Institution: Cardiff University

Unit of Assessment: 11

Title of case study: Realising the potential of 3D scanners through reverse engineering and digital shape reconstruction

1. Summary of the impact (indicative maximum 100 words)

3D scanning technology has enabled multiple opportunities for innovation in diverse areas such as manufacturing, design, and the arts. However, *full* utilisation of this technology requires not just the scanning hardware, but accompanying software that can build meaningful, editable models. This development has been pioneered by research conducted in the School of Computer Science and Informatics, at Cardiff University. Innovative algorithms for reverse engineering and digital shape reconstruction were devised that enabled the reconstruction of complex computer aided design (CAD) models from data captured by 3D scanners. The algorithms have been endorsed by Geomagic Inc, a market leading American software corporation (recently acquired by 3D Systems), that has subsidiaries in Europe and Asia and global distributors, and incorporated into their software product suite. This is accessed by nearly 10,000 licensed users worldwide, who have applied the product for industrial applications including aerospace and automotive engineering, product design, cultural heritage preservation, and healthcare. Accordingly, the impacts claimed are twofold: a) economic gain manifesting in the benefits to Geomagic and a plethora of end users who have utilised the software, b) impact on practitioners and professional services in diverse domains.

2. Underpinning research (indicative maximum 500 words)

3D scanners, coupled with 3D printers, allow copying of shapes, but a much more useful idea is to perform *reverse engineering*. Analysis of the captured point cloud, decomposing it, and using it to build a CAD model allows many other downstream engineering processes, such as shape editing for new applications and shape indexing in databases – compare the analogous benefits provided by using OCR to analyse scanned text rather than simple photocopying. This vision was put forward by Cardiff and their partners in the late 1990s; they also defined a pipeline of steps needed to put it into practice [3.1]. The work has been cited over 600 times, and can be claimed to have laid the foundation for today's CAD reverse engineering industry. Cardiff's algorithms for steps of the pipeline have also been incorporated into **Geomagic Studio**, a world-leading commercial product at the forefront of this industry.

Most of the work to realise the pipeline was done in an EU-funded project in which the main developments came from a Cardiff University team involving Prof R R Martin and Prof A D Marshall, and the Geometric Modelling team at the Hungarian Academy of Sciences, led by Dr T Varady. The EU project and subsequent work up to 2002 devised algorithmic techniques for solving many of the sub-problems identified in the original reverse engineering pipeline [3.2-3.6].

In 2003, Varady was recruited to Geomagic, the world's leading software provider in this field. Varady served as Geomagic's Chief Technology Officer and Chief Technology Adviser from 2003 to 2010. During this period, he was responsible for incorporating key elements of the Cardiff work – including the pipeline [3.1] and several of the algorithms in [3.2-3.6] – into new components of the Geomagic Studio product (including Geomagic Shape in 2003 and Geomagic Fashion in 2009). He commented, in 2011, that 'Prof Martin's outstanding research … represents a series of important technological innovations which have strengthened the competitiveness of Geomagic Studio'.

The research essentially covers nearly every sub-problem that must be solved during shape reconstruction. This includes registering and combining scans from different viewpoints, data thinning, computing basic geometric properties, and removing noise from input scanner data while preserving sharp features. Segmentation [3.2, 3.4] – grouping points into clusters corresponding to different parts of the object – and surface fitting [3.2, 3.3, 3.5] – choosing and fitting an appropriate surface model to each part – are interrelated problems which must be considered both independently and in combination. Additionally, stitching [3.2] the surfaces into a complete CAD model requires care; surfaces may meet in sharp edges, or smooth blends of fixed or varying radius [3.6]. It may be necessary to build models from objects with wear due to use; numerical and scanning errors also lead to sub-optimal results when each surface is treated independently. To make models which are more likely to represent the original engineering design intent, Cardiff's algorithms detect potential regularities, congruences and symmetries in the data, and use them to build constrained models [3.3]. Such geometric constraints can then be preserved when models are edited for redesign, or used to simplify finite element analysis.

Cardiff researchers and roles during the research period: RR Martin (Senior Lecturer 1997-2000; Professor 2000-present), AD Marshall (Lecturer 1997-2000; Senior Lecturer 2000-2004; Reader 2004-2010; Professor 2010-present), G Kós (RA, 2000), G Lukacs (RA, 1998).

3. References to the research (indicative maximum of six references)

[Scopus citation counts, where available, are correct as of 18/10/13]

3.1 Varady T, **Martin RR** and Cox J. Reverse engineering of geometric models—an introduction. *Computer-Aided Design* 29(4):255-268, 1997. First paper to set out the tasks to be solved to carry out reverse engineering, providing a research agenda for the subject. [613 Scopus citations] http://dx.doi.org/10.1016/S0010-4485(96)00054-1

3.2 Benkő P, **Martin RR** and Várady T. Algorithms for reverse engineering boundary representation models. *Computer-Aided Design* 33(11):839-851, 2001. Solved several key problems in data segmentation, swept surface reconstruction, blend reconstruction and model building. [107 Scopus citations] http://dx.doi.org/10.1016/S0010-4485(01)00100-2

3.3 Benkő P, Kós G, Várady T, Andor L and **Martin RR**. Constrained fitting in reverse engineering. *Computer Aided Geometric Design* 19(3):173-205, 2002. Shows how to ensure multiple fitted surfaces meet engineering constraints, such as perpendicularity, coaxiality, etc. [112 Scopus citations] http://dx.doi.org/10.1016/S0167-8396(01)00085-1

3.4 **Martin RR**, Lukacs G, and **Marshall AD**, Robust segmentation of primitives from range data in the presence of geometric degeneracy. *IEEE Trans. Pattern Analysis and Machine Intelligence* 23(3):304-314, 2001. Gives algorithms to robustly segment spheres, cones and cylinders from scanner data. [98 Scopus citations] http://dx.doi.org/10.1109/34.910883

3.5 **Lukacs G**, **Martin RR** and **Marshall AD**, Faithful least-squares fitting of spheres, cylinders, cones and tori for reliable segmentation. In *Proc European Conference on Computer Vision*, pages 671-686, 1998. Provides methods that degrade gracefully as surfaces become flatter and tend to surfaces of a simpler type. http://dx.doi.org/10.1007/BFb0055697

3.6 **Kós G**, **Martin RR** and Várady T. Methods to recover constant radius rolling ball blends in reverse engineering, *Computer Aided Geometric Design* 17(2), 127-160, 2000. Shows how to handle minor blend surfaces, linking primary surfaces, as typically found in real-world objects. [38 Scopus citations] http://dx.doi.org/10.1016/S0167-8396(99)00043-6

4. Details of the impact (indicative maximum 750 words)

We first discuss direct economic benefits to Geomagic before describing wider impact on practitioners and professional services, many of which carry further economic benefits.

<u>**Economic Impact**</u> **-** Cardiff University's research has orchestrated significant economic benefits for Geomagic. The pipeline and algorithms form integral parts of Geomagic Studio, the company's flagship product. This has provided important new functionalities that have considerable advantages over competitive software products. Geomagic studio now builds CAD models which respect the design intent of the scanned original object – unlike other software which fits a single global surface or needs intensive user interaction to fit multiple independent surfaces, lacking the

constraints needed for a coherent overall design. Previously this facility was not possible but Geomagic are now able to publicly claim that Geomagic Studio has 'The industry's most accurate and comprehensive 3D scan data processing capabilities' (http://www.geomagic.com/en/products/studio/features/). Tamas Varady, who served as Geomagic's chief technical officer from 2003-2010 states [5.1] that Prof Martin's outstanding research has "helped to ensure a leading market position for the product and provide a basis for Geomagic to retain that leadership well into the future. The algorithms based on Prof. Martin's research are now integral parts of *Geomagic Studio*, and thus used by many thousands of industrial users."

The revenue and corporate value of Geomagic has markedly increased since the implementation of the research. During the REF period there were 10,000 licensed users, with current pricing ranging from $8,000 to $30,000. [5.1,5.2] The CEO of Geomagic stated that during 2008-2013 'annual revenue growth has exceeded 20%..despite very bad market conditions'. The company reports that it approached by multiple buyers in 2012-2013 but a sale was agreed in January with 3D systems for $55 million. 3D Systems have commented that they expect Geomagic to be 'accretive to earnings and contribute approximately $17 million of revenue over the next year' [5.3].

Impact on Practitioners and Professional Services - The innovative and pioneering features of Geomagic Studio, implemented as a direct consequence of the research, have enabled new approaches to be adopted in a wide range of industries and areas including engineering, product design, medicine and cultural activities. The novel capacity to allow nearly every sub-problem of shape reconstruction has, for example, benefited aerospace and automotive engineering through the ability to capture existing components for computational fluid dynamic and finite element analysis. Alternative product designs can also be rapidly assessed by making and scanning physical prototypes to turn into computer models, which can be analysed and modified, and then used as a basis for computer aided manufacturing. Classic handcrafted designs can be re-used in a manufacturer's latest products. Analysis can be performed on actual rather than ideal shapes – alleviating problems with manufacturing processes that often result in objects whose shapes differ slightly from the design. Furthermore, in art and archaeology, digital models allow restoration and reconstruction of objects from fragments, as well as enabling a permanent record, and wider access by public and scientists to rare and precious artefacts. In medicine and dentistry, prostheses can be tailored to an individual patient much more quickly and accurately than by previous handcrafting, and treatment planning can be based on an individual patient rather than a generic anatomical model.

These industry applications have generated far-reaching social and economic gain. Specific examples are provided below and a further 40 significant cases are evident from the company's website [5.4]:

Motor Industry Research Association, UK – special vehicles, engineering analysis of existing designs [5.5]. When there is no original design information available, accurate 3D digital models of components or vehicles can be made as the basis for new designs and analysis processes, facilitating downstream engineering activities. According to a Senior Engineer: "There's no doubt that the use of Geomagic Studio has enabled us to offer services that we couldn't offer before. More than that though, perhaps the biggest benefit internally is that with a 3D digital model, management can see what is being done and can have confidence in the process, as well as in the end result."

Shriners Hospital, USA – planning a new treatment for severe cleft lip and palate [5.6]. Here, reverse engineering leads to a less invasive, computer-controlled process with more consistent results and greater accuracy in correcting the growing palate and gum shape prior to lip repair.

Greenhatch Group Ltd / English Heritage – cultural preservation: modelling of Stonehenge [5.7]. Geomagic Studio was used to create the highest resolution, most dimensionally accurate 3D digital model ever of Stonehenge.

Royal Australian Air Force – aircraft inspection & repair [5.8]. Traditional processes for crack repair, which previously could take up to six weeks, were reduced to just one day in the best case.

Timberland, USA – last design for shoes [5.9]. Timberland currently produces over 100 lasts per year. Switching to a process based on reverse engineering reduced the need for last rework by 75%. Large time-savings come from being able to modify lasts quickly, and by digitally transferring 3D last files to overseas factories instead of physical products. Timberland state that "if we effectively employed technology tools such as Geomagic and rapid prototyping to reduce the design and development segment of the cycle, the possibility exists to produce 75 to 90 styles every three months… it could mean a 25 percent increase in revenue since buyers will have additional opportunities to place new and original Timberland products in their stores."

Germanic Studio Helps German Police Force [5.10]. Reverse engineering was used to redesign motorcycle luggage compartments to carry speed detection and video recording equipment for unmarked autobahn policing vehicles.

5. Sources to corroborate the impact (indicative maximum of 10 references)

5.1 Testimony from former Chief Technology Officer / Chief Technology Advisor of Geomagic (2003-2010) *Corroborates the important contribution of the Cardiff University team to algorithms underpinning Geomagic Studio and the number of users.*

5.2 http://www.dirdim.com/prod_software.htm *Corroborates the price range of Geomagic products.* [Saved as PDF 25/7/13; available on request from HEI]

5.3 http://geomagic.com/en/community/press-releases/3d-systems-completes-the-acquisition-of-geomagic/ *Corroborates the financial information relating to the sale of Geomagic and revenue figures.* [Saved as PDF 25/7/13; available on request from HEI]

5.4 http://www.geomagic.com/en/community/case-studies/byproduct/18/ *Case studies corroborating range of uses of Geomagic Studio.* [saved as PDF 25/7/13; available on request from HEI]

5.5 MIRA case study, 15 April 2009: http://www.geomagic.com/en/community/case-studies/geomagic-software-helps-mira-increase-the-scope-of-its-automotiv/ *Case study corroborating use of Geomagic Studio by MIRA.* [Saved as PDF 25/7/13; available on request from HEI]

5.6 Shriners Hospital case study, October 2009: http://www.geomagic.com/en/community/case-studies/new-treatment-from-shriners-hospital-uses-geomagic-studio-to-bri/ *Case study corroborating use of Geomagic Studio by Shriners Hospital.* [Saved as PDF 25/7/13; available on request from HEI]

5.7 Stonehenge case study, 25 October, 2011: http://www.geomagic.com/en/community/press-releases/geomagic-3d-imaging-software-used-to-create-most-accurate-3d-dig/ *Case study corroborating use of Geomagic Studio by English Heritage.* [Saved as PDF 25/7/13; available on request from HEI]

5.8 RAAF case study (originally reported June 2006 though RAAF has continued to operate the Tornado aircraft during 2008-2013): http://www.geomagic.com/en/community/case-studies/australian-air-force-reduces-time-on-ground-with-geomagic-revers/ *Case study corroborating use of Geomagic Studio by RAAF.* [Saved as PDF 25/7/13; available on request from HEI]

5.9 Timberland case study, January 2009: http://www.geomagic.com/en/community/case-studies/timberland-uses-geomagic-reverse-engineering-software-to-reinven/ *Case study corroborating use of Geomagic Studio by Timberland.* [Saved as PDF 25/7/13; available on request from HEI]

5.10 German police force case study, 26 March 2010: http://www.pddnet.com/news-geomagic-studio-helps-german-police-force-032610/ *Case study corroborating use of Geomagic Studio by German police force.* [Saved as PDF 25/7/13; available on request from HEI]