MEASUREMENT OF MIRROR PANELS USING COLOURED PATTERN DEFLECTOMETRY

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Abstract

This paper introduces the Coloured Pattern Deflectometry (CPD) method for measuring solar concentrating mirror panels. The method was developed with the aim of outperforming currently used photogrammetry and flux mapping techniques, and as an alternative to deflectometry techniques that utilise phase shifting. CPD has been used to measure the radii of curvature and slope errors for ANU dish mirror panels. The method agrees with photogrammetry to within 5% for radius of curvature measurements, but currently exhibits a systematic error in the form of a skewing of the panel shape. CPD slope error measurements agree with those obtained from flux mapping. Further testing and debugging of the developed software is required to reduce the errors, after which it it will be released as open source software.

Keywords: deflectometry mirror panel facet dish measurement

1. Introduction

An accurate method of measuring mirror panel optics is needed when prototyping new mirror panel designs or manufacturing processes for central tower and parabolic dish solar concentrators. Factory production of mirror panels also requires accurate measurements to give feedback to the manufacturing process and as a quality control.

The prototype parabolic dish SG4 (shown in figure 1) at the Australian National University (ANU) Solar Thermal Group (STG) has a reflective surface made up of 380 nominally identical ~1.4 m^2 mirror panels, with an average radius of curvature of 31 m [1]. The motivation to develop an improved mirror panel radii of curvature (RoC) and slope error measurement system came from weaknesses in existing measurement techniques employed by the STG. Photogrammetry measurements are time consuming and do not produce adequate slope error data. Flux mapping of individual panels is also time consuming and, whilst yielding the slope error of the mirror panel as a whole, it gives little insight into the slope error distribution over the panel surface.

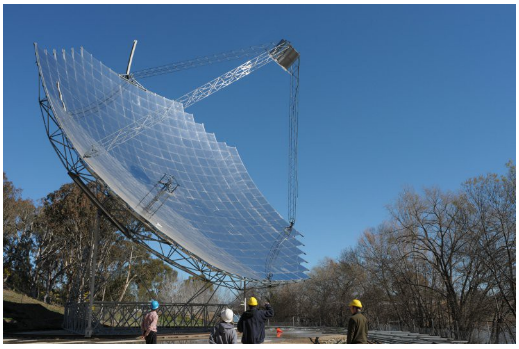

Fig. 1. SG4 parabolic dish, with a surface made from 380 mirror panels.

Deflectometry, an optical measurement technique originating in the car manufacturing industry [2], has recently been proving its worth as a technique for the measurement of mirror panel slope errors.

Deflectometry systems directly measure surface slopes whilst triangulation techniques such as photogrammetry measure surface positions in 3d space. For concentrating mirror applications, surface slopes are the more important quantity to measure, as a deviation in mirror slope affects the dish optics more than a surface position offset.

The new method known as Coloured Pattern Deflectometry (CPD) was designed to be cheap, fast, easy to operate, compact and to provide not only slope error information, but also the overall shape and principal RoCs of a mirror panel. This method differs from other deflectometry systems in that a coloured pattern is used instead of phase shifting techniques. One advantage of the coloured pattern is a reduction in system price and complexity, since it can be a printed sheet of paper instead of the LCD monitor typically used with phase shifting. Also only 2 photographs need to be taken where phase shifting requires upwards of 6.

A second key difference of the CPD method is in the way that it calculates mirror surface positions. The surface slopes and positions are recursively calculated by extrapolating the surface out as the calculation proceeds. This has the potential of producing more representative and detailed surface position information.

2. Coloured Pattern Deflectometry

The basic setup of the CPD method is shown in figure 2. A camera views the reflection of a patterned object in the surface of a mirror panel. A photograph is taken and the resulting image is processed. For each pixel that views a section of the mirror, a mirror surface position and normal vector are calculated. Mirror panel RoCs are extracted by fitting an elliptic paraboloid to the position results. Slope errors at each point are given by the difference of the measured surface normals from the fitted surface normals.

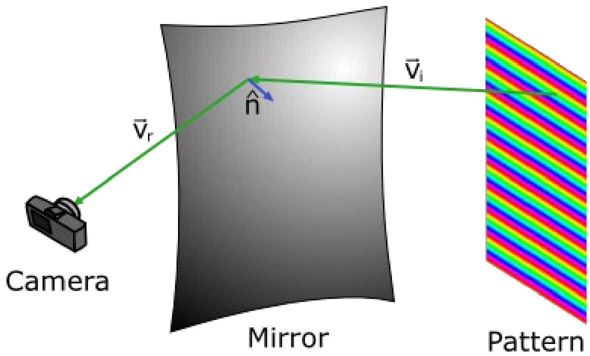

Fig. 2. Overview of measurement procedure.

Given the incident and reflected light ray unit vectors ($\hat{v}_i$ and $\hat{v}_r$), the surface normal of the mirror at a point is given by:

$$\hat{n}=\frac{\hat{v}_r-\hat{v}_i}{|\hat{v}_r-\hat{v}_i|} \tag{1}$$

The reflected unit vector can be determined for a given camera pixel if the orientation of the camera is known (explained in section 2.1). In order to calculate the incident vector, the point where the light ray leaves the pattern $\vec{p}_{pat}$ must be known, as well as the point where it strikes the mirror surface $\vec{p}_{mir}$:

$$\vec{v}_i=\vec{p}_{mir}-\vec{p}_{pat} \tag{2}$$

$$\hat{v}_i=\frac{\vec{v}_i}{v_i} \tag{3}$$

$\vec{p}_{pat}$ can be worked out from the colour of the pixel (explained in section 2.2), but the mirror surface position $\vec{p}_{mir}$ is the other unknown we are trying to measure. This leaves a circular argument where we can't know the mirror surface normal without first knowing the mirror surface position and vice versa.

Other deflectometry systems have gotten around this by assuming a fixed surface shape which normals are calculated relative to. More sophisticated approaches fit a mathematical function to the surface whilst trying to minimise the slope error produced [3].

In CPD the rough position of one point on the mirror surface is estimated, which allows a surface normal to be calculated for that point. This information can then be used to find the surface position of a neighbouring point by extrapolating the surface out (explained in section 2.3).

The following sections explain in more depth how each required quantity for equation 1 is calculated.

2.1. Reflected Light Vector

A directional vector can be assigned to each pixel in the camera sensor, which defines the direction of incoming light striking that pixel. The camera/lens principal distance and the physical size of the camera pixels are required to calculate this directional vector. The camera position and orientation is then used to convert this vector from the camera frame of reference to a global frame of reference where it represents the reflection vector $\hat{v}_r$ for a pixel.

The approach taken to locate the camera is to include 3 reference dots, arranged around the mirrored surface where they will be captured in measurements. These dots define the x-y plane of the global coordinate system as shown in figure 3.

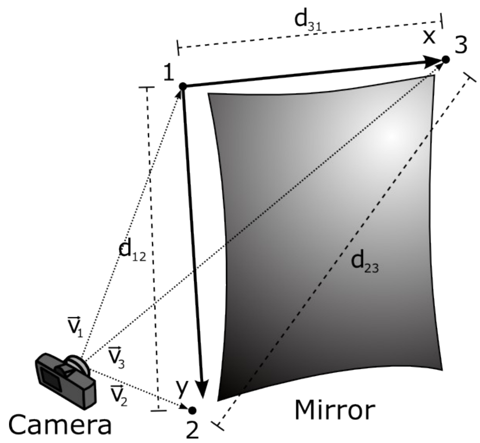

Fig. 3. Camera locating dots positioned about mirror.

A system of 3 equations can be constructed and solved numerically for the 3 unknowns v_1, v_2 and v_3. These vectors are then used to calculate the position and orientation of the camera in the global reference frame.

2.2. Pattern Source Position

The coloured pattern provides a way of working out the source position $\vec{p}_{pat}$ of a light ray. There are many different types of patterned surfaces that could be used for this purpose. The initial idea to use colour in the pattern came from color-coded target dish measurement system [4]. It turned out that the design of the pattern needed to be different so that high resolution slope measurements could be made over short distances.

The coloured gradient acts like a ruler, where the hue value of light captured by a camera pixel can be converted to a distance along the coloured pattern. Using a coloured pattern has lower costs and allows the pattern to be made significantly larger than phase-shifting techniques which usually use a LCD monitor. A larger pattern size allows mirror panels to be measured at distances much shorter than their focal length.

The pattern is broken up into repeating segments as shown in figure 4. The hue values change continuously in one segment, returning to the same hue that the segment starts on. By taking two photos, with the pattern rotated 90º between each photo, the two hues obtained for each pixel define a set of potential source points. If the pattern has n segments, then we need to identify which of the n^2 potential source points is the true source. If the patterned surface was made of only one large segment, then this would be trivial, however in practice multiple segments are required to obtain a higher spacial resolution of the pattern surface.

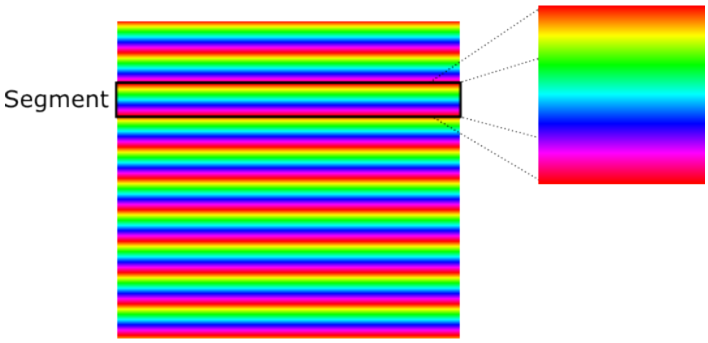

Fig. 4. Coloured pattern.

The calculation of source positions starts with a pixel in the camera that reflects a known segment of the coloured pattern. If the mirrored surface is sufficiently smooth, then the source location of a neighbouring pixel must not be more than half a segment away. Using this rule, pixel source positions are calculated one at a time, working away from the starting pixel. By keeping a record of the current segment, the whole mirrored surface can have its pattern source positions identified.

The smaller the segment size, the higher the source position resolution, because the full range of hues are spaced over a smaller distance. However if a segment is too small, then there is a greater risk that two neighbouring camera pixels reflect a part of the pattern that is more than half a segment apart, which could lead to the misidentification of a pattern source point.

The size of a pattern segment should be chosen by considering the pattern distance to the mirror panel, and the smoothness of the mirror surface. Figure 5 shows how the minimum segment size can be calculated. Point 1 and 2 on the pattern surface are the source points for neighbouring pixels in the camera. Both mirrored surface reflection points have been superimposed since they are close to one another, and the reflection vector $\vec{v}_r$ is assumed to be approximately the same for neighbouring pixels. The coloured pattern is assumed to be ~90º to the incident vectors, and at a distance of d_{patt}. θ_{max} is the maximum expected change in surface slope for two neighbouring pixels. The segment width s should therefore be no less than:

$$s=4\,d_{patt}\tan\theta_{max}\approx 4\,d_{patt}\,\theta_{max} \tag{4}$$

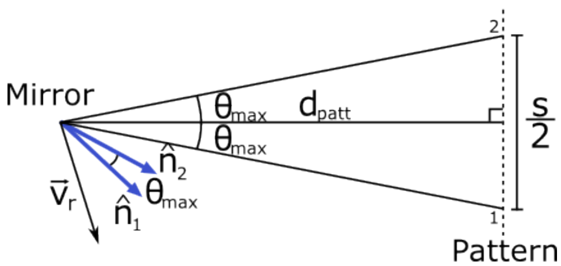

Fig. 5. Minimum segment size relation.

In practice there is not a continuous range of hue values in a segment. There must be some resolution due to screen pixel size or printer resolution, or to the maximum number of hues that the camera can reliably distinguish. Figure 5 can be used to work out how this translates to a surface slope resolution. In figure 5 set $s/2$ equal to the smallest distance that can be represented on the pattern surface s_{res}. Replace θ_{max} with the slope resolution θ_{res}, and equation 4 becomes:

$$\tan\theta_{res} \approx \theta_{res} \approx \frac{s_{res}}{2\,d_{patt}} \tag{5}$$

2.3. Surface Position

Surface positions are calculated in an iterative manner, similar to how the pattern source positions are calculated. A surface position is assumed for a starting pixel and its surface normal is calculated using equation 1. If the mirrored surface is sufficiently smooth then the slope of the surface won't change much between one pixel and its neighbour. This allows the surface position of a neighbouring pixel to be estimated by extrapolating the surface out to intercept the neighbouring reflected vector. The slope of the neighbouring pixel is then calculated and the process continues.

Figure 6 shows the vectors relating two surface points for neighbouring pixels.

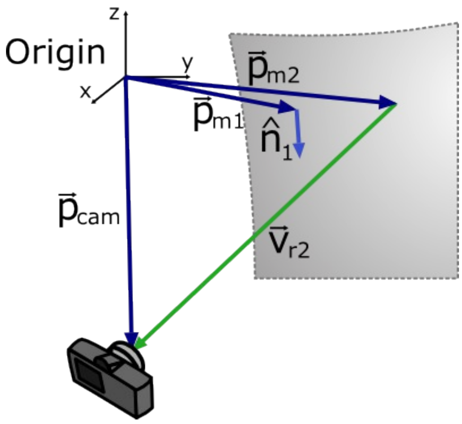

Fig. 6. Extrapolation of surface out from know location.

The surface position $\vec{p}_{m1}$ and normal $\hat{n}_1$ is known for the first pixel. Assuming the second surface point is perpendicular to the surface normal of the first surface point, then:

$$v_{r2} = \frac{(\vec{p}_{cam} - \vec{p}_{m1}) \cdot \hat{n}_1}{\hat{v}_{r2} \cdot \hat{n}_1} \tag{6}$$

The surface position of the second point is then given by:

$$\vec{p}_{m2} = \vec{p}_{cam} - v_{r2}\hat{v}_{r2} \tag{7}$$

The mirror panel is positioned so that the position of a starting point on the mirror surface is roughly known. It is not possible to analytically determine the accumulated error associated with the uncertainty in the starting point position. This was the main motivation for performing the simulation presented in the next section.

2.4. Simulation

A python script was written to model the deflectometry method. This simple model provides a quick way to get an indication of the expected errors, and for determining which conditions give the most accurate results.

The model works on a 1D curve instead of 2D surface to simplify the calculation. A starting point offset error was introduced into the model to simulate an error in positioning the mirror panel as discussed in the previous section.

A series of tests were run on a 30 m RoC circular test curve. The results are summarised as follows:

- Increasing the distance between the camera and the mirror panel produces a better matching curve and smaller required pattern size. However as the camera moves further away, fewer pixels capture the surface, so the surface resolution is lowered.
- A camera viewing angle of the mirror panel that is more acute produces a slightly better matching curve but again as the angle gets too sharp, surface resolution is lost.
- A more distant pattern produces a better matching curve, but it increases the required pattern size.
- As expected, having a larger starting point offset error produces poorer matching results.

A starting point offset error of 2 mm produced a RoC error of 0.52% and a maximum error in slope error of 0.021 mrad. This shows that the method in principal should produce accurate results, however the model used here has been greatly simplified.

3. Implementation

A rotating pattern frame and mirror panel frame were constructed and calibrated. The coloured pattern is a 2x2m coloured printout that is fixed to a rotating board. This pattern gives a designed mirror surface slope resolution of between 0.0435 mrad and 0.0825 mrad. The whole pattern can be easily rotated to either the horizontal or vertical stripe alignments. The mirror panel frame holds a mirror panel steady in the correct position for a measurement and has 3 camera locating dots. Figure 7 shows the final setup of the measurement system.

Fig. 7. Mirror panel frame (blue on left) and coloured pattern frame.

The relative positions of the mirror frame dots and the coloured pattern were measured using photogrammetry. These results were used to get a representation of the pattern position and alignment in global coordinates.

The hue to spacial distance relation for the coloured pattern was calibrated with a Nikon D300 camera. The result was found to have a good repeatability at a range of illumination levels for a cool-white fluorescent white balance.

A program to process the photos, retrieve surface normals and positions and then calculate overall RoCs and slope errors was written in the C programming language. It takes approximately 3 seconds for the program to process the images and produce a result.

4. Verification

5 mirror panels were measured using CPD. The RoCs and slope errors produced were compared to those obtained from photogrammetry (using the method outlined in [5]) and flux mapping.

4.1. RoC Comparisons

For each mirror panel, two orthogonal principal radii of curvature (R_1 and R_2) are obtained from elliptic paraboloids fitted to the CPD and photogrammetry spatial data. The RoCs from photogrammetry and CPD are compared in figure 8.

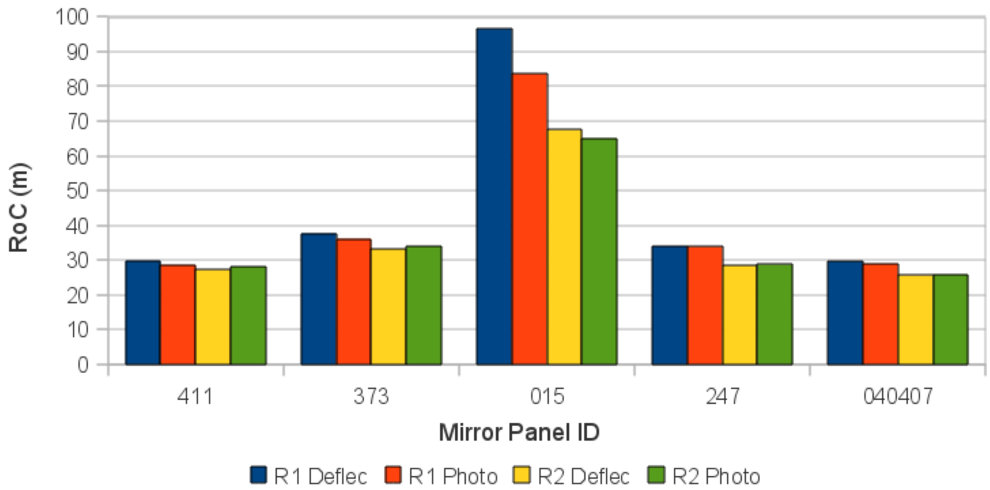

Fig. 8. RoC results for 5 mirror panels compared to photogrammetry result.

Deflectometry currently tends to overestimate R_1, and underestimate R_2, compared to the photogrammetry results. Standard RoC (~30 m) panels are within 5% of the photogrammetry results. A larger RoC panel (#015, ~90 m) is 15% off. These errors are an order of magnitude higher than the simulation analysis anticipated. Figure 9 shows a 3D mesh plot of CPD surface positions for a typical panel.

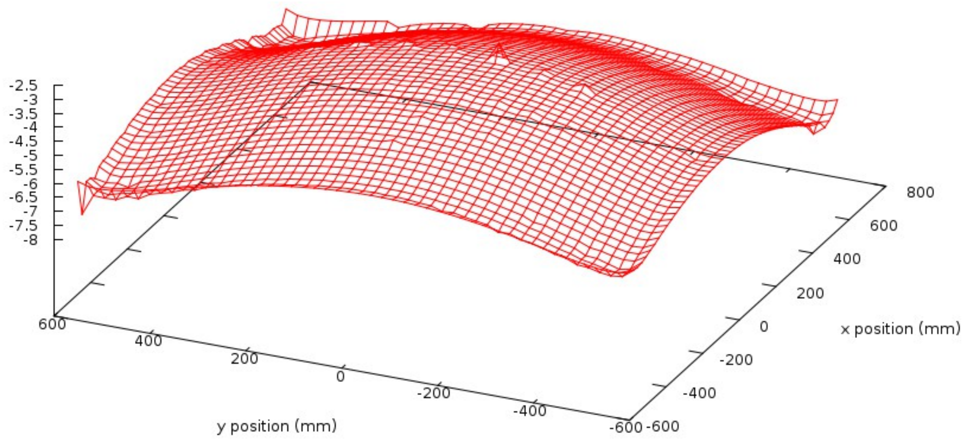

Fig. 9. Solved surface mesh exaggerated in the axis normal to the panel.

4.2. Slope Error Comparisons

Slope errors were calculated for two orthogonal axes across the mirror panel surface, and compared to flux mapping data for a number of panels. Flux mapping slope errors were not calculated relative to the best fit surface like CPD, but to an ideal surface defined by the panel to target distance, which limits the usefulness of the comparison. CPD slope errors agree with flux mapping to within around 12%.

Figure 10 shows the slope error distributions for panel 035. Panel 035 is a poor quality panel (due to a failure in the manufacturing process); a large buckle in its shape can be clearly seen in the CPD data.

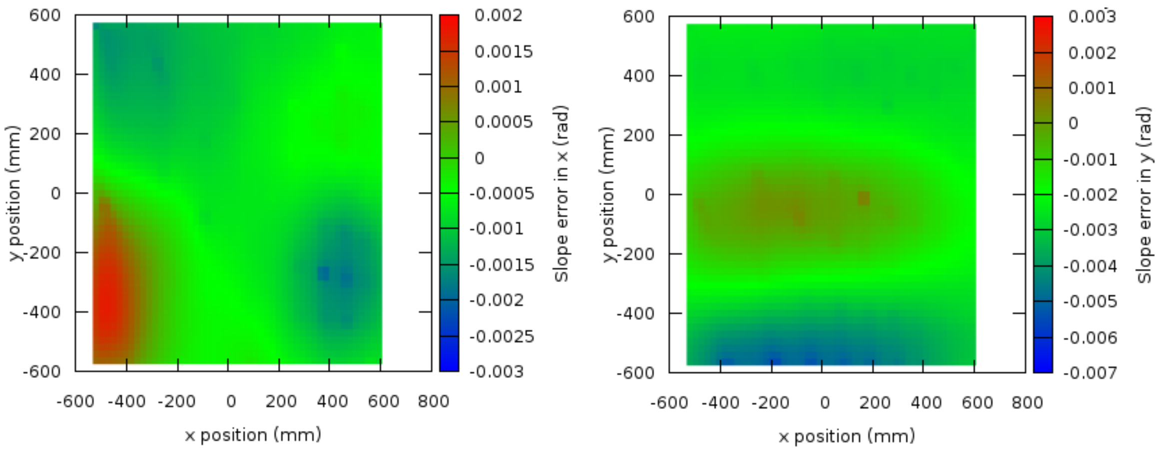

Fig. 10. Mirror panel slope errors for panel 035 in two orthogonal directions.

4.3. CPD Errors

A systematic error was found to be present in all CPD measurements. This error is the cause of the large discrepancy between the results expected from the simulation analysis and those present in reality. The cause of the error is yet to be identified in part due to the the complexity of the processing software, and the large amount of data that it processes.

The sensitivity of the method was tested by changing ambient lighting colour, mirror surface dirtiness, camera positioning and the camera focus. The results were resilient to changes in these parameters however any finer detailed analysis is prevented by the systematic error swamping these other errors. The sensitivity of CPD was also tested by varying calibration settings.

5. Conclusion

A new method of measuring the radii of curvature and slope errors of a mirror panel has been demonstrated. Coloured Pattern Deflectometry (CPD) was developed with the requirements of low cost, speed and simplicity in mind. CPD provides more detailed and accurate slope error results than the photogrammetry technique previously used at ANU; however RoC measurements currently have an unresolved systematic error.

After further debugging and verification it is expected that the CPD program will be released as open source code so that other interested parties can use or improve upon it.

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