Low cost three-dimensional virtual model construction for remanufacturing industry.

Muftooh UR Siddiqi[1§], Winifred L. Ijomah[1], Gordon I. Dobie[2], Mutahir Hafeez[1], S. Gareth Pierce[2], William Ion[1], Carmelo Mineo[2], Charles N. MacLeod[2]

[1]Department of Design, Manufacture & Engineering Management, Faculty of Engineering, University of Strathclyde, Glasgow, UK.

[2]Department of electronic & electrical engineering, Faculty of Engineering, University of Strathclyde, Glasgow, UK.

Email addresses:

MURS: muftooh.siddiqi@strath.ac.uk
WLJ: w.l.ijomah@strath.ac.uk
GID: gordon.dobie@strath.ac.uk
MH: muthair.hafeez@strath.ac.uk
SGP: s.g.pierce@strath.ac.uk
WI: w.j.ion@strath.ac.uk
CM: carmelo.mineo@strath.ac.uk
CNM: charles.macleod@strath.ac.uk

Abstract

Remanufactured products can save up to 80% of production and energy costs whilst generating lower CO^2 emissions. The key success factors for remanufacturing are quality, lead-time and cost. Extensive work within the industry and the detailed analysis of the remanufacturing process has shown that component inspection has significant bearing on overall productivity. Currently, the remanufacturing process is performed manually. Automation of remanufacturing process will not only decrease the number of non-remanufacturable components, through decreasing cost and increasing consistency in quality, but also attract industries to design for remanufacture. In current work an automotive engine (in as received condition) is 3D reconstructed virtually, using the Visual Structure for Motion (VSFM) technique. These initial experiments assess the feasibility of using Videogrammetry to acquire pre-disassembly 3D model of the engine. Multiple 2D images were acquired and processed to find matching common features. The location of the camera was calculated through the matching features, producing a three-dimensional digital representation of the captured volume. A sparse point cloud was initially created and was then converted into a dense 3D point cloud. The 3D point cloud was converted into a meshed model. 2D images are stitched together to create a virtual model of the engine with surface texture and colour. Small features of a few millimetres in size are clearly visible in the 3D model.

Key words: Remanufacturing, 3D reconstruction, machine vision, Digital Manufacturing.

Introduction

Remanufactured products can save up to 80% in production and energy costs whilst generating lower CO^2 emissions. Up to 85% of a remanufactured product's weight can come from used parts thus reducing environmental and recycling impacts. The key remanufacturing success factors are quality, lead-time and cost [1]. Currently, the remanufacturing process is performed manually. It is crucial to apply emerging technologies and concepts in digital manufacturing to remanufacturing to exploit its full potential whilst reducing lead time and cost [2-5]. In current work, initial experiments are performed to assess the feasibility of Videogrammetry to acquire pre-disassembly 3D model of the engine. The application of this vision based technique will help automate the remanufacturing process.

Sustainable and Digital manufacturing

The most important strategy to deal with the rising threat of climate change is to opt for a low carbon economy which will enable reductions in pollution, emission of greenhouse gases and energy consumption [6, 7]. Recent legislation and engineering accomplishments have reduced automotive emissions. Improved automotive component utilization, specifically the engine, is being achieved through remanufacturing. [8]. This work is part of an ongoing research focusing on remanufacture of engines, using robots and digital technology. The application of cost effective digital technology such as 3D reconstruction and visualisation will help to broaden the spectrum of remanufactured products and incorporate automation.

Cloud-based design manufacturing (CBDM) systems incorporate communication and information infrastructure and employs the internet of things (IOT) to merge design and manufacturing related data [9]. The essence of this system is to present physical systems and objects e.g. an engine) in digital form, and connect humans with machines [10]. These data can then be used to automate the remanufacturing process or for other purposes, such as inspection. The concept of CBDM can be directly used to remanufacture products, in areas such as design for remanufacturing, reverse supply chain management, information management, automation, inspection and metrology. Metrology has been widely used in many areas to capture the dimensional deviations of parts geometries [11].

Metrology

The data generated through 3D-Metrology can be effectively used in remanufacturing, reverse engineering, quality control and simulations. Thanks to the recent advancements of technology, three-dimensional geometric measurement can be done by either interacting with the given component mechanically (contact metrology) or radiometrically (non-contact metrology) [12]. Over the last few decades, non-contact metrology technologies have made a big contribution to precise manufacturing and cost reduction. Cost reduction of remanufactured parts is always a big challenge for remanufacturers of automotive components. There are various kinds of non-contact metrology devices used to manufacture automotive components (e.g. engines), but it is a big challenge to define appropriate metrology technology, techniques and devices, which could be utilized to remanufacture components. There are several non-contact metrology techniques to measure components, such as laser scanning [13], laser tracking [14], structured light techniques [15], 3D reconstruction [16]. Comparisons of these techniques are provided in Table 1. Although most of these methods are used extensively in the manufacturing industry, 3D reconstruction was selected because of the additional information which can be acquired through this method, such as colour and texture [17]. Furthermore, this technique is low cost and easy to use.

Table 1 - Comparison of non-contact metrology techniques.

	Cost (£)	**Inspection range (m)**	**Resolution (mm)**	**Speed (points per sec)**	**Accuracy (mm)**
Structured Light Scanner	2000-5000	up to 2	up to 0.1	up to 1,300,000	up to 0.05
Laser tracked scanner	500-3000	up to 35	0.0005	up to 10,000	up to 0.016
Scan arms	4000-18000	up to 3.65	0.0254	up to 450,000	0.025-0.1
Portable Scanners	250-2000	0.2–6	0.050	up to 205,000	up to 0.1
3D Structure from motion	25-500	up to 1000	8688x5792 pixels	up to 255,045	up to 0.72

Data acquisition through 3D reconstruction

It is now possible to reconstruct components' geometry due to the advancements in data acquisition and digitization techniques [18]. 3D reconstruction is widely used for large scale buildings and cultural heritage, by means of photogrammetry methods that produce significant improvements in accuracy and scalability. Most of the photos used to be taken from ground level so the Multi-view stereo (MVS) reconstructed data was normally very detailed [2, 19-22]. This technique has not been used in the context of manufacturing or remanufacturing. Appropriately reconstructed components can decrease the cost of remanufacturing by facilitating metrology and robot path-planning. Moreover, remanufacturers often do not have access to components' original CAD files and technical drawings, required to remanufacture the components. 3D reconstruction techniques also provide additional data, such as surface texture and colour [17], which help to digitize the remanufacturing processes. This is one of the reasons why such techniques have been preferred to other non-contact metrology techniques. SFM is applied to reconstruct the surface geometry and texture of an "as received" automotive engine.

Structure for Motion

SFM integrates point matching, feature extraction and existing knowledge of vision systems [22, 23]. Generally, SFM has been used either with a limited number of images or using costly commercial software such as Autodesk remake [24], Agisoft [25] to combine large numbers of images. Currently, open-source SFM packages such as VSFM [17] and OpenMVG [26] are available. It is a low-cost method generally used in multi temporal surveys [25]. These packages offer fast and free processing of several thousand of images and produce results comparable to commercial software.

Aim and methodology

The main purpose of this research work is to demonstrate the usability of SFM technique for remanufacturing, by 3D reconstructing an automotive engine. In the next step of this research, the authors intend to improve and integrate 3D reconstruction to robotics for remanufacturing processes.

In this work, video-based photogrammetry (Videogrammetry) was used to acquire data. Videogrammetry is already applied in industrial manufacturing and robotics [27]. SFM techniques are not fool proof though; various parameters such as dynamic background, rapid movement of the camera, shiny surfaces and extreme changes in light can complicate the reconstruction process. Different types of features, background and different amounts of overlap between the pictures affect the reconstruction quality and time. Thus a video was taken with consistent background and lightning. A 3D model was reconstructed through the SFM technique using a sequence of images, without prior knowledge of the camera pose (location, orientation and field of view). Although it uses several modern techniques for detection of key points and dense reconstruction, it also borrows methods developed for classic photogrammetry, such as self-calibrating bundle adjustment [28] to automatically estimate the camera pose. Viewing parameters and 3D structure of a scene was simultaneously solved through SFM while using multiple feature recognition algorithms and computer vision techniques. The output meshed model was saved in Stereo-Lithography format (STL), which can be used for manufacturing and remanufacturing purposes.

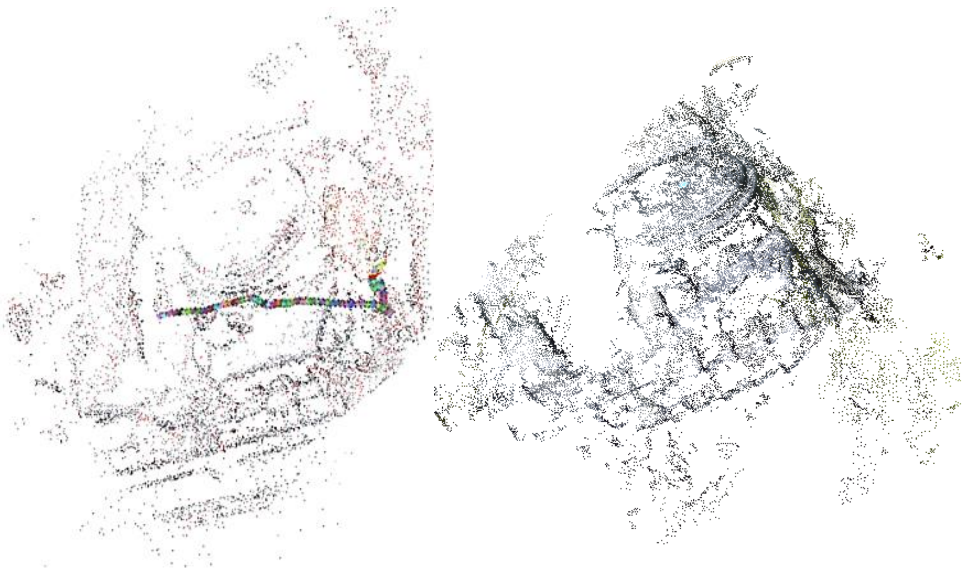
Results and discussion

A smartphone camera of 16 megapixel, 4.3mm focal length and F1.9 aperture was used for current work. This information increases the quality of the reconstruction. The use of a smartphone demonstrates the low cost characteristic of the reconstruction method. It can be easily accessible by the remanufacturers with no particular setup required. Another advantage is that the user can monitor the acquisition of the video and of the pictures in real-time, thus improving the data acquisition process. An ultra-high definition video with frame size of 3840 by 2160 pixels was acquired and images were then extracted from the video stream (see Figure 1). VSFM compares every image in a set with every other one to find the best match. Although this technique guarantees to find the best match, the time taken to complete the 3D reconstruction increases exponentially with the number of pictures. The advantage of using a video footage is that it restricts the comparison within neighbouring images. Thus, reconstruction time is reduced to a linear relationship, which allows for much larger datasets to be used in the reconstruction. This approach provided with necessary overlap between the pictures and did not compromise the performance of the SIFT algorithm, as VSFM resize images and corrects radial distortion before processing.

Figure 1 - As received automotive engine.

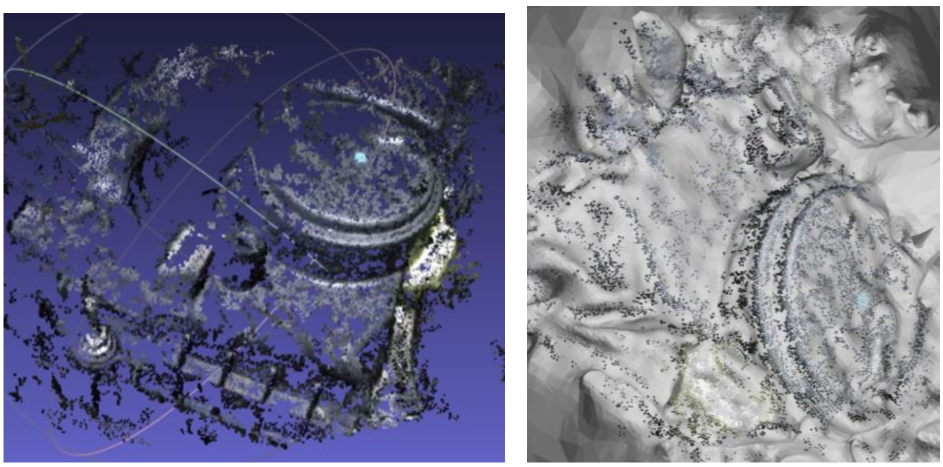
The SFM process for the engine was based on the following steps: (1) feature detection, (2) alignment, (3) bundle adjustment and (4) reconstruction. SFM is available under the Berkeley Software Distribution (BSD) License [23]. The set of features defined by SIFT can contain outliers or points not common to both images (depending on the overlap). VisualSFM quickly and robustly matches images by using the iterative technique RANdom SAmple Consensus (RANSAC) [29], which constructs an eight-point alignment model in linear time. Bundle adjustment refines a visual reconstruction to jointly produce the optimal 3D structure and the viewing parameters. Sparse point-cloud (PC) with camera locations and dense point-cloud are shown in Figure 2a. After bundle adjustment, VSFM uses multi-view stereo (CMVS) [30, 31] to create a dense point cloud from the scene as, shown in Figure 2b. 15,561 points were created through 101 pictures extracted from the video for the engine.

Although this work does not aim to compare the obtained models with the outcomes from other scanning techniques, it can be performed through the STL output and the post-processing steps, using an algorithm available in the Cloudcompare software. The point-cloud was used to create a polygonal mesh of the geometry using the Meshlab software [Figure 3]. While several post-processing tools are available, Meshlab was selected due to its flexible post-processing and editing capabilities. The point-cloud was loaded in the Meshlab. Then it was cleaned; outlier points were removed from the cloud through the appropriate Meshlab tools. The point-cloud was finally used to create a smooth and textured mesh.



(a) (b)

Figure 2- Point cloud; (a) Sparse PC of engine with camera location, (b) Dense PC of engine with colour.



(a) (b)

Figure 3- Virtual models in Meshlab: (a) Textured Mesh of Engine, (b) Un-smoothened surface of engine.

The smoothened surfaces were rendered and texture was applied to create a 3D virtual model of the as received engine, as respectively shown in Figure 4. Not only the colours are exact in the virtual model but details of even a few millimetres, such as the small truss and the folded tape can be easily observed on the virtual model of the engine. Future work will use this process for the automation of remanufacturing.

Figure 4- Virtual model of Engine.

Conclusion

Mostly, remanufacturers do not have access to the component's technical drawings, CAD models, surface features and texture. Conventional optical metrology methods used in the manufacturing industry to acquire this data are expensive and require expertise. Initial experiments were performed to check the feasibility of using Videogrammetry with a low-cost 3D reconstruction method VSFM. A 3D Virtual model of an automotive engine including geometry, surface texture and colour was developed using a cell-phone camera. Future work will use this process for metrology, robotic path planning and inspection purposes in order to enhance remanufacturing productivity.

Acknowledgements:

This work was supported by the Engineering and Physical Sciences Research Council funding for Autonomous Inspection in Manufacturing & Remanufacturing (AIMaReM) [EP/N018427/1]. The authors will also like to thank Dr. Rahul Summan for his suggestions.

References

1. Ijomah, W., et al., *Development of robust design-for-remanufacturing guidelines to further the aims of sustainable development.* International Journal of Production Research, 2007. **45**(18-19): p. 4513-4536.
2. Chu, P.M., et al., *3D Reconstruction Framework for Multiple Remote Robots on Cloud System.* Symmetry, 2017. **9**(4): p. 55.
3. Holmström, J., et al., *The direct digital manufacturing (r)evolution: definition of a research agenda.* Operations Management Research, 2016. **9**(1): p. 1-10.
4. Fargani, H., W.M. Cheung, and R. Hasan, *An Empirical Analysis of the Factors That Support the Drivers of Sustainable Manufacturing.* Procedia CIRP, 2016. **56**: p. 491-495.
5. Chiodo, J. and W. Ijomah, *Use of active disassembly technology to improve remanufacturing productivity: automotive application.* International Journal of Computer Integrated Manufacturing, 2014. **27**(4): p. 361-371.
6. Ali, G., S. Abbas, and F.M. Qamer, *How effectively low carbon society development models contribute to climate change mitigation and adaptation action plans in Asia.* Renewable and Sustainable Energy Reviews, 2013. **26**: p. 632-638.
7. Gonzalez, E.D., et al., *Making real progress toward more sustainable societies using decision support models and tools: introduction to the special volume.* Journal of Cleaner Production, 2015. **105**: p. 1-13.
8. Latham, G., *Vehicle Remanufacturing: Economic and Environmental Expansion of the Life Cycle*. 2016, SAE International.
9. Foster, I., et al. *Cloud computing and grid computing 360-degree compared*. in *Grid Computing Environments Workshop, 2008. GCE'08*. 2008. Ieee.
10. Wu, D., et al., *Cloud-based design and manufacturing: A new paradigm in digital manufacturing and design innovation.* Computer-Aided Design, 2015. **59**: p. 1-14.
11. Stull, R.B., *Meteorology for scientists and engineers: a technical companion book with Ahrens' Meteorology Today*. 2000: Brooks/Cole.
12. Nishikawa, S., et al., *Non-contact type on-machine measurement system for turbine blade.* Procedia Cirp, 2014. **24**: p. 1-6.
13. Son, S., H. Park, and K.H. Lee, *Automated laser scanning system for reverse engineering and inspection.* International Journal of Machine Tools and Manufacture, 2002. **42**(8): p. 889-897.
14. Aguado, S., et al., *Identification strategy of error parameter in volumetric error compensation of machine tool based on laser tracker measurements.* International Journal of Machine Tools and Manufacture, 2012. **53**(1): p. 160-169.
15. Tsai, M.-J. and C.-C. Hung, *Development of a high-precision surface metrology system using structured light projection.* Measurement, 2005. **38**(3): p. 236-247.
16. Crandall, D., et al. *Discrete-continuous optimization for large-scale structure from motion*. in *Computer Vision and Pattern Recognition (CVPR), 2011 IEEE Conference on*. 2011. IEEE.

17. Wu, C., J.-M. Frahm, and M. Pollefeys, *Detecting large repetitive structures with salient boundaries.* Computer Vision–ECCV 2010, 2010: p. 142-155.
18. Franceschini, F., et al., *Large-scale dimensional metrology (LSDM): from tapes and theodolites to multi-sensor systems.* International Journal of Precision Engineering and Manufacturing, 2014. **15**(8): p. 1739-1758.
19. Mohanarajah, G., et al., *Cloud-based collaborative 3D mapping in real-time with low-cost robots.* IEEE Transactions on Automation Science and Engineering, 2015. **12**(2): p. 423-431.
20. Hugenholtz, C.H., et al., *Geomorphological mapping with a small unmanned aircraft system (sUAS): Feature detection and accuracy assessment of a photogrammetrically-derived digital terrain model.* Geomorphology, 2013. **194**: p. 16-24.
21. Wu, C. *Towards linear-time incremental structure from motion*. in *3DTV-Conference, 2013 International Conference on*. 2013. IEEE.
22. Shan, Q., et al. *Accurate geo-registration by ground-to-aerial image matching*. in *3D Vision (3DV), 2014 2nd International Conference on*. 2014. IEEE.
23. Byrne, J., et al., *3D Reconstructions Using UnstabilizedVideo Footage from an Unmanned Aerial Vehicle.* Journal of Imaging, 2017. **3**(2): p. 15.
24. Flores, D., D. Marcillo, and J. Pereira, *3D Scanner Based on an Autonomous Wi-Fi Unmanned Mini Quadcopter*, in *Recent Advances in Information Systems and Technologies: Volume 3*, Á. Rocha, et al., Editors. 2017, Springer International Publishing: Cham. p. 551-558.
25. Francis, C.M., *Enhancing cultural resource documentation with terrestrial photogrammetry*. 2016, Northern Arizona University.
26. Moisan, L., P. Moulon, and P. Monasse, *Automatic homographic registration of a pair of images, with a contrario elimination of outliers.* Image Processing On Line, 2012. **2**: p. 56-73.
27. Bailey, T. and H. Durrant-Whyte, *Simultaneous localization and mapping (SLAM): Part II.* IEEE Robotics & Automation Magazine, 2006. **13**(3): p. 108-117.
28. Triggs, B., et al., *Bundle Adjustment — A Modern Synthesis*, in *Vision Algorithms: Theory and Practice: International Workshop on Vision Algorithms Corfu, Greece, September 21–22, 1999 Proceedings*, B. Triggs, A. Zisserman, and R. Szeliski, Editors. 2000, Springer Berlin Heidelberg: Berlin, Heidelberg. p. 298-372.
29. Fischler, M.A. and R.C. Bolles, *Random sample consensus: a paradigm for model fitting with applications to image analysis and automated cartography.* Communications of the ACM, 1981. **24**(6): p. 381-395.
30. Furukawa, Y. and J. Ponce, *Accurate, dense, and robust multiview stereopsis.* IEEE transactions on pattern analysis and machine intelligence, 2010. **32**(8): p. 1362-1376.
31. Wu, C., *VisualSFM: A visual structure from motion system.* 2011.