3D inspection microscope using holographic primary objective

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ABSTRACT

With refraction microscope optics it is generally understood that as magnification increases field-of-view will decrease. This constraint has posed scaling limitations for microscopy of large objects. We have shown in theory and proven in a reduction-to-practice that in the special case of grazing incidence diffraction, as magnification increases, field-of-view remains constant while efficiency goes down. This distinction has utility for many 3D optical inspection tasks. A holographic optical element (HOE) is used as the microscope's primary objective, and a laser stripe is used to interrogate target surfaces. The microscope's HOE can be embossed in polycarbonate and offered as a consumable part that can be replaced inexpensively if it becomes contaminated. Specimens can be placed on a moveable stage and advanced to collect a sequence of 3D profiles. Laser speckle is ameliorated as a natural consequence of the scanning mechanism. A prototype of the microscope has been demonstrated in a desktop embodiment. It is contemplated as a profiler for industrial inspection and quality control.

Keywords: 3D, microscope, holography, HOE, profilometry

1. INTRODUCTION

3D optical microscopy has been practiced with stereoscopic optics, but interpretation of stereo pairs to generate three dimensional surface co-ordinates for computer machine vision calls for either human intervention or computationally intensive photogrammetric software that resembles the stereo vision process. Alternatively, surface co-ordinate data suitable for computer image analysis can be acquired using structured illumination and triangulation profilometry, but extension of this method to microscopic regions presents some challenges, partly due to the considerable diameter of a microscope primary objective which can interfere with the placement of a pair of objectives in the near-field. Moreover, there are intrinsic limitations on the resolving power of both stereo and triangulation range finders, because the parallax offsets upon which their range measurements depend actually minify rather than magnify the range dimension.

A range finder based on primary objective grating (POG) configurations was introduced by one of the authors in 1987 with a patent, "Range Finding by Diffraction." [1]The method is extensible to microscopy, because the parallax disparity between higher diffraction orders is measurable to point-of-contact with the POG. An embodiment using a standard microscope as the secondary was demonstrated in 1995. [2] As disclosed, multiple off-axis views of a surface appeared through a co-axial optical path. Further investigation led to the discovery that the parallax disparity could be normalized to produce telecentric and perspective-free 3D profiles by chirping the grating pitch of the POG. [3] The hologram of a point source forms a holographic optical element (HOE) that is well suited for this purpose. By 1997 the exploitation of a HOE as a POG was demonstrated in a hand held profilometer. [4] The demonstration unit was not a microscope. Another improvement was needed.

A notable feature of POG optics is that unlike conventional microscope primary lenses, diffraction gratings are typically off-axis systems. Taken to an extreme, POGs can be configured at grazing incidence and/or grazing exodus. The former configuration lends itself to microscopy, because the entry aperture is smaller than the exit aperture when the secondary is along the grating plane normal. The magnification can be quantified as the ratio of the grating length to the input aperture. The magnification is anamorphic, and if the dimension being magnified is distance, the resulting profile is a slice of the depth dimension along that interrogating beam. A detailed description of the geometric optics behind this improvement is disclosed in a prior publication.

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2. PRINCIPLE OF OPERATION

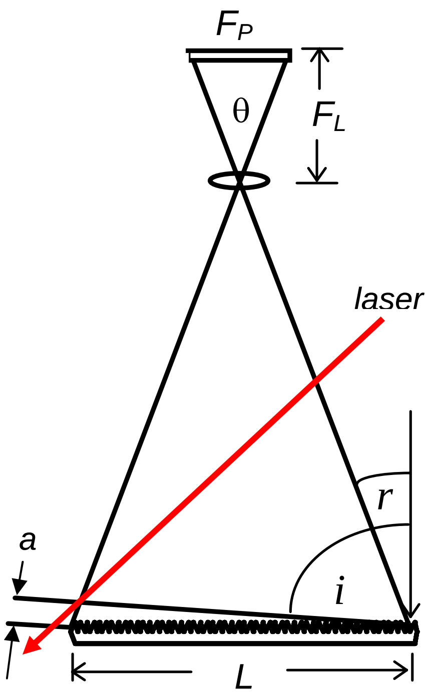

Fig. 1 Parameterization of model

Figure 1 identifies parameters used in the geometric model of the HOE-based POG microscope. For a given grazing incidence angle i the receiving angle r varies across the face of the grating. The variation in r across the POG requires that grating pitch p vary across its considerable length L according to the Diffraction Equation which dictates:

$$p = \frac{\lambda}{\sin(i) - \sin(r)} \tag{1}$$

The magnification M determined by the ratio of

$$M = L/a \tag{2}$$

Magnification is only in one dimension where the HOE pitch variation results in formation of an image on focal plane F_P corresponding to aperture a. However, the field-of-view for a lens of focal length F_L is θ in both dimensions. Therefore if the diffraction higher-order is along one axis, the magnification feature is anamorphic, and the non-diffracting axis exhibits a field-of-view θ that is not magnified by the HOE.

The magnification feature is correlated to the angle of grazing incidence i. As i increases, the magnification geometrically increases to an asymptotic limit at i = 90° where magnification is putatively infinite. A plot of the relationship is shown in the log graph of Figure 2. The trade-off is that as the magnification grows, the efficiency e of the HOE decreases proportionately as per the correlated graph of Figure 3. Unlike refractive primary objectives, the field-of-view does not change as magnification increases. Instead, the image starts to disappear due to photon starvation.

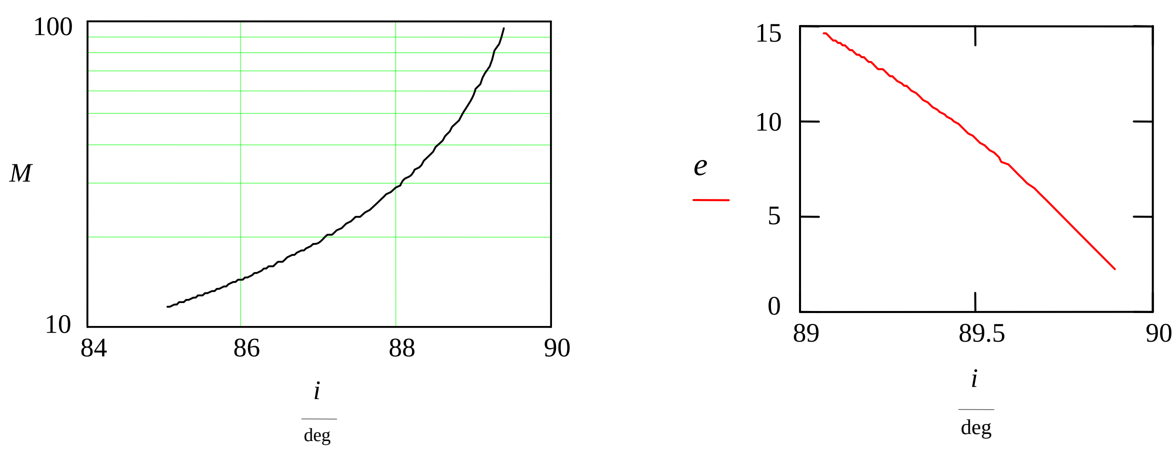

Fig. 2 As magnification M increases asymptotically toward infinity, the efficiency e of the POG decreases toward zero

Geometric optics does not fully describe the magnification feature. Just as lenses have their diffraction limits, POG elements cannot resolve sub-wavelength details. The limitation is similar to lenses, that is, the wavelength of light cannot propagate without reinforcing itself at wavelength intervals. However, the anamorphic magnification feature exhibited by a POG is significantly greater than can be achieved with lenses, and wide fields-of-view in one dimension are independent of the magnification in the other dimension.

3. HOE PRIMARY OBJECTIVE

We use a HOE that is a hologram of a point source, a simple hologram. It is the intersection of a plane wave and a spherical wave. However, the grazing incidence playback angle of the POG microscope makes it very difficult to record the HOE at the playback wavelength. For that reason, we recorded the HOE at a shorter wavelength. The recording laser for our HOE is a HeCd type that has a nominal wavelength of 441 nm.

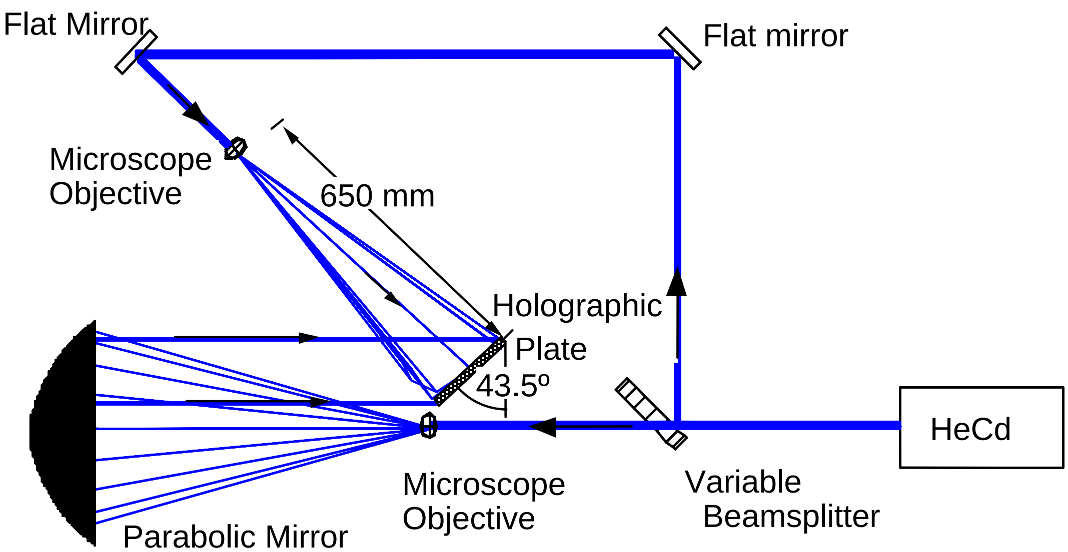

Fig. 3 Bench set-up for recording a HOE with a HeCd laser at 441 nm for playback with a diode laser at 635 nm

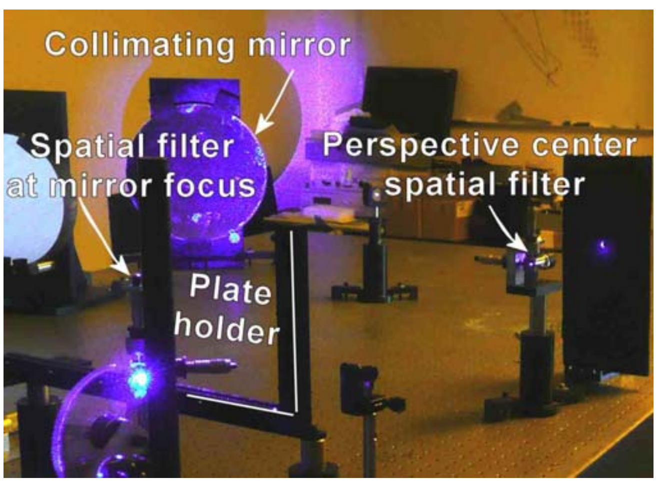

Fig 4 HOE master recording bench at New Light Industries

The recording was made by New Light Industries in Spokane, WA. A photograph of the setting is shown in Figure 4. The glass plate was coated with Shipley photoresist and the resulting master was a surface relief HOE which lends itself to mass replication. Efficiency of the HOE was of paramount importance. Based on prior work with a POG telescope configured to work at grazing exodus, a pitch depth of 0.150 microns was considered optimal. Electron micrographs of the master are shown in Figures 5 & 6.

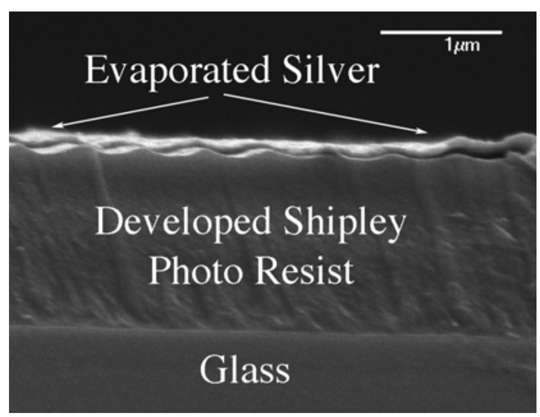

Fig. 5 SEM section of HOE master plate

Electroplating was used to copy the master onto a nickel shim which was replicated by Novia Innovation Lighting of Leeds, NY. Replicas were tested in both transmission and reflection modes where the reflection copies were coated with evaporated aluminum in a vacuum. Duplicate aluminum coated masters directly from the bench were also stockpiled for comparison testing.

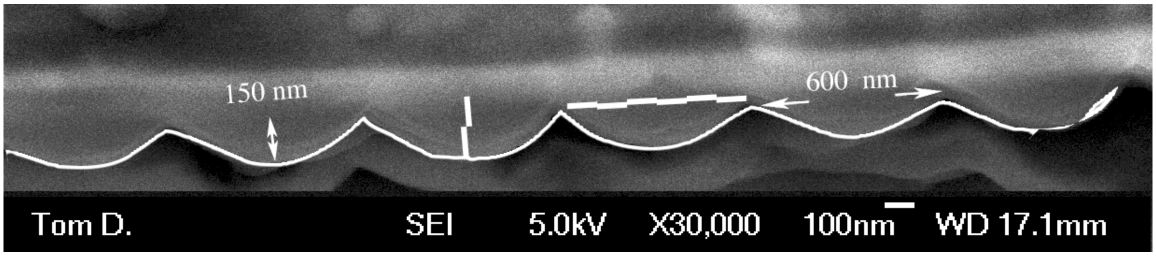

Fig. 6 Annotated FSEM section of HOE master plate showing groove pitch, depth and shape

4. PROTOTYPE

Aspex, Inc. makes a computer vision microscope for spinneret inspection called the Spintrak®, and our prototype 3D POG microscope uses a table top T25 Spintrak® motion controlled x,y stage and gantry with a z stage as its mechanical base. The diagrammatic configuration, Figure 1 is embodied in the actual physical prototype with a counter clockwise rotation of 90° so that the entry aperture *a* is below the POG as shown in Figure 7. A sheet of light generated by a laser scanner interrogates a target surface which is detectable inside the entry aperture window. The sheet of light creates a stripe from which is extracted a profile. An illuminated target diffuses light toward the POG. After the light is diffracted by the POG, the diffraction image is picked up by a camera parallel to the work table. The table can advance underneath the POG under computer control. The camera and POG are elevated on a z axis motion controlled platform.

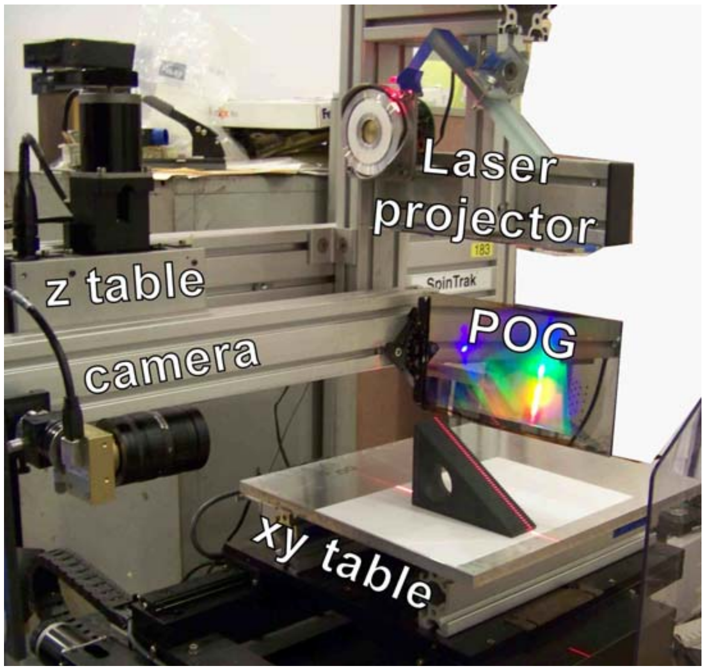

Fig. 7 Spintrak platform supporting POG 3D microscope optics

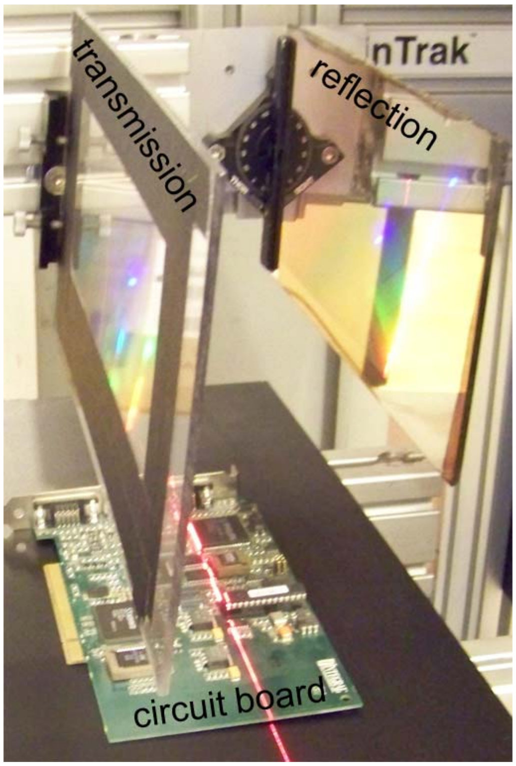

Fig. 8 Ganged transmission and reflection POGs

In addition to the reflection POG, the camera is positioned to look through a transmission POG on the same optical axis. The combination of both a transmission and reflection POG allows the camera to see both sides of a target, producing two profiles. Shadowing artifacts that are caused by occluding surfaces on one side of the target surface are typically visible from the other side. The dual POG configuration is shown in Figure 8. An example of the occlusion immunity is shown in Figure 9 where a profile is taken of a populated printed circuit (PC). Pins blocked by an integrated circuit body in the reflection diffraction image appear in the transmission image while a section of the PC occluded in the transmission grating is seen in the reflection diffraction image.

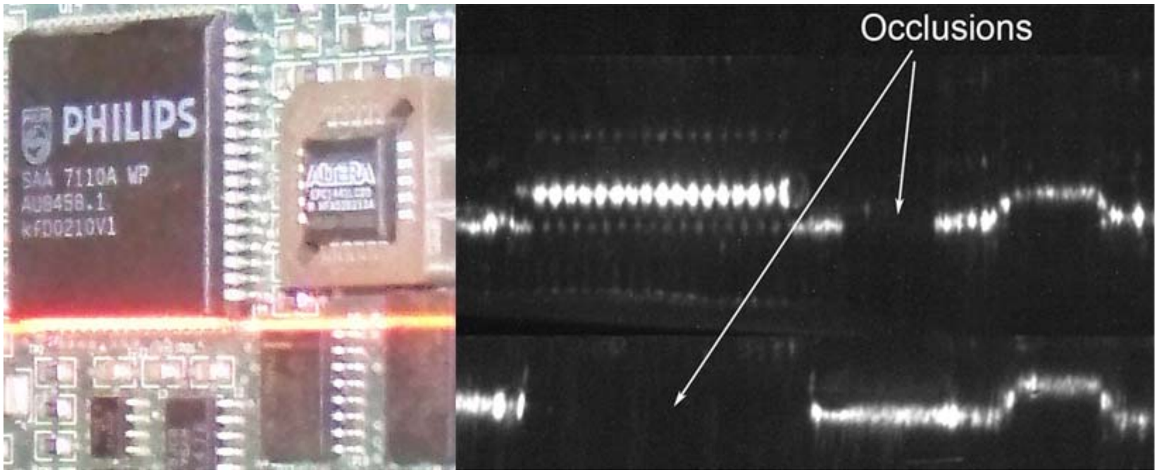

Fig. 9 A typical PC with occlusions caused by integrated circuit bodies can be profiled with ganged POGs

The structured illumination for the profile comes from a laser projector that has a footprint of 200 mm in length by 300 microns in width. Typical of laser illumination, there are speckle artifacts. These are eliminated by a temporal despeckling method shown in the comparison of Figure 10. At this time in the development of the projection system, about of half the available coherent light is being sacrificed to achieve the speckle reduction.

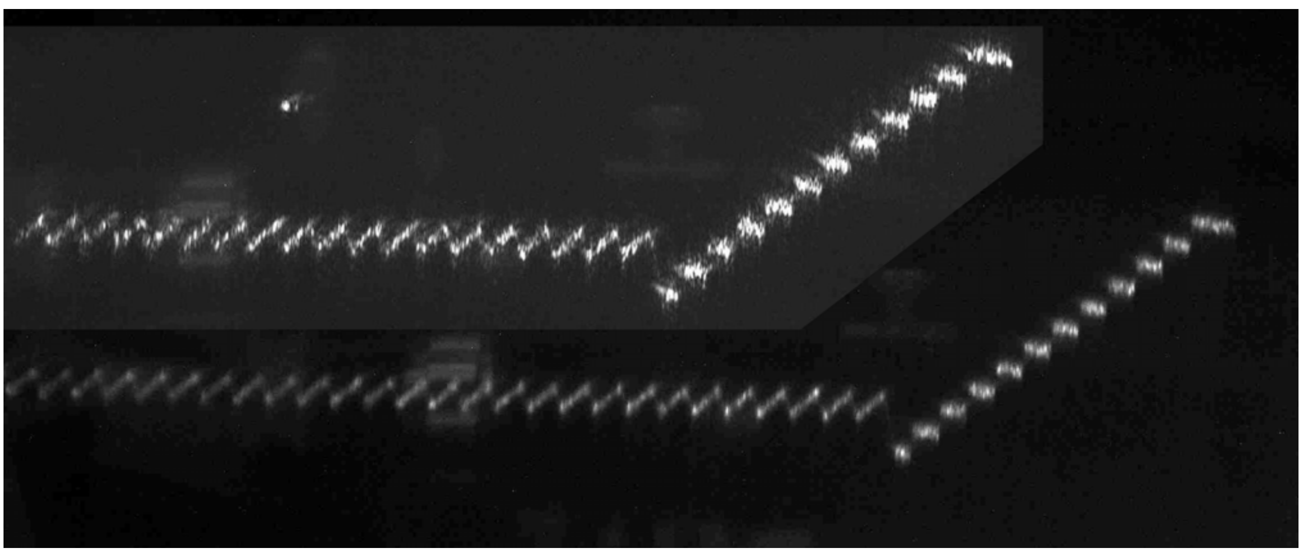

Fig. 10 Eighth inch incremental steps shown with speckle (above) and despeckled (below) sheet of light projection

Measurements are taken following a normalization that uses a reference flat at the baseline to calibrate a slight aberration in the profile. The output of the camera, Epix 5C10 monochrome ½ inch CMOS type, is shown in Figure 11.

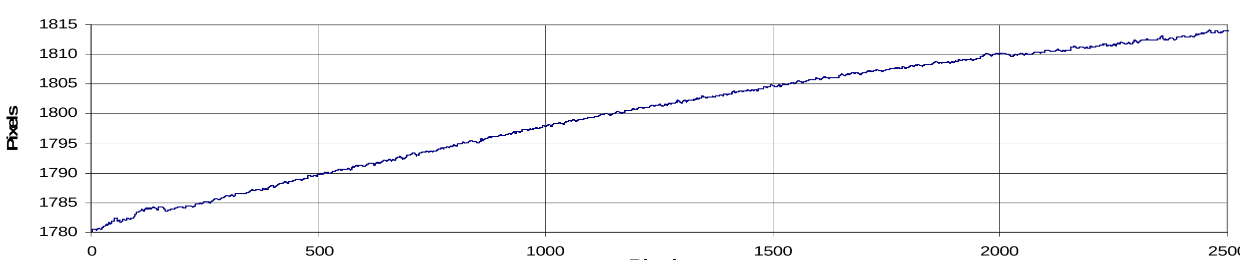

Fig. 11 Camera output of calibration flat used to generate a normalization curve

The camera output is processed with a centroid extraction algorithm that enhances the profile resolution. An experiment was conducted using a ribbon cable with valley depths at a nominal 300 microns. The cable was scanned and centroids taken, Figure 12. Raw camera data is sampled using signal amplitude and line width to refine the raw data. A graph showing the ribbon cable dimensional profile is show in Figure 13. The resolving power with centroid extraction is approximately 30 microns.

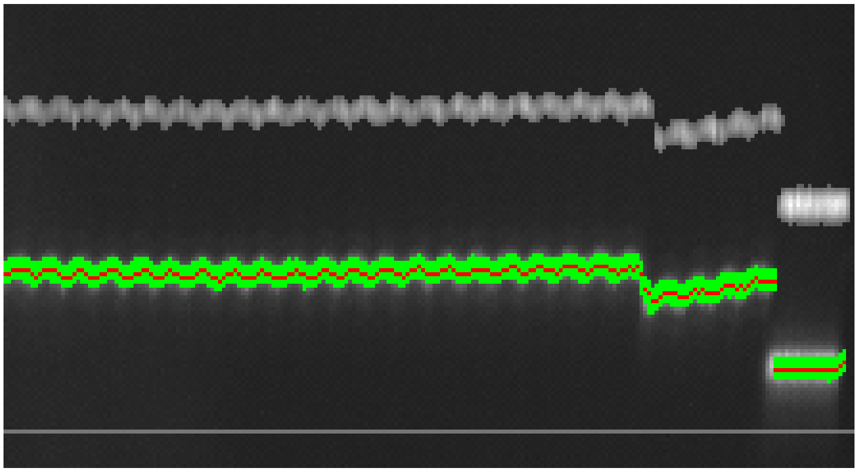

Fig 12 Camera image (above) centroid extraction (below)

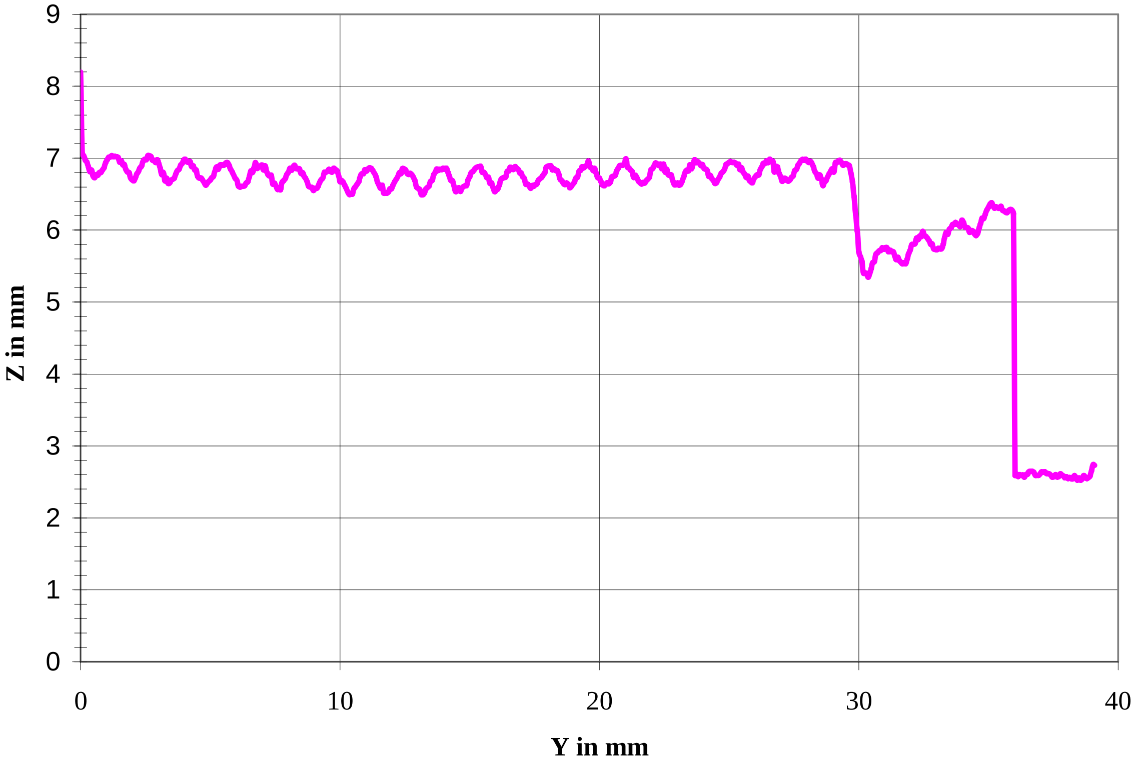

Fig. 13 A graph of the extracted 3D profile co-ordinates of a split IDE ribbon cable..

5. EFFICIENCY VERSUS MAGNIFICATION

POG 3D profilometry differs from triangulation in that there is a magnification power associated with the POG on the diffraction axis. We compare triangulation and POG magnification in Figure 14. Triangulation minifies the target profile while the diffraction image, set to the same occlusion liability angle as the triangulation image, magnifies it

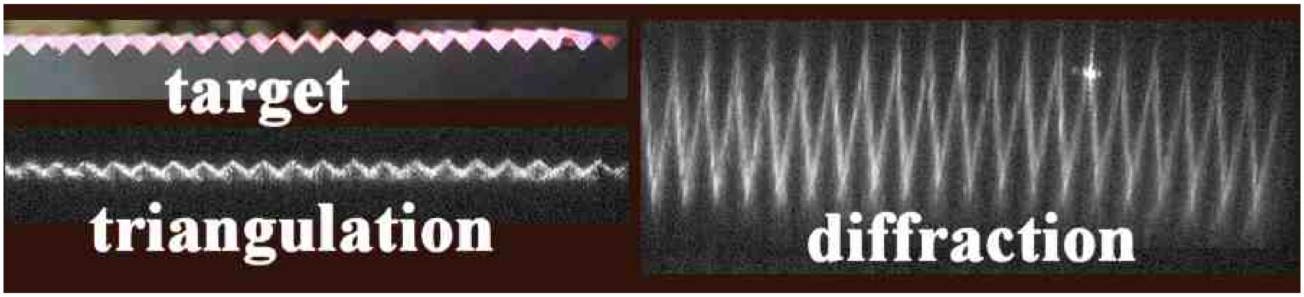

Fig. 14 A step target seen in profile (left above) is acquired by triangulation (left below) and diffraction (right above)

Both methods can use an interrogating laser beam, but with triangulation the wavelength of the beam is largely irrelevant. However, with the diffraction range finding method, the wavelength of the structured illumination is a critical parameter and is directly proportional to the resulting magnification. The wavelength drives up the angle of grazing incidence which then narrows the effective entry aperture. As the aperture decreases, magnification increases as per Equation 2.

There are at least two trade-offs when magnification is driven up. One is the familiar diffraction limit on resolving power, common to both primary objective lenses and gratings. A discussion of the theory of the diffraction limit is not within the scope of this paper but can be found in a prior publication which predicts resolving power for a diffraction range finder. [12] In with both lenses and POG's the considerable diameter is a critical parameter, that is, larger gratings have greater resolving power

.A second trade-off unique to the POG is that as the angle of grazing incidence increases, POG efficiency decreases. The effect occurs only in the direction of the diffraction axis. The non-diffracting axis does not alter the field-of-view of the camera lens. The anamorphic magnification feature can be achieved with cylindrical primary objective lenses up to a 2:1 ratio and is practiced in triangulation range finders. In those instruments there is no loss of efficiency of the lenses as a consequence of the anamorphism. On the other hand, the POG's anamorphic feature exhibited in the POG microscope is much greater.

A sequence of increasing magnification using grazing incidence diffraction range finding is shown in Figure 15. Note the loss of light intensity, notwithstanding the constant flux level of the interrogating laser beam.

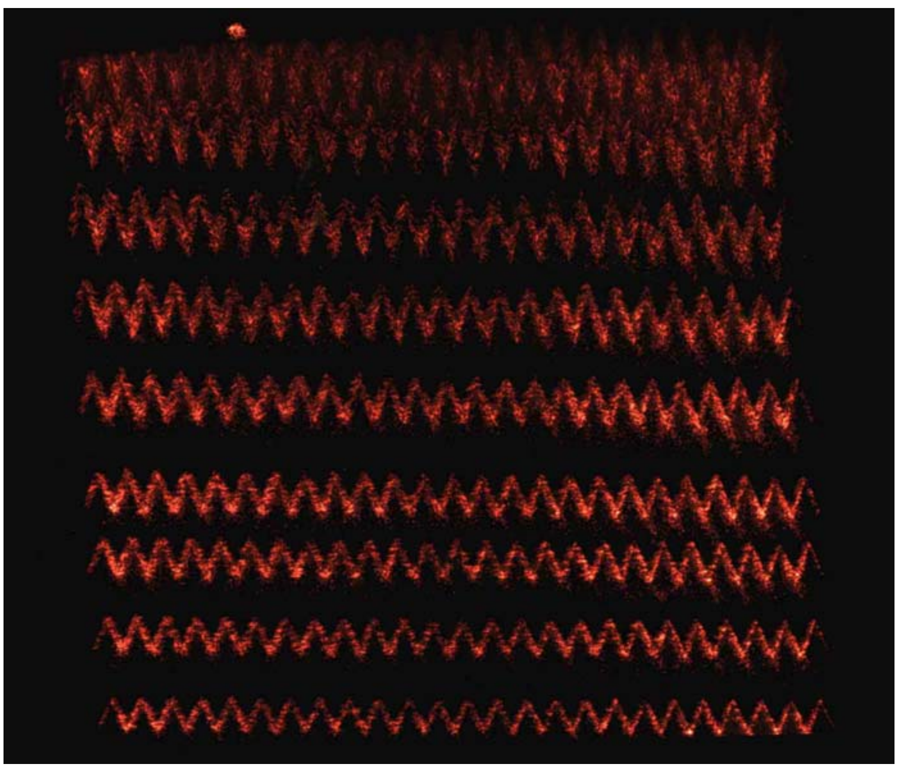

Fig. 15 As magnification increases, grating efficiency decreases. The example shows a doubling of magnification for a 1/10th inch step block, bottom to top. Profile width remains unchanged as depth magnification increases.

6. CONCLUSION

A 3D profilometer with magnification features has been demonstrated in a functional prototype using a holographic optical element as a primary objective grating. As a surface relief diffraction grating, the primary objective can be replicated by embossing methods. A distinguishing feature of the microscope is its anamorphic magnification, allowing fields-of-view in one dimension to remain constant while the other dimension, the depth dimension in a profilometer, undergoes magnification. There is a trade-off in the efficiency of the system as the magnification increases.

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