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3D Scanning Solution for Textured Object using Photometric Stereo with Multiple Known Light Sources

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Abstract

Photometric Stereo is an efficient image-based 3D reconstruction technique that has been used to reproduce very high-quality reconstructions. However, it faces a couple of limitations: first, one needs to capture images of the 3D scene with different illumination directions. It implies that the 3D scene remains motionless during illumination changes, which prevents the reconstruction of deforming objects. Second, the captured images must be obtained from a single point of view. This leads to depth-map based 2.5D reconstructions, instead of full 3D surfaces.

But compared to other 3D imaging methods such as geometry modeling and 3D-scanning, this solution is a valuable tool when examining embossed surfaces where grain texture, carving, deteriorations can be identified.

In this paper, we give an outline of Photometric Stereo and provide a case study of our 3D scanner.

Motivation & Problem

i2S today relies on 40 years of experience in image capturing and processing technology, especially in the development of scanners and associated software for digitizing books, maps, pictures, paints and other heritage documents.
Nowadays, in some cases, Archives Services have the need to use information about the relief of objects they manage. And it happens that the color information does not reveal roughness.
Technology improvements are welcome here to gather information about surface topography of digitized objects in addition to the full color image (e.g. on coins, writing tablets, grain of the wood, fossils, wallpapers, paintings) to improve display and rendering.

There are many ways to highlight the relief of a surface [1] such as the RTI [2] (Reflectance Transformation Imaging) or many other 3D solutions (e.g. photometric stereo [3], stereoscopic vision [4], active triangulation [5]).
To determine the most suitable approach, we took into account the limitations we are facing in this field regarding the scan quality, which are the following:

- Propose a solution to capture real 3D data (not only color or only visual 3D appearance)
- Apply ICC and keep colorimetry information on the color image (ISO 19264, Metamorphoze and FADGI standards)
- Be able to capture 3D information while maintaining a high resolution of the color image.
- Possibility to capture large formats. International A0: 841mm x 1189 mm, American Quad Demy: 45-inch x 35-inch.
- Provide flexibility between quality and productivity time
- Share and visualize the file in a software as full resolution. Allow the store in a form of a set of measurement points known as cloud of points.
- The possibility to save digitized objects into a digital gallery. To enable universal access to the 3D objects, we need to develop several, complementary methods of presenting measurement data online.

To meet these different constraints while considering scanners' architecture, photometric stereo has emerged as the best solution.

Approach

Photometric stereo is a technique in computer vision to estimate the normal surface of objects by observing that object under different lighting conditions. It is based on the fact that the amount of light reflected by a surface is dependent on the orientation of the surface in relation to the light source and the observer. By measuring the amount of light reflected into a camera, the space of possible surface orientations is limited. Given enough light sources from different angles, the surface orientation may be contained to a single orientation. From this data, it is therefore possible to acquire height information at each point of the object by advanced computation, vector analysis and differential equations.

The arrangement of light sources and the reflection of lights rays on the surface allows 3D reconstruction and gives the system its effectiveness.

The technique was originally introduced by Robert J. Woodham of the University of British Columbia in 1980 [3]. Since that time, this method has been explored for different uses, whether it has been to improve its ability to deal with complex materials [6] or lighting conditions [7]. The myriad of papers published on the topic testify to the interest that this technique has gained in the community.

Requirements

Main hardware features are about lighting. It requires at least 3 images captured with known non-coplanar directional lighting, meaning they have to illuminate in opposite directions. Besides, the lights beams must be at all points of the surface in both ways:

- *Uniform, same intensities* (1)
- *Parallel, same lighting directions* (2)

This method also requires a camera capable of capturing multiple images from the same angle of view.

Hardware Setup

We can notice that the hardware system is simplified compared to other more conventional techniques (e.g. stereoscopic vision with the calibration of at least two cameras) and is therefore adapted to the existing physical set up of scanners used for heritage preservation.

Indeed, our linear scanners in the QUARTZ range are made up of a linear camera connected to two lighting ramps. At each scan, this fixed setup travels the east-west axis by capturing at each position a line north-south axis of the scene. (figure 1)

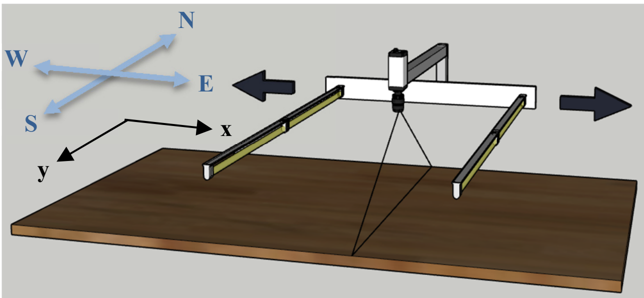

***Figure 1**. Setup of linear scanner*

Knowing that each lighting strip consists of two lights, we have 4 ways of lighting the scene in opposite directions. (North East, South East and North West, South West).

In our case study, we are going to use photometric stereo as a 3D reconstruction using 4 color images, obtained from a single camera, under 4 different illuminations. Using 2D images to reconstruct 3D object allow us to retrieve these two pieces of information at the same time from only one process.

Finally, since it is possible to trigger the 4 lights sequentially at high frequency, at each camera position, we can retrieve information under the 4 lights rather than one. The advantage of going through the scene once instead of four times (once for each of the lights) is the speed of scanning process while maintaining the comfort of the user who will have the impression that the object is constantly lit.

Constraints

We have almost all the conditions to implement photometric stereo on the scanners.
As a reminder, the aim is to retrieve information on the orientation of the surface for calculating heights. This is accomplished through the reflection of light on the east-west and north-south axes, more commonly referred to as the normal x and y image respectively.

- Variation of the normal surface of the object on x:
During the travel on the east-west axis, for each light, all columns of the scene are well lit under identical conditions (same direction and intensity). The normal x image will be correct.

- Variation of the normal surface of the object on y:
With regard to the geometrical north-south axis, we notice that each row of the image does not fully comply with the two lighting conditions mentioned above. For each light, a pixel near the middle of the scene does not receive the same intensity as a point at its north-south extremity due to non-uniformity of the lighting received (1). The same applies to the angle of reflection of light rays (2). The normal y image will be erroneous. Let's see below how these two problems can be solved from an algorithmic point of view.

Proposed Algorithm

Below, we present the main steps of the workflow implemented (figure 2). This solution is ideal for relatively flat and differentiable surfaces.

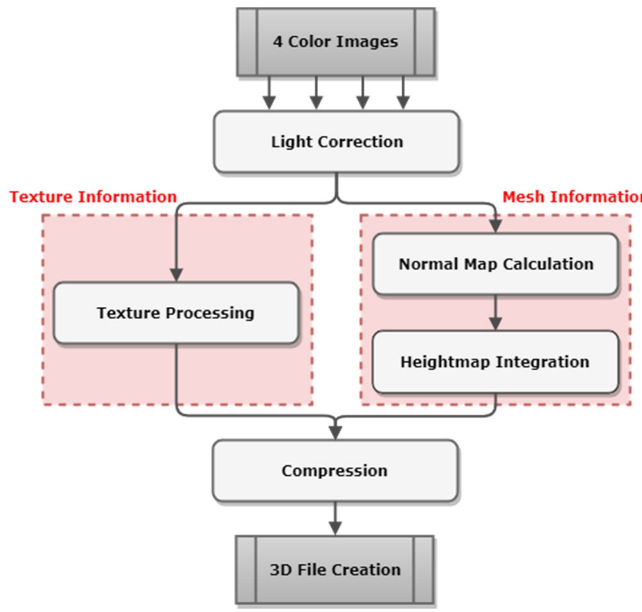

***Figure 2**. Simplified workflow of the proposed algorithm*

Light correction:
To solve the problem of varying intensity received causing an error on the normal image y that we previously highlighted (1), a light correction is made for each lighting. The value of each line of the input images is adjusted by a factor to simulate an identical perceived intensity at each point of the scene.

Then, the workflow is separated in two steps before the final construction of the 3D object, one concerning the mesh with 3D information and the other its texture, the color.

Mesh information:
Knowing the orientation of the reflection of light rays on the object highlighted by differences in intensity between images, it is now possible to calculate the inclination of surfaces in three dimensions at each point of the scene.
This reflectance map is called normal field, gradient field or normal image.

Thereafter, it is necessary to proceed with the integration of the normal field which is the most crucial and complex step. This means that we use an algorithm that solves the normal equations to calculate the height at each point of the image according to its own surface orientation and the one of its neighborhood until these two pieces of information match. The idea is to correlate the height of each point according to the orientation of its surface. (figure 3)

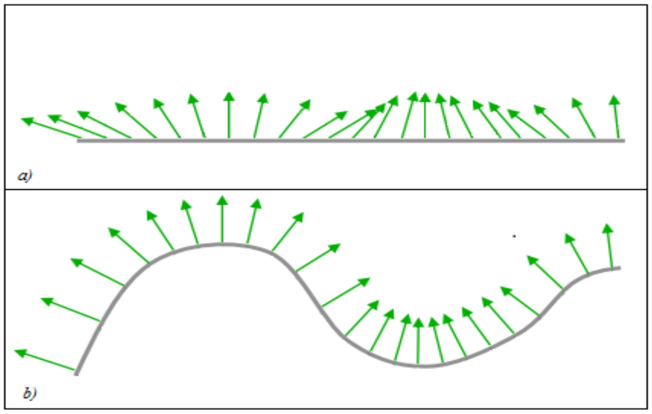

Figure 3. *Representation of the surface and the reflection of light rays on it. a. normal field, b. match height information with normals*

Depending on the method, a little error on the normal field can spread and amplify along the gradient integration resolution. Especially for local solutions that run the gradient field from one point to another. The aim is to reduce the impact of normal field errors on the integration of height map. To that extent, we compute the global least squares reconstruction of a surface from its gradient field. [8]

Moreover, Tikhonov Regularization [9] is used during the integration process to compensate the non-parallelization of light rays perceived on the normal y image that we saw earlier (2). Doing so, we correct the artificial curvature calculated of the object without crushing the relief information.

Texture information:
The 4 input images are combined to create the texture image.
As the camera is positioned above the scene, we will not acquire the color information of the 3D object's borders. An edge detection on the texture image is done and an inpainting applied at this location.

Compression:
After these two steps, we have color and height information. We just need now to arrange the cloud of points into a mesh with Delaunay triangulation to create the output 3D file. In addition, we developed a complementary smart compression method according to the most relevant zones. The size of the output file can be chosen for future use : For instance, highly compressed file for digital gallery or full 3D resolution file for quality.

Results & Limitations

This 3D imaging technique permits an access to the digitization world for roughly flat and differentiable objects with diffusely reflecting surface (figure 4).

For an optimal result, the surface needs to be within 5 cm depth of field. The limitation is due to the specificity of our cameras, which imply a shallow depth of field and the configuration of the lighting ramps, which implies that the object is illuminated only over a limited height range.

Figure 4. *Chinese wooden tablet*

The height accuracy depends on the resolution of the input images. In the case of a less-resolved image, the real intensity information of the scene will be averaged to the size of a pixel for the input images. This will result in less precise orientation of the surfaces calculation and therefore less accurate height information. And it is important to note that we do not know the real height of each point of the object. We have a proportional height variation information in relation to the other points of the object.
So, we add a parameter that can be adjusted according to the specificity of the hardware setup. It allows to adjust the height of the 3D file as close as possible to the actual value.

Once the scan is complete, the reconstruction of the 3D object can start (figure 5). The processing time depends on the compression setting and the resolution of inputs but remains close to a few seconds. It is therefore a solution that can be described as real-time if scan time is considered.
We focused on giving users the ability to select the size of the 3D output file in megabytes before starting the process. Thanks to this specificity, the solution adapts to the customer's needs. For instance, a viewer runs with a high-quality object, when a 3D printer only needs medium quality, and a display in a digital library [11] requires a highly compressed file.

Currently, technical limitations of visualization software slow down the file manipulation when it is acquired from precise 3D measurements in a full resolution. For example, an object with a size of 50 cm x 16 cm at 600 dpi has a size of 10 gigabytes. It is composed of 60 million of polygon's vertices.
Users have then to make a compromise between quality and accessibility by choosing an appropriate file size.

Future Work

One of the next steps will be to develop a mode where the quality/size ratio will be calculated automatically by selecting the best compromise to remove redundant information that increases the size of the file and the fluidity of its handling without undermining data too much.

But the most important work would be to add a formula to the gradient field integration step that manages non-derivative surfaces such as vertical edges or holes [10]. Indeed, right angles tend to be rounded with the proposed algorithm.

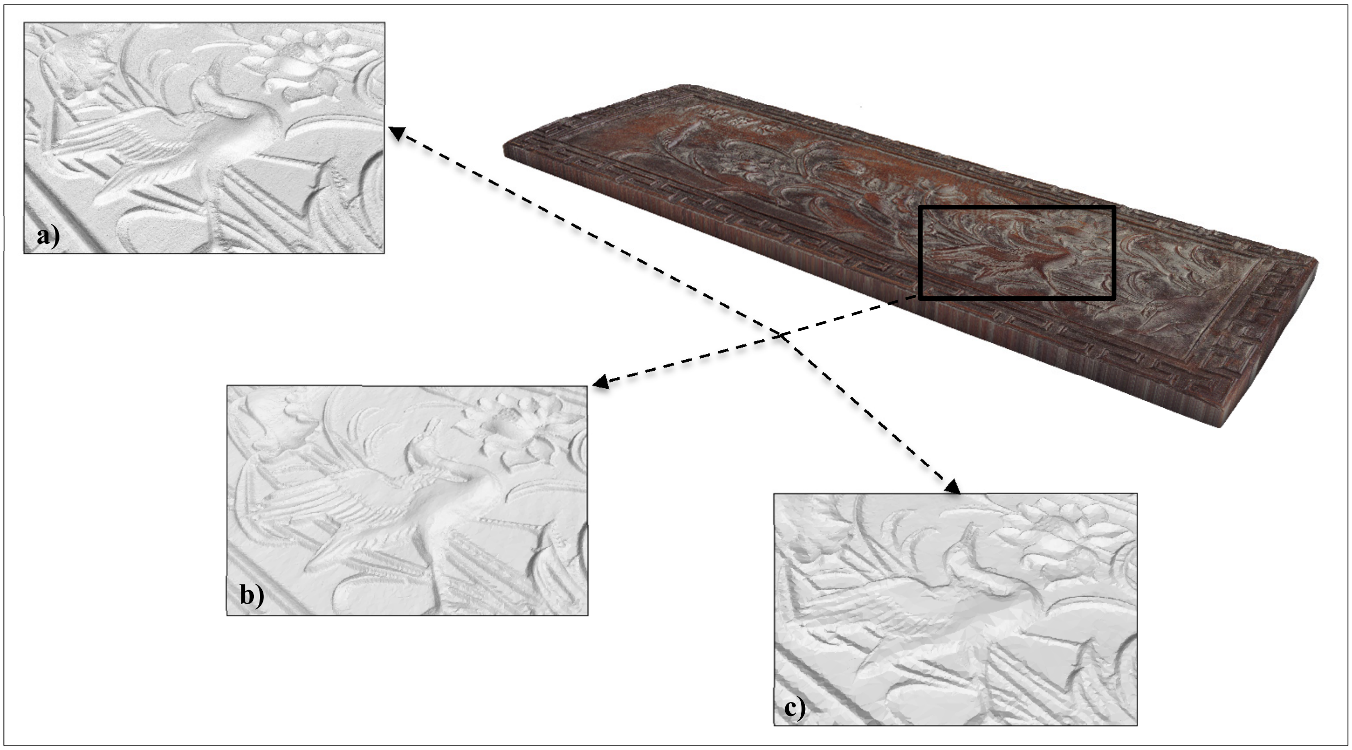

***Figure 5**. Full result of the Scan 3D with texture and zoom on the mesh in different qualities.*
a, High quality, b. Medium quality, c. Low quality

Conclusion

Our method is not a suitable solution for capturing complex objects like statuettes, in particular due to the hardware configuration with one camera above the scene. We can only reconstruct the surface of the object and interpolate borders.

However, with relatively flat objects and differentiable surface, photometric stereo is a suitable industrial solution for cultural heritage imaging applications. Its use allows to capture and highlight effectively three dimensions details and coloring information at the same time.

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Author Biography

Arnold Cheveau received his Master's degree in Image Processing and Artificial Intelligence from the University of Burgundy in France in 2014. Since 2015, he has been an Image Processing Engineer at i2S company and works essentially on the division to digitize patrimonial documents.