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Saturation reduction in fringe projection using polarization sensors and varying light intensities

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Abstract

Fringe projection systems are well established as metrology tools for fast measurements of (large) workpieces. However, as specular surface reflectivity causes camera saturation, the accuracy of fringe projection for (semi-)reflective parts is limited. The use of polarization filters can reduce the effect of this specular reflectivity, but lowers the signal-to-noise ratio (SNR), resulting in lower quality measurements. In this paper, a hybrid method which combines a polarization camera and an adaptive fringe projection technique, is proposed and validated. As four images are captured simultaneously, choosing the most appropriate polarization channel will partly reduce saturation and enhance the pointcloud integrality. To completely eliminate camera saturation in highly reflective areas, an adaptive fringe projection algorithm is moreover used to vary the intensity of the projected light. The hybrid approach proves to be promising as it provides an accurate and complete 3D reconstruction for complex workpieces with a high dynamic range.

Keywords: Optical Metrology, Fringe Projection, Surface Reflectivity, Polarization Camera

1. Introduction

Fringe projection (FP) is an optical measurement technique that uses structured light to capture complex surfaces. Due to its ability to provide high-resolution 3D reconstructions in a non-contact, non-destructive manner; fringe projection has become increasingly relevant in various fields like manufacturing, quality control, aerospace and medicine[1, 2]. However, for many of its applications it can not yet reach its full potential as the state-of-the-art industrial fringe projectors remain unable to (accurately) measure reflective surfaces and high-dynamic-range (HDR) sceneries [2]. A common solution is to spray the surface with an anti-reflective coating, which can be a time-consuming task and may be undesirable for delicate surfaces. Furthermore, the uniformity and thickness of the powder will influence the measurement accuracy [3].

During the measurement of shiny workpieces, saturated pixels caused by specular reflection directed towards the camera, are the main reason for the loss of 3D information. Therefore, Lin et al. developed an Adaptive Fringe Projection (AFP) technique that calculates the optimal pixel-wise projection intensity to avoid camera saturation [4]. This method ensures a high signal-to-noise ratio (SNR), but proves to be less effective when dealing with HDR situations.

Placing a polarization filter in front of the projector and camera of a FP system, can reduce specular reflection and enlarge the dynamic range. However, this approach tends to be rather inneficient and time-consuming. A more recent approach is to use a polarization camera that can capture four images with different polarization directions simultaneously. Salahieh et al. introduced a method where the most appropriate polarization channel is chosen to ensure a better SNR compared to a single polarization image [5]. The four polarization images are used to form one measurement. However, polarization filters can not eliminate reflection caused by external light sources. Additionally, they tend to lower the intensity range. Both AFP and polarization algorithms contribute to image saturatation avoidance, however neither will cause complete elimination.

In this paper, a hybrid method that combines an adaptive fringe projection method and a polarization camera is proposed to enable accurate and complete measurements of complex workpieces with both bright and dark areas. In section 2, the general fringe projection process is described and the methodology of the different experimental methods is given. Section 3 provides a description of the experimental setup. Section 4 compares the proposed methods to a reference dataset and section 5 summarizes our conclusion.

2. Methodology

2.1. N-step phase shifting algorithm

During the fringe projection process, an N-number of sinusoidal fringe patterns are projected onto the workpiece to create a phase map [3]. The intensity I of the fringe patterns can be expressed as:

$$I_i(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) + \delta_i] \qquad (1)$$

where (x,y) is the pixel coordinate of the image plane, $I'(x,y)$ is the average intensity, $I''(x,y)$ is the intensity modulation, $\phi(x,y)$ is the unknown phase value and $\delta_i = 2\pi/N$ is the phase shift between the fringe patterns (with $i = 0, \dots, N-1$).

A phase map is needed to retrieve the height information of the workpiece. For an N-step phase shifting algorithm [2], the phase is calculated as:

$$\phi(x_c,y_c) = \tan^{-1}\left[\frac{\sum_{n=0}^{N-1} I_i(x_c,y_c)\sin(2\pi n/N)}{\sum_{n=0}^{N-1} I_i(x_c,y_c)\cos(2\pi n/N)}\right] \qquad (2)$$

where $I_i(x_c, y_c)$ is the pixelwise intensity of the captured camera image. Equation (2) results in a wrapped phase map that ranges from $-\pi$ to π. As a continuous phase map is needed, it has to be unwrapped by removing the 2π discontinuities. In this paper, a binary coded pattern [6] will be used to retrieve the absolute phase. From the unwrapped phase, the height information of the workpiece is calculated and a pointcloud is generated.

2.2. Adaptive fringe projection (AFP) method

The amount of camera image saturation is dependent on the exposure time and the intensity of the projected light. While changing the exposure time has a global effect, the projected intensity can be adjusted locally. The optimal pixelwise projection intensity is calculated such that the camera image stays below the saturation limit, while maintaining a decent SNR. The different steps of the AFP method are visually represented in Figure 1 and further described in the next paragraphs.

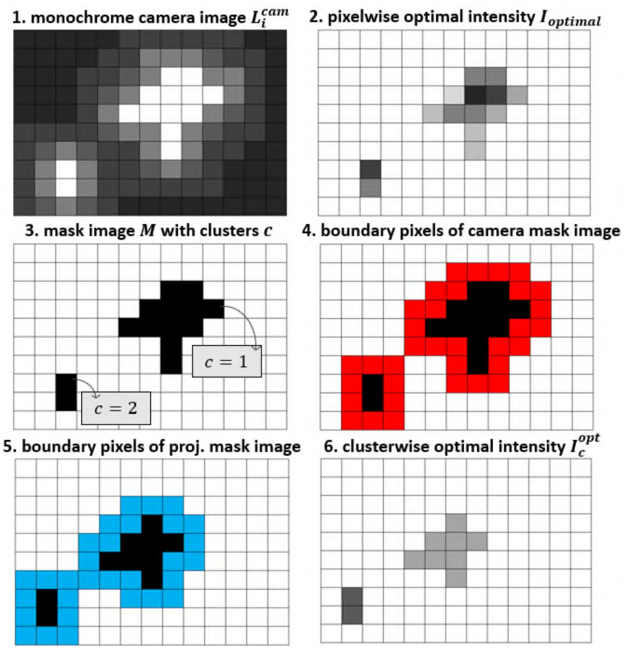

Figure 1: Visual representation of the AFP method

A series of images $L_i^{proj} = \left\{\frac{255i}{n} \mid i = [1, n]\right\}$ with a uniform intensity are projected onto the artefact to be measured. A corresponding camera image L_i^{cam} is captured for each projected image. For every individual camera pixel, a set $A(x, y) = \{i \text{ such that } L_i^{cam}(x, y) < 255\}$ is defined. From this, the optimal intensity $I_{optimal}$ is calculated for each pixel position:

$$I_{optimal} = \begin{cases} \max_i\{L_i^{proj} \mid i \in A\}, & \text{if } A \neq \emptyset \\ 0, & \text{if } A = \emptyset \end{cases} \quad (3)$$

Once the optimal intensity is known for the camera pixels, their value has to be mapped to the corresponding projector pixels.

By applying the phase shifting algorithm, the correlation between camera and projector image is found. Because the phase value cannot be evaluated correctly for saturated pixels, a camera mask image M^c is created to exclude them:

$$M(x, y) = \begin{cases} 0, & \exists i \in [1, n] \text{ such that } I_i(x, y) \geq T \\ 255, & \text{otherwise} \end{cases} \quad (4)$$

where I_i are the phase shifts captured by the camera and T is the chosen mask treshold, often a bit lower than the saturation threshold of 256 as a safety margin for noise. All pixels for which $M = 0$, are assigned a cluster number c, where the pixels belonging to the same cluster are connected to eachother. For each of the enclosed saturation clusters within the masked image, a global optimal cluster intensity I_c^{opt} is calculated as:

$$I_c^{opt} = \begin{cases} \min_{(x,y) \in c}\{I_{optimal}(x, y)\}, & \text{if } \overline{I_{optimal}} > 100 \\ 100, & \text{otherwise} \end{cases} \quad (5)$$

The optimal intensity clusters can be mapped towards the projector image, using the phase value of the pixels that directly surround the saturated clusters. Their location is found by applying boundary tracing techniques [7] to the mask image. The workpiece is scanned again with the adapted fringe patterns.

2.3. Multi-polarization Fringe projection

A polarization camera has a polarization filter array placed directly on top of the image sensor grid [8]. The array consists of a repeated 2x2 pattern of polarization filters with four different angles (0°, 45°, 90° and 135°) as shown in Figure 2. This enables the camera to capture four polarization images in a single shot. The projected fringes pass through a linear polarizing filter, before falling onto the workpiece. The surface and reflectivity of the workpiece modulate the Degree and Angle of Polarization (DoLP, AoLP), resulting in different behaviour on the four polarized camera images. For each pixel, the most appropriate polarization channel can be selected.

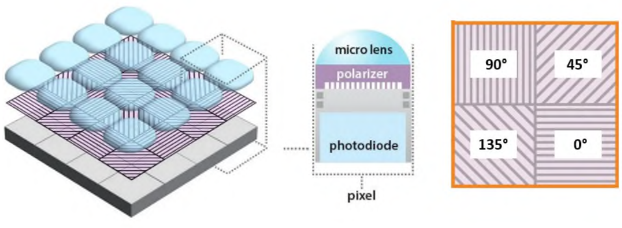

Figure 2: Polarization camera image sensor

The multi-polarization technique in this paper will, for each pixel, select the polarization channel with the highest greyvalue p_{max} that lies below the saturation threshold:

$$p_{max}(x, y) = \max_p\{I_p(x, y) \mid I_p(x, y) < 255\} \quad (5)$$

with $I_p(x, y)$ the intensity of a certain pixel in the polarization images ($p = [1,4]$). When the intensity of a pixel is above the threshold in all polarization channels, a random channel can be selected but no valuable height information will be retrieved.

For all phase shifts, data will be extracted from the optimal channel. This ensures the highest possible intensity range and therefore a better SNR in comparison with using a single polarization filter.

2.4. Hybrid fringe projection method

In our hybrid fringe projection method, adaptive fringe projection and multi-polarization fringe projection are combined consecutively to further eliminate saturation and get more accurate and stable results. To ensure the highest SNR, the fringe pattern is only adapted for pixels that are saturated in all four polarization channels.

3. Experimental setup

The experimental fringe projection setup, as seen in Figure 3, consists of a projector (DLP LichtCrafter 4500 Texas Instruments, 912x1140 pixels), a monochrome camera (Basler Ace acA4024-29, 4024x3036 pixels) and a polarization camera (Blackfly S USB3, SONY sensor Polar-Mono, 2448x2048 pixels). The projector and one camera are installed on a rigid aluminum baseplate, attached to a tripod stand. The cameras can be interchanged and the projector lens can be equipped with a linear polarizing filter. An N-step phase shifting algorithm (N=10) is used to scan one side of an aluminum workpiece (200 mm x 200 mm), produced by incremental sheet forming (see Figure 4). It comprises both convex and concave surfaces.

Five different measurements are performed:

- M0 : reference measurement with anti-reflective spray (monochrome camera)
- M1: normal measurement, without any additional algorithms (monochrome camera)
- M2: AFP measurement (monochrome camera)
- M3: polarization measurement (polarization camera, + linear polarizing filter)
- M4: hybrid measurement (polarization camera + linear polarizing filter)

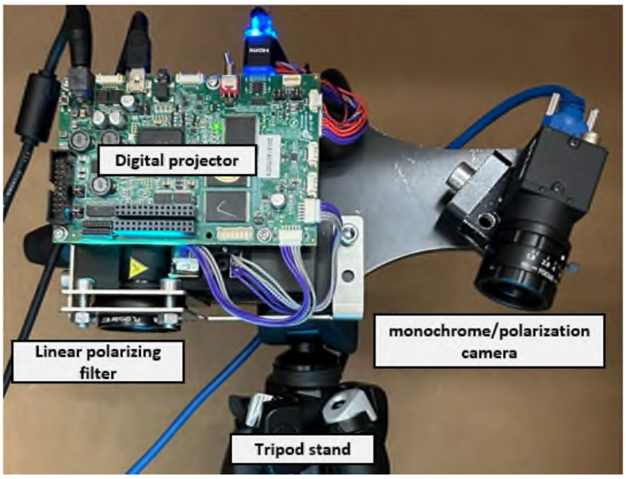

Figure 3: Experimental fringe projection setup

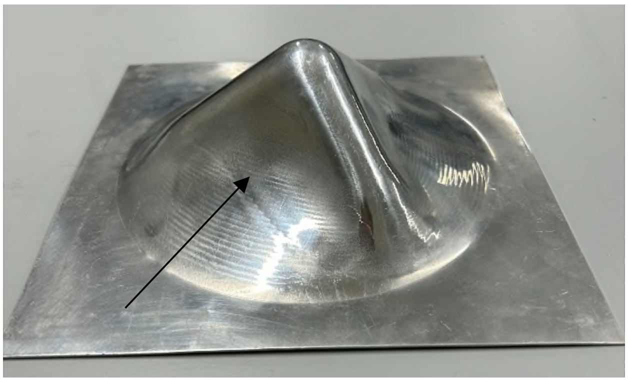

Figure 4: Aluminum workpiece produced by incremental sheet forming, with an arrow indicating the scan direction

4. Results and discussion

The measurement quality of the different 3D reconstructions is determined by two important factors. The point cloud integrality (PCI) serves as a metric for coverage percentage and is the ratio of the number of points in a certain area (M1-M4) and the number of points of the reference measurement with full coverage (no holes, M0) [3]. The topography fidelity measures the bias and standard deviation (std) of the deviation between the measurements (M1-M4) and the reference (M0).

Special attention is given to two surface areas: a bright area where the light is reflected directly to the camera and a dark area where the light is reflected away from the camera. On Figure 5, they are indicated with a red box and green triangle respectively.

It has to be noted that the measurements executed with the polarization camera (M3 and M4) have a lower lateral resolution compared to the monochrome camera(612x512 pixels instead of 4024x3036 pixels for each polarization channel). Also, when repeating the individual measurements (M0-M4) multiple times, the average deviation between them stays below 0.04 mm.

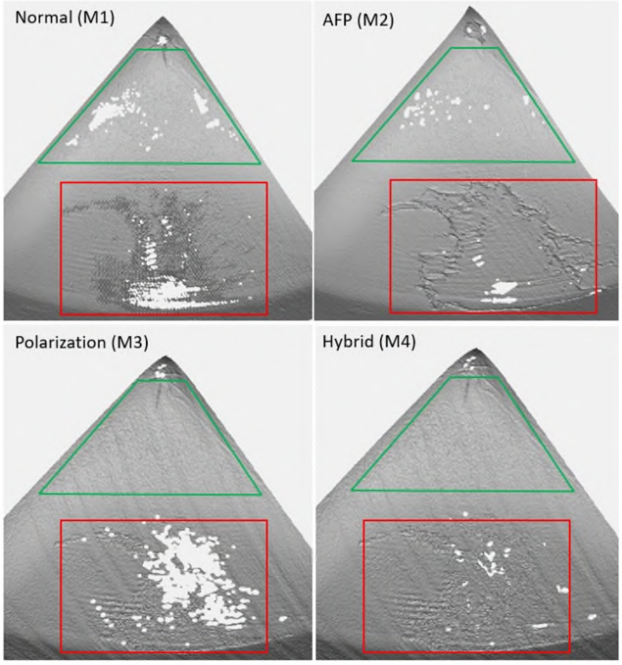

Figure 5: 3D reconstruction of a normal (M1), AFP (M2) , polarization (M3) and hybrid (M4) measurement. The red box and green triangle indicate the reflective and dark areas respectively.

4.1. Reflective area

In Figure 5, the 3D reconstruction of the normal measurement (M1) has a number of holes, as the areas that possess the most reflectivity could not be reconstructed. Meanwhile, areas that suffered from partially saturated pixels, cause a noisy and inaccurate point cloud. This observation is supported by table 1, which shows that the normal measurement deviates 0.223 mm on average from the reference measurement (M0). The large std shows the noisy character.

The AFP method improves both the bias and the integrality of the pointcloud (see Table 1). From Figure 5, it can be observed that the deviations in M2 are mostly situated around the edges of the reflective area. This is due to the sudden intensity change in the adapted fringe pattern that introduces slightly more errors in the phase unwrapping algorithm. The noise due to saturation however, is reduced.

The polarization method does not perform well for very bright areas, with M3 having the lowest PCI of all four. Similar to the normal measurement, the pointcloud is quite noisy with a higher deviation. This is partly due to reflections caused by an external light source, which can not be eliminated by the polarization camera. The PCI is also affected by the saturated areas and the random, sudden changes is the polarization channel surrounding them.

Table 1: Topography fildelity of the four fringe projection methods compared to the reference measurement (reflective area)

Method	PCI in %	Bias in mm	Std in mm
Normal (M1)	78.33	0.223	0.168
AFP (M2)	92.78	0.105	0.096
Polarization (M3)	67.38	0.213	0.175
Hybrid (M4)	96.26	0.116	0.086

The hybrid method produces the most complete pointcloud with 96.26% PCI. M4 has a bias equal to the AFP method, which is very good considering the lower lateral resolution. The measurement is less affected by the intensity change in the adapted fringe pattern, but shows a bit more general noise. This noise can be explained by the overall fringe intensity reduction associated with polarization filters and the limitations of the camera

4.2. Dark area

The normal measurement of the dark area has the lowest coverage percentage, which is clearly visible in both Figure 5 and Table 2. Especially on the left and right sides of the triangular area, the geometry of the workpiece reflects too much light away from the camera. As the contrast between the fringes is too low, there is no phase information available and no points are generated. Additionally, the presence of extensive clusters of saturated pixels tends to lower the overall intensity of the other pixels. The application of the AFP method addresses this aspect and therefore partly reduces the problem, increasing the PCI by 8% in Table 2.

Both the polarization method and the hybrid method prove to be very effective within the dark area, with a PCI above 99% . If the polarization direction of the incoming light is properly aligned, having four polarization channels ensures there is always one channel that will eliminate specular reflection directed towards the camera; increasing the dynamic range in other areas. The bias of the methods that use the polarization camera does not go below 0.1 mm. However this could be improved with a larger camera resolution.

Table 2: Topography fidelity of the four fringe projection methods compared to the reference measurement (dark area)

Method	PCI in %	Bias in mm	Std in mm
Normal (M1)	78.15	0.103	0.076
AFP (M2)	86.87	0.075	0.026
Polarization (M3)	99.86	0.116	0.091
Hybrid (M4)	99.92	0.113	0.091

4.3. Overall performance

From the results for the reflective and dark area, it is clear that the AFP and polarization technique prove to be most effective in opposing areas. While the AFP technique effectively improves the coverage and accuracy within the reflective area, the polarization technique fails to do so. In the dark area however, the polarization technique outperforms the AFP technique with almost full coverage.

The hybrid method effectively combines the benefits of both methods and provides an overall coverage of 98% with a bias of 0.116 mm. The hybrid methods proves to be highly suitable for workpieces with a high dynamic range and complex forms, which is an improvement compared to the other methods. To further improve this method, a polarization camera with a higher resolution can be used and/or the monochrome camera and the polarization camera can be operated simulatiously to reduce time and complexity.

5. Conclusion

The measurement of reflective objects is still a challenge, especially when they require a HDR due to a complex surface geometry. Adaptive fringe projection performs great in reflective areas, however lacks to provide full 3D reconstruction in areas with low intensity. Polarization filters on the other hand broaden the dynamic range, but still struggle with high reflectivity towards the camera. In this paper, a hybrid method is developed, that effectively combines the benefits of both AFP and polarization filters. It proves to provide (almost) complete 3D reconstruction of complex shaped workpieces with a high dynamic range with an accuracy of 0.1 mm.

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