Fringe Projection Metrology for Thermoformed Millimeter Wave Freeform Optical Elements

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Abstract: University of Arizona scientists have developed an efficient method of thermoforming panels for millimeter wave freeform antenna applications. We've implemented stereo fringe projection metrology to characterize these panels to 40μm RMS accuracy.

1. Introduction

Radio telescopes provide an alternative astronomical observation method to visible light astronomy. They can be operated day and night. Due to the lower energy of radio waves compared to visible light, collecting apertures of these telescopes need to be large to make observations. Collecting apertures are typically paraboloidal or even freeform reflectors. For ease of manufacturing, these reflectors are commonly made in segments, and assembled to make up a single acting reflector. These panels are traditionally made using machined aluminum or aluminum cassette techniques. [1] A new process is being developed at the University of Arizona to thermally slump sheets of aluminum into a desired freeform shape using an adjustable mold. [2]

The main inefficiencies in these telescopes stem from deviations from the ideal antenna shape. Contributors include deformation due to gravity and temperature change, as well as panel alignment and individual panel manufacturing accuracy compared to the designed optical shape. To reduce inefficiencies in the aperture, it is important that the shape of each panel is as accurate as possible to the ideal shape. [3] To do this, we utilize a fringe projection metrology method capable of measuring panel shape to 40μm RMS or better, which meets the requirement of λ/25 RMS for a 1 mm (300 GHz) wavelength.

2. Stereo Fringe Projection

Photogrammetry is the method of obtaining information about objects through the processing and analysis of images taken of that object. Stereo Vision (SV) shown in Figure 1 is a method of capturing two or more images of an object from different perspectives and extracting the distances to different points on that object. The distance resolution of a stereo camera pair is well established through the field of computer vision, and is given by:

$$\delta z = \frac{z^2}{bf}\delta p_x \tag{1}$$

where δz is the depth resolution, z is the perpendicular distance from the baseline to the object, b is the baseline distance (separation between the camera pair) and f is the focal length of the two cameras, assuming they are identical. δp_x is the disparity accuracy, or the error in matching the real-world object to specific locations on the image plane of each camera.

To meet the accuracy requirement of the millimeter wave antenna application, we need δz to be less than 40 μm. This can be achieved by adjusting z, b and f. There are practical limitations on these values, considering the Unit Under Test (UUT) needs to remain in the field of view (FOV) of both cameras. Tuning these parameters reveal practical configurations to reach high depth resolution. This assumes accurate point matching, which is one of the most challenging parts of SV.

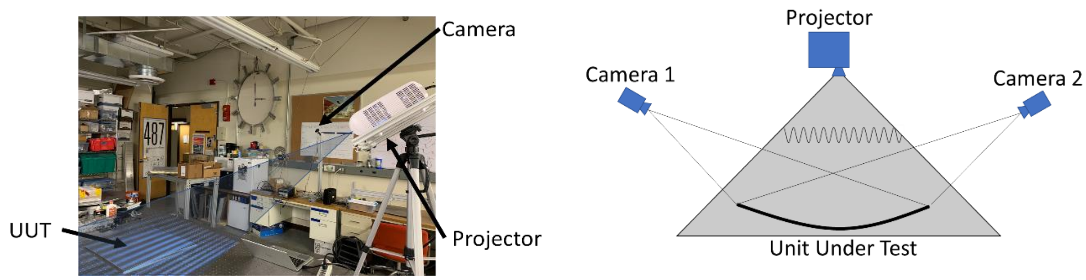

Fig. 1. Stereo fringe projection layout for millimeter wave freeform antenna metrology. Second camera not pictured.

Fringe Projection alleviates the challenge of matching image points by using a projector to place fiducial patterns on a surface, and therefore improves depth resolution by decreasing the uncertainty in matching, δp_x. Phase shifted sinusoidal or binary bar patterns are commonly used. The four-step phase shifting method can be used to recover the phase of a shifted sinusoidal pattern in two orthogonal directions.

After applying a phase unwrapping algorithm [4] to remove the 2π discontinuity of multiple periods landing on the object, each pixel in one camera has two unique phase values from each orthogonal fringe pattern. These can be matched to a location on the other camera that also has those unique values, meaning that those two points represent the same location in 3D space. Once each pixel is matched to a location on the other camera, well known triangulation equations can use the matched points and camera calibration parameters [5] to produce world 3D coordinates representing the freeform UUT shape.

3. Experimental Demonstration

We used two 5 – 50 mm varifocal camera lenses with Sony IMX179 detectors, with 1.4 µm pixels. We assumed we could match objects to a disparity error of 1 pixel or less using our phase correlation method, so the δp_x value was 1.4 µm. For measuring 0.5 m square aluminum panels, we were able to find reasonable configurations that exceed this theoretical depth resolution, while still covering the whole panel in the field of view of both cameras. We used a distance of 1 m, focal lengths of 20 mm, and a baseline distance of 6 m. Our results from measuring a sample aluminum panel compared to data from a portable CMM (Coordinate Measuring Machine) are presented in Figure 2.

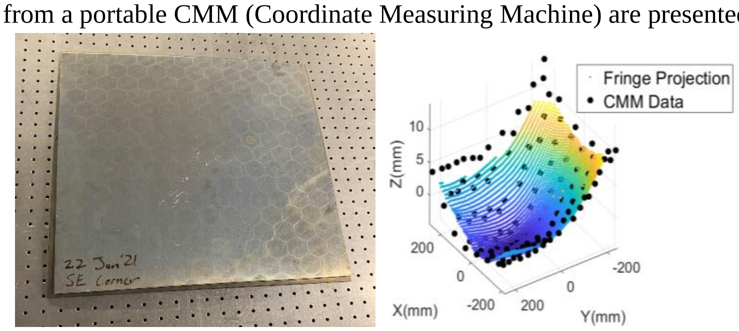

Fig. 2. Dense Fringe Projection point cloud overlaid with sparse measurement from a CMM for the 0.5 m square freeform antenna panel.

3. References

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Acknowledgement: This work was funded by the National Science Foundation (NSF)