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3D Reconstruction of mirror-like surfaces by smart deflectometry

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Abstract—Specular and mirror-like surfaces are difficult to reconstruct by the fact that light of the surrounding environment is reflected off the surface. Nowadays, it is still a challenge in many application fields to get a fast and accurate reconstruction of specular objects. 3D acquisition by deflectometry involves estimating the 3D profile of a specular surface by analyzing the image of a light source or a pattern captured by a camera after reflection on the surface. These techniques require the knowledge of the location and the orientation of the camera and the orientation of the light source. If camera calibration is a process widely known and controlled and guaranteeing good accuracy, estimating the orientation of the light source is still an issue. We propose to overcome it by using a light source whose the color changes according to the orientation. Indeed, we implement a vision system of light source’s position recognition by the color in simulation with the 3D computer graphics software Blender, we define a calibration technique and we suggest some possible light sources to export our simulated vision system to reality. Plus, we explore the potential benefit of light field in order to model such a system.

Index Terms—deflectometry, 3D reconstruction, specular, mirror-like

I. INTRODUCTION

The 3D reconstruction of the surface of specular objects is an important process and it is still a challenge for many application fields as the automobile industry, astronomy and advanced manufacturing to get a fast and accurate reconstruction of such objects. Deflectometry is a big set of techniques established to make the acquisition of specular surfaces. Among these techniques, *shape-from-distortion* is commonly used. It requires the reflection of a known pattern at the surface of the specular object. Another deflectometry technique, *direct ray measurements*, shows very accurate measurements which makes it promising. It is a geometric method which traces the light rays on the surface of the specular object. In other words, it employs the principle of light field applied to illuminations. The main drawback of these techniques of deflectometry in general is the light pose estimation. Indeed, as the pattern or the light source is generally displayed by LCD screens or by big plane objects, the estimation of the position of the light source remains a problem.

In this paper, we consider the problem of calibration encountered by the previous techniques. To solve it, it is necessary to reduce the size of the light source of the system in order to estimate it as a single point in space. As a solution, we propose a new deflectometry method based on a variation of the light field illumination principle. Indeed, our method is smart in a sense that it estimates the direction of the

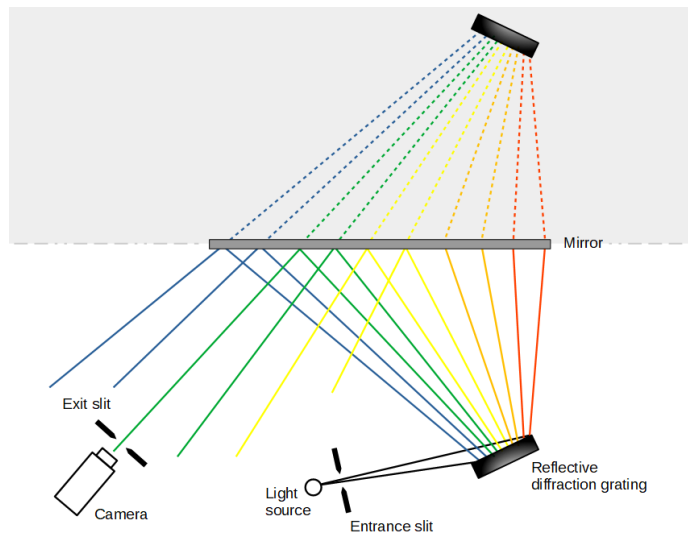


Fig. 1: Schema of the principle of our method: each ray emanating from the light source has its own properties of wavelength and direction.

reflected light ray thanks to its color properties to thus be able to get the perpendicular line to the mirror-like surface by triangulation. A reflective diffraction grating could represent such a light source, since its color varies depending on the view-point, meaning every light rays have their own properties of wavelength and direction. Plus, the optical formulas of the reflective diffraction grating are well-known and then usable. The light source we propose to use has never been studied in the field of deflectometry. We prove that 3D reconstruction of mirror-like objects can be achieved using a light source that employs a new manner to use the light field illumination principle. Then, we propose an appropriate calibration process to estimate the position of the light source of our system.

This paper provides in Section II a brief overview of related works concerning deflectometry and the light field principle. Then, in Section III we describe the proposed principle of our method and its calibration in details. Section IV presents our system simulated with the computer graphics software Blender, and experimental results proving the effectiveness of our approach.

II. RELATED WORKS

A. Deflectometry

Deflectometry is a set of techniques to make the 3D reconstruction of specular surfaces. Ihrke et al. [1] category

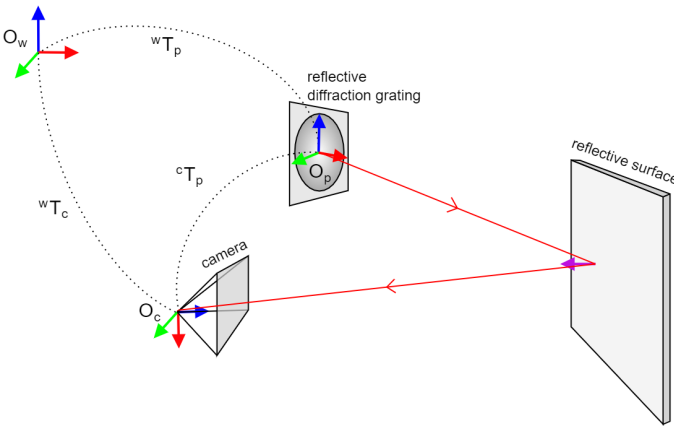


Fig. 2: Coordinate systems of objects of the system.

all acquisition approaches for reflective objects. *Shape-from-distortion* [2] is a technique based on the principle of the phase measuring deflectometry [3]. The basic principle is to project two-dimensional sinusoidal fringe patterns onto a screen located remotely from the surface under test and to observe the fringe patterns reflected via the surface, then estimate the difference between the reflected and the real fringe pattern by applying the phase-shifting algorithm. This technique has established itself powerful and is used with great success in many industrial applications, even if it remains major challenges and deficiencies, especially for calibrating the screen [4]. *Direct ray measurements* is another technique used to avoid the depth-normal ambiguity, a main problem in deflectometry. As we can guess by the by the name of the technique, viewing rays reflected by the specular object can be measured. In general, a calibrated planar target is located at different positions and the distorted pattern is observed by a camera. The technique consists in measuring the reflected ray by decoding two world positions for every pixel. Approaches based on triangulation [5] [6] and polarization [7] [8] have been demonstrated. By the computation of the direction of light rays, this technique employs the principle of light field. In deflectometry, the main problem which remains is the calibration of the light source. Indeed, the light is always a big plane object and is consequently difficult to calibrate.

B. Light Field

Light Field is a concept to describe the amount of light flowing in every direction through every points in space. The theoretical background for Light Field is the plenoptic function. [9] [10] Light Field principle has been first conceptualized for cameras. [11] [12] As said in Section II-A, some deflectometry techniques employ the principle of Light Field by the light source of their systems. The new formulation of this principle applied to light sources is called Light Field Illumination [13]: the intensity of a light ray emanating from a light source depends on its own direction. The illumination component can be expressed as an directional light source [14] or a point light source [15]. In the field of deflectometry, this conceptualization of illumination leads to the *direct ray measurements* technique: it generally uses

two planes which are crossed by rays of a light source, and the reconstruction is parameterized by the direction and the intensity of the reflected ray. [8] [7] Furthermore, on the basis of this plenoptic illumination model, Herschbach developed an optical system generating a structured light field from an array of light sources by means of refracting or reflecting light structuring element [16]. This optical system is interesting since the optical formulas are well-known making the spacing between light rays calculable. Besides, it is possible to associate the light field illumination principle to the optical phenomena of diffraction. Indeed, diffraction defines light rays by their wavelength and orientation. So, by knowing the color value of a ray, it is possible to get its direction in space. We propose to use this variation of the Light Field Illumination principle in deflectometry. This could be done using a diffraction grating by reflection. Since the grating is very small, we could consider its center as the point light source of the system. This could ease the calibration process of a deflectometry system.

III. METHODOLOGY

A. Geometric model of the system

We propose a new deflectometry method which uses an illumination based on the Light Field principle. Since each light ray emanating from a single light point has its own properties of wavelength and direction, we are able to determine the light ray reflected in the mirror and perceived by the camera. We calculate its direction in space by using triangulation and get the normal line at the reflection location in the mirror. We have conceived our method based on the behavior of the reflective diffraction grating : an incident white light ray is diffracted by the grating in multiple colors at calculable angles. Figures 1 and 2 illustrate the principle of our method.

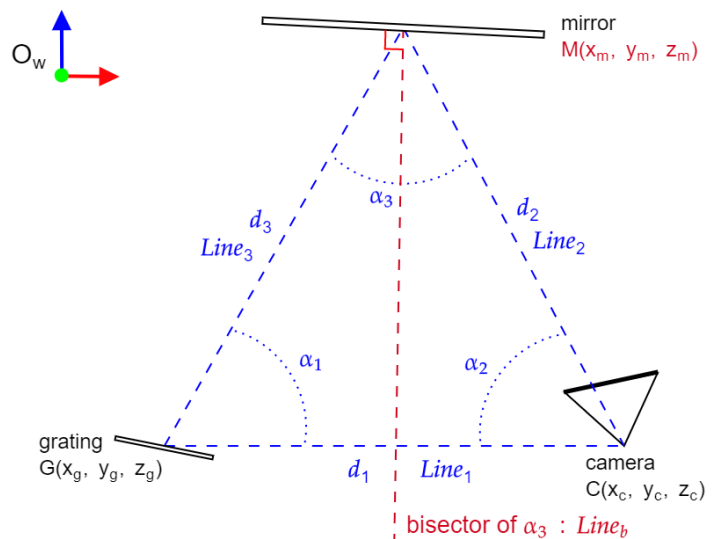


Fig. 3: System's triangulation. The bisector $Line_b$ of the angle α_3 is in fact the normal line of the mirror at point M .

B. Triangulation

We base our calculations described in this Section, on the triangulation schema in Figure 3. Once the camera captures the reflected light source on the mirror, we binarize the image to extract pixels which reflect the light source in the mirror. We compute the part with reflection in HSV domain, in order to obtain the hue value of these pixels. Then, we have selected two methods to get the hue value of the perceived color:

- Associate each pixel to its own hue value and get several hue values with corresponding pixels in one image.
- Compute the mean hue value of all colored pixels and the mean position of all these pixels.

Once having the hue value, we recover the direction of the incident ray of the light source by computing the first angle of the triangulation α_1 pointing the light source (Figure 3). Since the light source provides information about wavelength and direction along a single axis, we only take into account the horizontal position of the reflected light source on the image sensor. Knowing this information and the configuration of the camera, we get the equation of the line $Line_2$ (Figure 3) passing through the focal point, image sensor and the mirror. Moreover, by computing the equation of $Line_1$ with the location of the light source and the one of the camera, we compute the angle α_2 at the intersection of these two lines $Line_2$ and $Line_1$. Then the distance d_1 between the illumination and the camera is calculated. Hence, we have two angles and one side of the triangle and we can proceed to the triangulation calculations to get the last angle α_3 of the triangle and the distances d_2 and d_3 between the mirror and the camera and the light source (Figure 3):

$$\begin{aligned} \alpha_3 &= 180^\circ - \alpha_1 - \alpha_2, & d_2 &= d_1 \times \frac{\sin(\alpha_1)}{\sin(\alpha_3)}, \\ & & d_3 &= d_1 \times \frac{\sin(\alpha_2)}{\sin(\alpha_3)}. \end{aligned} \quad (1)$$

Thus, we get the x_m and y_m coordinates of the third point of the triangulation, with a_2 the slope of $Line_2$:

$$x_m = \sqrt{\frac{d_2^2}{a_2^2 + 1}}, \quad y_m = \sqrt{\frac{d_2^2}{1 + \frac{1}{a_2^2}}}. \quad (2)$$

A first 2D bisector $Line_b$ is calculated with $Line_2$ and $Line_3$. For now, we consider the three points on a same plane. To get the 3D bisector and the third coordinate z_m of the point at the mirror, we turn the light source to 90° and we get the color value the same method as described previously. This new color gives a new angle of the ray emanating from the light source in the third axis (vertical). We add this new angle as a rotation of the bisector and the M point on their third axis (Figure 3). So the 2D bisector and the 2D M point becomes 3D elements, and the 3D bisector is in fact the normal line of the mirror at the observed reflection point M .

C. Calibration

Our proposed calibration method uses a pattern equipped with a mirror on its center. The well-known method of Zhang [17] allows us to estimate the position and orientation of our

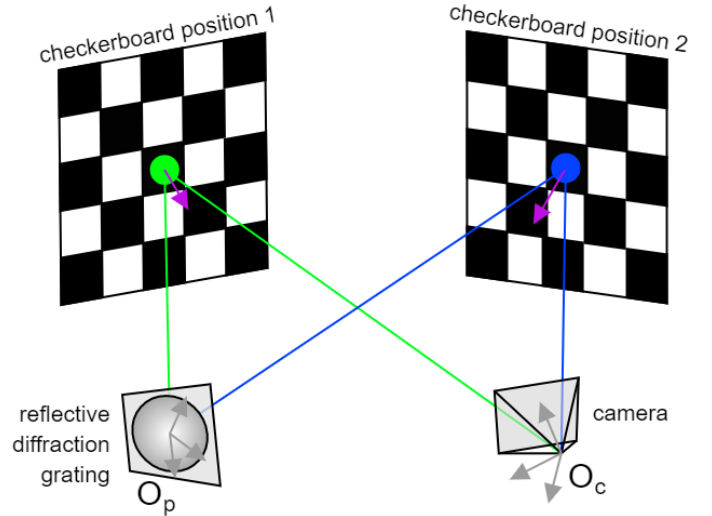


Fig. 4: Calibration principle adapted for our system. The position of the light source, here the reflective diffraction grating, is estimated by calculating the normal line of the pattern on its center point.

pattern, and so, the position and orientation of the mirror at the center of the pattern. Depending on the position and the orientation of the mirror, the color of the light source perceived by reflection in the mirror varies. By capturing images of the pattern for different reflected colors, we are able to define the light ray descended from the light source for each image. This way of doing allows to configure the camera and the position and orientation of the light source in a same calibration process. We place a small mirror on the center of the pattern so that it is possible to see the reflection of the light source on its surface. Such an object is possible by cutting a hole in the center of the checkerboard and paste it on a plane mirror. We capture images for different pattern positions and when the light source is reflected in the mirror of the pattern. In this way, the camera observes different colors reflected in the mirror, as illustrated in Figure 4. Thanks to Zhang's method [17], we are able to obtain the intrinsic and extrinsic parameters of the camera and then the positions of the checkerboard's corners in the world by projection. Once having 3D points of corners, by taking the first and the last corners of the pattern, we can estimate the 3D position of the mirror :

$$M = \left(\frac{x_{C_1} + x_{C_2}}{2}, \frac{y_{C_1} + y_{C_2}}{2}, \frac{z_{C_1} + z_{C_2}}{2} \right), \quad (3)$$

with $C_1 = (x_{C_1}, y_{C_1}, z_{C_1})$ and $C_2 = (x_{C_2}, y_{C_2}, z_{C_2})$ the first and the last corners of the checkerboard and M the central point of the pattern, where the mirror is located. We need at least three positions of corners to compute the perpendicular line of the pattern. Mathematically speaking, the perpendicular line of the pattern is the perpendicular vector of two other vectors laying on the same plane, and can be calculated by the cross product of the two vectors. This line positioned in the middle of the pattern is in fact the normal line of the mirror. Afterwards, knowing the angle between this normal line and the perceived light ray, we estimate the vector of the reflected

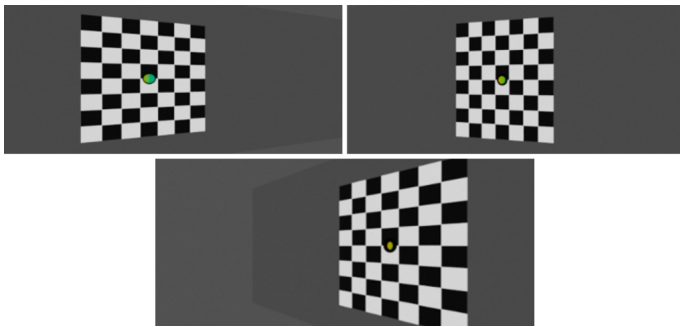


Fig. 5: Examples of images to simulate the calibration process. The light source is reflected in the center of the pattern.

ray going from the mirror to the light source, using the rotation matrix described by the Euler-Rodrigues formula :

$$\theta = a \cos \frac{V_1 \times V_2}{\|V_1\| \|V_2\|}, \quad (4)$$

with θ the angle between the vector V_1 representing the line from the mirror to the camera, and the vector V_2 representing the normal line of the pattern, and :

$$U = V_1 \times R(a, b, c, d), \quad a = \cos \frac{\theta}{2}, \quad (5)$$

$$b = c = d = \frac{-V_2}{\sqrt{V_2 \times V_2}} \times \sin \frac{\theta}{2},$$

with U the vector representing the line from the mirror to the light source calculated with V_1 and the rotation matrix R . Finally, we need at least two images to get two different line equations of the reflected ray, to calculate their intersection which is in fact the estimation of the position of the light source in the world.

IV. EXPERIMENTS

A. Implementation

We simulate our system with the 3D computer graphics software Blender, and design the light source presented in Figure 6. This pinhole light source provides a color which varies depending on the point of view.

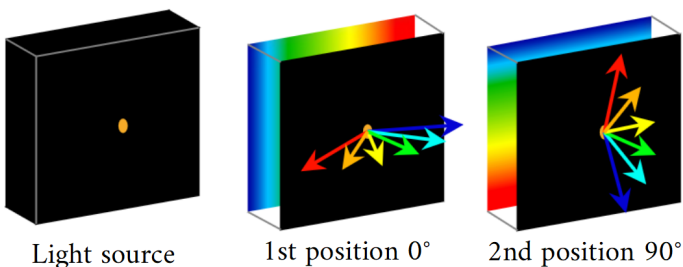


Fig. 6: The pinhole light source. Depending on the viewpoint, the hole provides a different color.

We implement the method described in Section III-B and we base our simulation the most possible on a real system, in order to estimate some noises or errors that we could encounter in real world. The idea is to prove the feasibility and reliability

of a deflectometry system which uses a new light source based on the light field principle. During the process, we move the object to be reconstructed along 2 axis since this is the most general motion established in deflectometry. Calibration images in Figure 5, made with Blender, show that it is possible to create such a pattern and visualize the reflection of the light source for different positions of the pattern.

B. Results and discussion

	Reconstructed points			
	Spherical object		Plane object	
	method 1	method 2	method 1	method 2
ϵ_{mean} (%)	3.718	6.069	1.270	2.938
ϵ_{min} (%)	0.188	0.003	0.177	0.358
ϵ_{max} (%)	9.442	21.292	3.026	4.661
ϵ_{mean} (m)	0.186	0.303	0.202	0.465
ϵ_{min} (m)	0.009	0.0001	0.028	0.057
ϵ_{max} (m)	0.472	1.065	0.498	0.755

TABLE I: Experimental errors for the position of the reconstructed points. Sphere diameter is 12 meters.

First, we consider the error due to calculation. Indeed, we use the equation based on the behaviour of the hue emitted by the light source according to the angle from the view point to the normal line of the light source. We separate this behaviour in multiple parts and compute a linear regression to every part in order to get the equation line with the smallest root-mean-square (RMSE) possible, varying between 0.7° and 0.1° . The more the behaviour is linear the smaller the RMSE is, and vice versa. It means that the value of this error really depends on the behavior of the direction and color properties of the rays of the light source. In a further work, the selection of another light source will have to take into account this problem of rays' behaviour in order to reduce or, if possible, remove this error by getting a light source with a linear behaviour of color versus viewpoint.

We evaluate two different object shapes: a plane and a sphere. Table I evaluates the errors for 126 reconstructed points and Figure 7 allows to get a first glance at the results obtained with point clouds and normal lines to the mirrors. The fact that the plane provides less errors than the sphere leads us to emit an hypothesis: it could be caused by a geometric distortion of the perceived color due to the curved surface of the sphere. Indeed, as we capture a beam of rays, the beam covers a larger part of the surface than just a single ray. So, for a sphere, this part of the surface is curved and not planar, and it means it has multiple normal lines which have different orientations, whereas this part for a plane has multiple normal lines which have the same orientation since they are parallel to each other. Having such a difference of orientations of normal lines in a small part of the surface of the mirror may lead to an unintended range or separation of colors. Then, the perceived color would be in fact a distorted image of the reflected color caused by spherical aberration, which we would not obtain with a plane mirror.

According to table I, the method n°1 which computes the mean hue value of all the colored pixels and the mean position of all these pixels in the image, is way more better than the

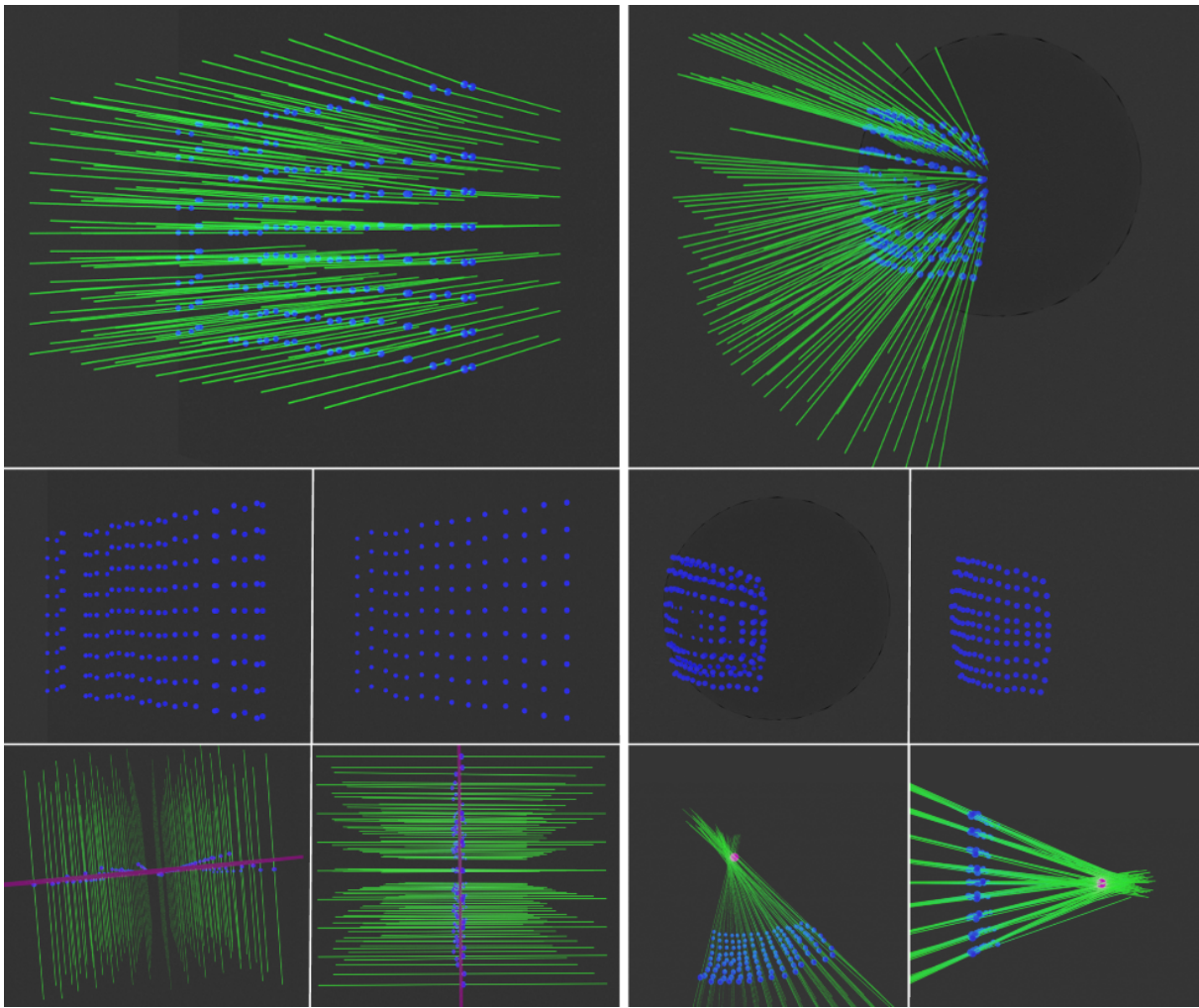


Fig. 7: Reconstructed point clouds (blue) and normal lines (green) for a planar and a spherical mirror. The planar mirror is represented in pink as the center of the sphere.

method n^2 , the pixel-by-pixel method (Section III-B). This shows it is preferable to apply a method based on the position and color average of pixels. Indeed, the theoretical ray-by-ray method is in practice a "beam-by-beam" method : the system captures a small beam of several light rays.

Normal lines are directly linked to reconstructed points (Section III-B). Moreover, since we choose a spherical and a planar object to reconstruct, it is interesting to visualize their normal lines. Indeed, for the sphere, the normal lines should meet at the center point of the sphere. In spite of some errors due to the position of the reconstructed points, we can see in Figure 7 the normal lines are all directed in the area around the center of the sphere. In the case of the plane mirror, all the normal lines are supposed to be parallel to each other. We observe this situation in the images captured during the experiments in Figure 7. To conclude, the correct behaviours of normal lines among the tested objects are encouraging and validate our method.

V. CONCLUSION

We have proposed a simple yet efficient way to calibrate a deflectometry system following the widely known method of Zhang [17]. We have integrated the light field as a solution in deflectometry, by studying RGB in a different manner than other RGB methods: compared to Tarini et al. [2] which uses color property of an RGB light source as patterns, we use color property of an RGB light source to recover the direction of the reflected light ray. This solution is an extension to the plenoptic illumination function, which is mainly used in deflectometry through *direct ray measurements* techniques. Indeed, whereas the common used plenoptic light sources are defined by the light intensity varying with the direction of their rays, our proposed plenoptic light source is defined by the color varying with the direction of its rays. So, the color value has a real importance in our system and this makes our deflectometry method unique.

Our experimental results are encouraging and validate our proposed approach. One limitation is clearly the behavior of direction and color properties of light rays which is not linear for the chosen light source. Besides, we have made the

hypothesis that some of the obtain errors could be caused by a color distortion due to the curves of the mirror. One of the next steps is to elaborate a real system by leaning on the established simulated system. As we proved through simulation that a 3D reconstruction of specular surfaces is possible by using the proposed technique, we need to evaluate its limitations and capacities in real world.

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