a preliminary report. Journal of Cranio-Maxillofacial Surgery 40(1), 36–42 (2012).
15. Yan, K.-X., Liu, L., Li, H.: Application of machine learning in oral and maxillofacial surgery. Artificial Intelligence in Medical Imaging 2(6), 104–114 (2021).
16. Liang, X., Yang, X., Yin, S., Malay, S., Chung, K.C., Ma, J. and Wang, K.: Artificial Intelligence in Plastic Surgery: Applications and Challenges. Aesthetic Plastic Surgery 45, 784–790 (2021).

17. Herlin, C., Subsol, G., Gilles, B., Captier, G. and Chaput, B.: Three-dimensional surface imaging is not enough for surgical simulation. Plastic and Reconstructive Surgery 137(1), 246e–247e (2016).
18. Popat, H., Richmond, S., Benedikt, L., Marshall, D., and Rosin, P. L.: Quantitative analysis of facial movement – A review of three-dimensional imaging techniques. Computerized Medical Imaging and Graphics 33(5), 377–383 (2009).
19. Edler, R., Rahim, M.A., Wertheim, D. and Greenhill, D.: The use of facial anthropometrics in aesthetic assessment. The Cleft Palate – Craniofacial Journal 47(1), 48–57 (2010).
20. Todd, S.A., Hammond, P., Hutton, T., Cochrane, S. and Cunningham, S.: Perceptions of facial aesthetics in two and three dimensions. European Journal of Orthodontics 27, 363–369 (2005).
21. Sharma, V.P., Bella, H., Cadier, M.M., Pigott, R.W., Goodacre, T.E.E. and Richard, B.M.: Outcomes in facial aesthetics in cleft lip and palate surgery: A systematic review. Journal of Plastic, Reconstructive & Aesthetic Surgery 65, 1233–1245 (2012).
22. Richmond, S., Wilson-Nagrani, C., Zhurov, A., Farnell, D., Galloway, J., Mohd Ali, A. P. P., and Katic, V.: Factors influencing facial shape. Evidenced Based Orthodontics. Wiley Blackwell, 69–81 (2018).
23. Chen, W., Qian, W., Wu, G., Chen, W., Xian, B., Chen, X., Cao, Y., Green, C.D., Zhao, F., Tang, K. and Han, J.D.J.: Three-dimensional human facial morphologies as robust aging markers. Cell Research 25(5), 574–587 (2015).
24. Shaffer, J.R., Orlova, E., Lee, M.K., Leslie, E.J., Raffensperger, Z.D., Heike, C.L., Cunningham, M.L., Hecht, J.T., Kau, C.H., Nidey, N.L. and Moreno, L.M.: Genome-wide association study reveals multiple loci influencing normal human facial morphology. PLoS Genetics 12(8), e1006149 (2016).
25. Hammond, P.: The use of 3D face shape modelling in dysmorphology. Archives of Disease in Childhood 92(12), 1120 (2007).
26. Hallgrímsson, B., Aponte, J.D., Katz, D.C., Bannister, J.J., Riccardi, S.L., Mahasuwan, N., McInnes, B.L., Ferrara, T.M., Lipman, D.M., Neves, A.B., and Spitzmacher, J.A.: Automated syndrome diagnosis by three-dimensional facial imaging. Genetics in Medicine 22(10), 1682–1693 (2020).
27. Hassan, B., Greven, M. and Wismeijer, D.: Integrating 3D facial scanning in a digital workflow to CAD/CAM design and fabricate complete dentures for immediate total mouth rehabilitation. The Journal of Advanced Prosthodontics 9(5), 381–386 (2017).
28. Swennen, G.R., Pottel, L. and Haers, P.E.: Custom-made 3D-printed face masks in case of pandemic crisis situations with a lack of commercially available FFP2/3 masks. International Journal of Oral and Maxillofacial Surgery 49(5), 673–677 (2020).
29. Stephan, C.N., Caple, J.M., Guyomarch, P., and Claes, P.: An overview of the latest developments in facial surface imaging. Forensic Sciences Research 4(1), 10–28 (2019).
30. Rocha, S.D.S., Ramos, D.L.D.P., and Cavalcanti, M.D.G.P.: Applicability of 3D–CT facial reconstruction for forensic individual identification. Pesquisa Odontológica Brasileira 17(1), 24–28 (2003).
31. Lee, W.J., Wilkinson, C. M., and Hwang, H. S.: An accuracy assessment of forensic computerized facial reconstruction employing cone-beam computed tomography from live subjects. Journal of Forensic Sciences 57(2), 318–327 (2012).
32. Wilkinson, C.M., Roughley, M., Moffat, R.D., Monckton, D.G., and MacGregor, M.: In search of Robert Bruce, part I: craniofacial analysis of the skull excavated at Dunfermline in 1819. Journal of Archaeological Science: Reports 24, 556–564 (2019).
33. Alexandre, G.R., Soares, J.M., and Thé, G.A.P.: Systematic review of 3D facial expression recognition methods. Pattern Recognition 100, 107108 (2020).

34. Jan, A., Ding, H., Meng, H., Chen, L., and Li, H.: Accurate facial parts localization and deep learning for 3D facial expression recognition. In 2018 13th IEEE International Conference on Automatic Face & Gesture Recognition (FG 2018) (pp. 466-472). IEEE (2018).
35. Vandeventer, J.: 4D (3D Dynamic) Statistical Models of Conversational Expressions and the Synthesis of Highly-Realistic 4D Facial Expression Sequences. Ph.D. Thesis, Cardiff University, Cardiff, UK, (2015).
36. Vandeventer, J., Gräser, L., Rychlowska, M., Rosin, P.L. and Marshall, A.D.: Towards 4D coupled models of conversational facial expression interactions. In Proceedings of the British Machine Vision Conference; BMVA Press: Durham, United Kingdom 142–141 (2015).
37. Okuwobi, I. P., Chen, Q., Niu, S., and Bekalo, L.: Three-dimensional (3D) facial recognition and prediction. Signal, Image and Video Processing 10(6), 1151–1158 (2016).
38. Kaur, P., Krishan, K., Sharma, S. K., and Kanchan, T.: Facial-recognition algorithms: A literature review. Medicine, Science and the Law 60(2), 131–139 (2020).
39. Zhurov A.I., Richmond S., Kau C.H., and Toma A.: Averaging Facial Images. In: Kau C.H., Richmond S. (eds.). Three-Dimensional Imaging for Orthodontics and Maxillofacial Surgery. Wiley-Blackwell (2010).
40. Richert, R., Goujat, A., Venet, L., Viguie, G., Viennot, S., Robinson, P., Farges J.-C., Fages, M. and Ducret, M.: Intraoral scanner technologies: a review to make a successful impression. Journal of Healthcare Engineering, 8427595 (2017).
41. Evans, S., Jones, C., and Plassmann, P.: 3D imaging in forensic odontology. Journal of Visual Communication in Medicine 33(2), 63–68 (2010).
42. Evans, S., and Plassmann, P.: 3D image capture for the analysis of bite mark injuries. Journal of Biocommunication 37(2-3), 36–42 (2011).
43. Child Protection Evidence Systematic Review on Bruising. Report by the Royal College of Paediatrics and Child Health (RCPCH) (2020).