Investigating the liquid Characterising the surface quality of 3D printed optical elements using interference reflection microscopy

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Optical microscopy has used the same manufacturing methods for milling and sanding glass elements to produce high-quality optics for over a century. Recent developments in 3D printing have opened the possibility of printing optical components, but the surface quality of these 3D prints remains unknown. To address this, I designed and printed several planoconvex lenses using a consumer-grade 3D printer, and then experimented with various post-processing methods to improve the quality of the lens surface. I then used a confocal microscope set up in reflection mode to image the topology of the lens surface following different post-processing methods. This method produced constructive and destructive interference patterns on the lens, displayed as fringes corresponding to the axial position of the lens surface. I wrote my own code to reconstruct a 3D visualisation of the lenses using the interference fringe data and then calculated the radius of curvature of the 3D printed lens. This data was compared to the specifications of the CAD model that was printed. By the end of my studentship, I had developed a workflow for manufacturing 3D printed lenses and written a custom analysis script that was used to characterise and quantify their surface quality.

Figure 1. An overview of lenses printed during the project. Multiple lenses were printed and processed using different spin coating conditions, tested by IRM, and their surface profile characterised and compared to a glass lens of the same prescription. Each of the 3D printed lenses were printed with a thin raft surrounding the lens to ease handling, these rafts did not alter the optical parameters of the lenses.

What was the aim of your project?

The aim of this project was to develop a workflow to produce high-quality 3D printed optical elements and to develop a microscopy-based method to characterise the 3D printed lenses.

How did you address the aim?

I began the project using a 3D printer that used digital light processing (DLP) technology to produce 3D printed lenses. The DLP method uses ultraviolet (UV) light to project, layer-by-layer, a slice of the computational model of my lens onto an LCD screen in contact with a resin bath. The UV light caused photo-induced polymerisation of the liquid resin into a solid printed layer matching the projection. The lenses created by this method were initially opaque, which was caused by incident light being dispersed due to the uneven surface of the raw printed layers. The surface quality was improved using different post-processing methods:

- Spin-coating: when a small volume of resin was applied to the apex of the lens and then rotated at high speed to pull the resin evenly over the surface.
- Drop casting: similar to spin coating in that resin was applied to the apex of the lens but, instead of spinning, the lens was left flat and gravity distributed the resin over the surface.
- Hand sanding and polishing: the use of very fine grit sandpaper and then applying clear acrylic polish to progressively remove/smooth surface features.

The lenses produced by each of these methods gave various levels of success. However, a quantitative method to characterise the surface quality of the lens was required. Therefore, the lenses were imaged using a confocal microscope setup for interference reflection microscopy (IRM), where a beam-splitting mirror is placed in the usual position of a dichroic mirror. This method resulted in interference patterns which mapped the surface of the lens, like

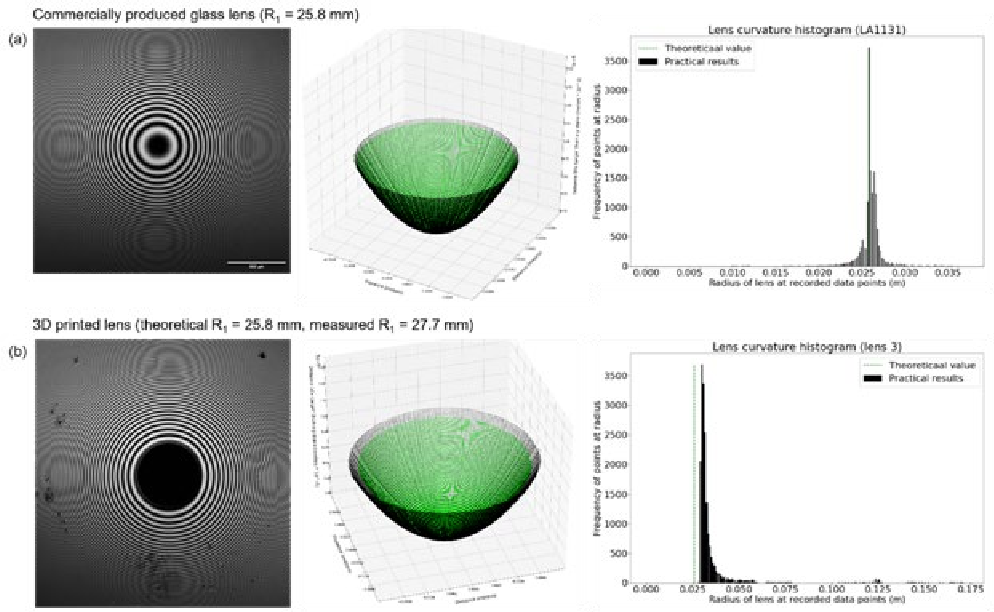


Figure 2. Characterisation of the surface quality and calculation of curvature from IRM data. (a) A commercially sourced glass lens with a known radius of curvature of 25.8 mm. The IRM image (left) shows the concentric rings of constructive and destructive interference corresponding to the topography of the lens surface. A 3D reconstruction is presented (middle) following processing of the IRM data (black) and compared to the theoretical curvature (green). The radius of curvature (R1) and surface quality were measured by calculating R1 in a radial sweep and presented as a histogram (right), with the theoretical radius of curvature denoted by a green dotted line. The spread of the data gives an indication to the surface quality of the lens. (b) the same as above, but for a 3D printed lens of the same prescription.

that of contour lines on an Ordinance Survey map. The height of the lens surface where constructive interference occurs was only dependent on the order of constructive interference, the refractive index of the medium the lens was in, and the wavelength of incident light. A 3D reconstruction of the lens was created using IRM and compared to their predicted geometry. This data was used to calculate the radius of curvature of the printed lens and compared to the theoretical lens curvature, or compared to a precisely manufactured glass lens of the same design specifications.

What did you find out?

The surface profile of the lenses was measured using the interference fringes present in the IRM data, which corresponded to the axial position of the curved surface. The axial position at which constructive interference occurred was used to create a 3D reconstruction of the lens using a dedicated python script. The curvature of the lens was then calculated and compared to the theoretical values.

During this project, most of my time was spent on the spin coating method. I found that it was possible to manufacture lenses with high surface quality, but the results could be inconsistent depending on the volume of resin, spin-time, spin-speed, and the method of resin application.

Hand polishing seemed promising at first, as this is the routine method for professional manufacturers to process glass lenses. However, these lenses were impossible to analyse as there was no interference pattern due to irremovable resin surface roughness, if lenses were instead polished by machinery, it may have yielded a better result.

The last method that I investigated was drop casting which seemed like a promising way to create a lens, however, needs to be investigated further to test the reproducibility of the method.

The model lens that we used was the LA1131 from Thorlabs which had a radius of curvature of 25.8

mm. The spin coating method produced the best quality lenses, with radii ranging from 27.7 mm to 32.1 mm, slightly larger than the manufacturer's values. The lenses that I drop cast had radii of curvature of 22.8 mm and 29.5 mm. As mentioned, the polished lenses were impossible to analyse with this method.

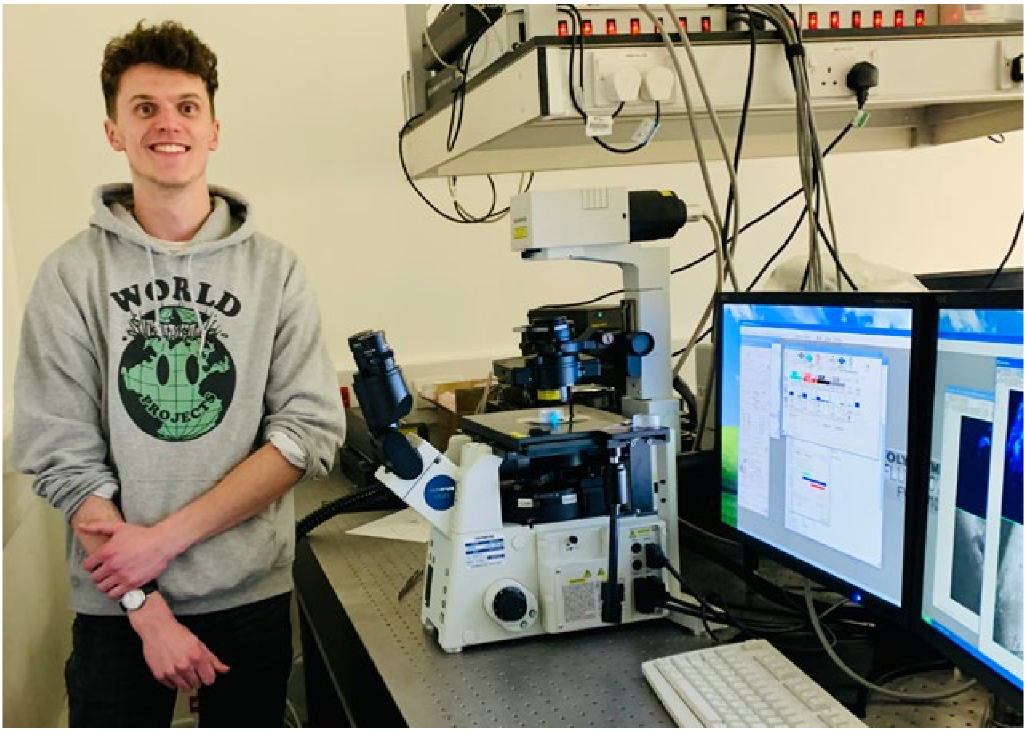
What did you learn from participating in this project?

Over my time working on my studentship, I learned a lot of practical skills such as how to operate a 3D printer and how to acquire IRM images using a confocal microscope. I was also able to gain an understanding of how to operate advanced imaging equipment, and expanded my understanding of the theory behind microscopes as well. I was able to apply and develop my coding skills when analysing the images taken using the microscope, which created a new method for characterising the surface of 3D printed lenses.

I gained experience working in a wet lab as part of a multidisciplinary research team which I would not have had the opportunity to do outside of this studentship. Also, at the end of the studentship I had the opportunity to present my data at a research seminar, which taught me how to create a presentation targeted toward an interdisciplinary audience.

How has this project affected your long-term goals?

Doing this project has given me a window into what it's like to work in research as part of the academic community, something which I was not able to get from studying for my degree alone. This project has expanded my network and put me in contact with academics, which will undoubtedly be useful in my next few years at university. Overall, this project has made me consider the possibility of having a career in academia more seriously.



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