euspen's 18th International Conference & Exhibition, Venice, IT, June 2018
www.euspen.eu

Photogrammetric coordinate metrology

Danny Sims-Waterhouse, Samanta Piano, Richard Leach

Manufacturing Metrology Team, University of Nottingham, UK

danny.sims-waterhouse@nottingham.ac.uk

Abstract
With the growing availability of micro-scale parts with highly complex geometries, there is a need for form measurement systems that operate over reasonable time frames. Although contact probe systems are able to provide the measurement accuracies required, the time taken to measure complex parts is unsuitable for many applications, and the contact nature of the probe may limit the geometries that can be accessed. As photogrammetry-based methods only require images in order to produce point clouds, data acquisition can be performed at high speed; the subsequent reconstruction process being the major time limiting factor. Recently, we have shown that photogrammetry is also able to achieve form measurement uncertainties on the order of 10 µm [1], suitable for parts with micro-scale features. In the work presented here, we measured a series of objects that exhibit key features representing the main challenges faced in coordinate metrology using photogrammetry systems, with various software and hardware adaptations. We then assess the current position of photogrammetry as an instrument for coordinate metrology and outline key areas of research required for photogrammetry to become an established metrological instrument. The key aspects of development to be discussed are the optical design, algorithms and measurement procedure development.

Photogrammetry, Micro-parts, Coordinate Metrology

1. Introduction

Photogrammetry uses a number of images of an object from different perspectives to determine the object's geometry and, as such, it has the potential to provide a fast and low-cost alternative to many coordinate metrology systems. In particular, the measurement of small parts with sub-millimetre features and complex geometries could be greatly accelerated through the use of photogrammetry.

Commercial applications of photogrammetry have mainly been limited to large-scale applications at around a metre [2]. Recently, with the development of technologies in imaging and reconstruction, the application of photogrammetry to the measurement of micro-scale features has become more common [3, 4]. However, limitations due to depth-of-field, optical resolution, reconstruction algorithms and feature recognition place constraints on the micro-scale applications of photogrammetry.

Not only do the physical components of the system play an important role in the use of photogrammetry in metrology, but the measurement procedure itself must be considered. However, because there is no general approach to measuring an object with photogrammetry, there is significant variation in the accuracy of photogrammetry measurements, even with similar specifications.

In this paper, several objects are measured using the system described in [1], demonstrating the current strengths and limitations of micro-scale photogrammetry systems. The key areas of development required to advance the use of photogrammetry in micro-part metrology are then discussed.

2. Part measurement

A set of objects that best represent the key benefits and challenges presented by photogrammetry have been measured and the results are presented in this section. Figure 1 shows a point cloud produced by the photogrammetric reconstruction of a gear. The gear represents a highly complex geometry that would take a significant amount of time to measure using contact techniques. However, using photogrammetry, the images of the gear can be taken in under two minutes and the subsequent reconstruction takes around ninety minutes. Although this time frame is still somewhat long, it is independent of the object geometry and dimension, and can provide a much faster measurement than contact methods. Figure 1 also shows the limitations of photogrammetry when measuring complex geometries. Due to the imaging process, the underside of the gear teeth is occluded from view and is not successfully reconstructed. This issue could be addressed by taking more images in order to cover the missing areas, however, more images would take longer to process. Another possibility would be to select appropriately the optimal camera poses for the measurement, based on the object geometry and features to measure.

Figure 1. 3D point cloud of a 21.8 mm radius gear produced by photogrammetry

2.1. Laser speckle projection

The main principle of photogrammetry is the process of finding correspondences between images from different perspectives. For surfaces with little observable texture, such as machined metal, there is typically insufficient texture to find correspondence. However, previous work on the development of a laser speckle based texture projection method allows textureless and near-specular objects to be measured [1]. Figure 2 shows the measurement of a near-specular machined surface that has been measured with the aid of laser speckle projection.

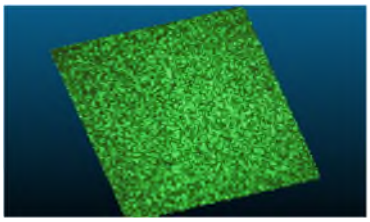

Figure 2. Near specular surface measured using laser speckle texture projection

Although laser speckle provides good correspondences on textureless surfaces, it incurs its own limitations. The size of the projected speckle intrinsically limits the spatial resolution of the measurement [5]. This in turn limits the minimum feature size that will be observable in any particular measurement. However, by tuning the spatial frequencie distribution of the speckle pattern, the spatial resolution of the measurement can be altered to meet a particular requirement.

2.2. Micro-scale features

The spatial resolution of a photogrammetry system is a trivial value to define by simply taking the physical size of the camera's pixels in space. However, as the reconstruction is dependent on the pixel size, optical resolution and feature detection accuracy, the resolution of the system is in fact difficult to define.

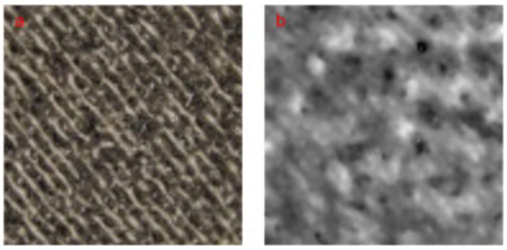

Figure 3. Colour (a) and depth map (b) information for a section of an additively manufactured metal part

As can be seen in figure 3, what is visible in the colour information of the reconstruction is not always seen in the height data. Whilst the blobs and holes are distinct in figure 3 (b), the printing tracks are much less obvious despite being clear in the colour data. As such, further work is required to better understand the resolution of a photogrammetry system, as well as the measurement uncertainty and accuracy.

3. Optical development

The optics used with the camera determine field-of-view, optical resolution and the depth-of-field of the images produced. Although the optics are typically chosen to achieve a particular magnification, this is done as a balance between depth-of-field and optical resolution. Given the high magnifications required to resolve micro-parts, depth-of-field becomes a significant issue and actions must be taken in order to substantially improve the depth-of-field of the imaging system. Attempts to address depth-of-field have already been made, in particular using focus stacking to produce images with a substantially extended depth-of-field [6, 7]. Although this method has been shown to be highly effective, the time required to acquire so many images negates this benefit of photogrammetry based methods.

Alternative methods of depth-of-field extension have also been explored, as such plenoptic, or light field, cameras capture the four dimensional light field information, allowing images to be reconstructed with a significantly improved depth-of-field [8]. Although plenoptic cameras provide an improved depth-of-field in a single shot, they do so at a significant reduction in spatial resolution. Despite the loss in spatial resolution, the improvement in the homogeneity of the reconstruction accuracy throughout the measurement volume further demonstrates the potential improvement. Through the integration of optical techniques for depth-of-field extension that do not result in the loss of spatial resolution, significant improvements to micro-part measurement can be made.

4. Algorithm development

Photogrammetric algorithms have mainly been developed to be robust to different camera orientations, intrinsic properties and environmental factors. Whilst photogrammetry algorithms also place high importance on accuracy, they disregard a significant amount of information about both the measurement system and the object being measured.

Typically in an environment in which an object will be measured, there will be stable lighting and some control over the motion of the camera. Additionally, the nominal geometry and surface properties of the object to be measured will also be known. The information about the system and the object measured provide a priori information that can potentially be used to improve both the speed of the reconstruction and the accuracy of the measurement. The use of a priori information could be implemented through better initialisation of the calibration process, or through the addition of terms in the minimisation equation.

5. Conclusion

In this paper, the potential of photogrammetry based methods for the measurement of micro-parts has been presented. Further to this, the key areas of work required to better establish photogrammetry as a measurement instrument have been outlined. The outcome of this work will be an optical coordinate measurement system capable of measuring micro-parts at a higher speed, with comparable accuracy to contact methods.

Acknowledgements

The authors would like to thank EPSRC (Grants EP/ M008983/1 and EP/L016567/1) for funding this work.

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