Coded Structured Light for 3D-Photography: an Overview

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Abstract

This survey describes the methodology of coding structured light for recovering depth information of scenes is and outlines the main approaches used in the area. A new taxonomy of the methods is proposed, and the trends in recent work are presented and discussed.

Keywords: coded structured light, range acquisition, 3D-photography.

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1. Introduction

3D Photography is one of the new "hot" areas of research in Graphics for several reasons. First, it combines techniques from computer vision, image processing, geometric modeling and computer graphics into an unified framework. In this respect, it can be considered a sub-area of *image-based modeling*. Second, the rapid development of commodity hardware and consumer electronics makes it possible to build low-cost acquisition systems that are increasingly effective. Third, the reconstruction of three-dimensional objects from images can be used in a vast number of important applications fields, ranging from Archeology, Cultural Heritage, Art and Education, to Electronic Commerce and Industrial Design.

Shape acquisition is one of the fundamental tasks in scanning objects. An object can be thought as made up of a collection of surfaces which in turn have geometric properties such as curvature and features as well as photometric properties such as color, texture and material reflectance. In the last two decades the problem of accurately capturing an object's geometry was extensively studied, while the acquisition of high-quality textures, an equally important problem, only in recent years has become subject of research.

In this survey we are going to focus attention in geometry acquisition, since it is a more mature field of research. A classification of shape acquisition methods is given in Figure 1. We concentrate in the optical approach, which allows using off-the-shelf hardware, reducing significantly the cost of the scanner.

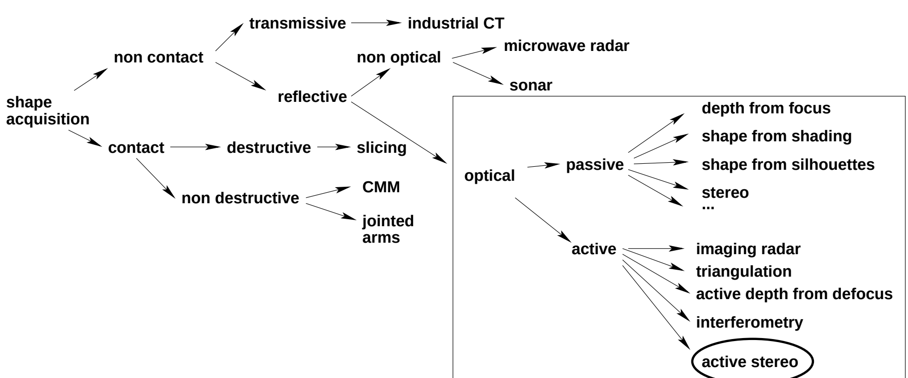


Figure 1: Shape acquisition methods.

The highlighted branch in figure 1 shows the classification of optical acquisition techniques. To choose among these techniques one has to consider their qualities and limitations, such as resolution and accuracy, to be applied in a specific context. It is important to know the application when choosing the hardware and software to be used. For instance, scanning a building is very different from scanning a vase. We are interested in objects with dimensions comparable with a vase, and we wish to scan objects, one at time, in a controlled ambient, which means that we can control the background and ambient light. The main limitations of optical range acquisition are that it can only acquire visible portions of surface, it is sensible to surface's properties like transparency, shininess, texture, darkness (no reflected colors) and subsurface scatter and, in addition, it can be confused by interreflections.

Our focus will be on active stereo methods, in which some kind of special lighting is directed to the object to be scanned, to allow recovering its geometry, as explained in section 2.. The active approach helps to solve the correspondence problem, which is a dificult task in passive methods. In particular we will study *coded structured light* (CSL) techniques, that consist in illuminating the object with one or more slides with patterns coded according to certain schemes.

There are many ways to code structured light. Early research on CSL methods was done in the 80's [Pos82, Boy87, Vuy90, Taj90]. The flavor of this work was to create empirically light patterns to capture the geometry of scanned 3D objects; some works from this period are outlined in section 3.. In section 4. the work done during the 90's is overviewed, and we observe that in that period theoretical results in coding were obtained and improvements in processing and error analysis were achieved.

In section 5. we propose a new taxonomy for CSL methods based on the natural analogy between these methods and a digital communication system. In section 6. recent developments are described and trends are discussed. In section 7. we discuss the limitations imposed by the use colors to code patterns and we show that it is not as restrictive as believed up to now.

2. Basic Principles

The basic principles that allow obtaining 3D shapes from images are the same as those of stereo vision. They are based on the fact that if two known cameras observe the same scene point X then its position can be recovered by intersecting the rays corresponding to the projection in each image. This processes is called *triangulation*.

The main problem of directly using stereo vision to recover 3D shape lies in the difficulty of automatically matching points in the two images. In order to avoid this problem, these *passive stereo* methods can be replaced by *active stereo* techniques. In these, one of the cameras is replaced by a calibrated and well defined light source, that mark the scene with some known pattern.

For instance, laser-based systems direct a laser beam (contained in a a known plane) to the scene and detect the beam position in the image. By intersecting the ray corresponding to each point with the known plane, one can compute the point's

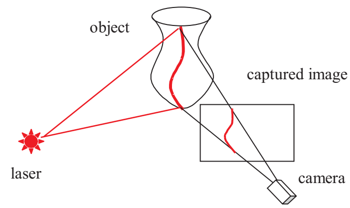


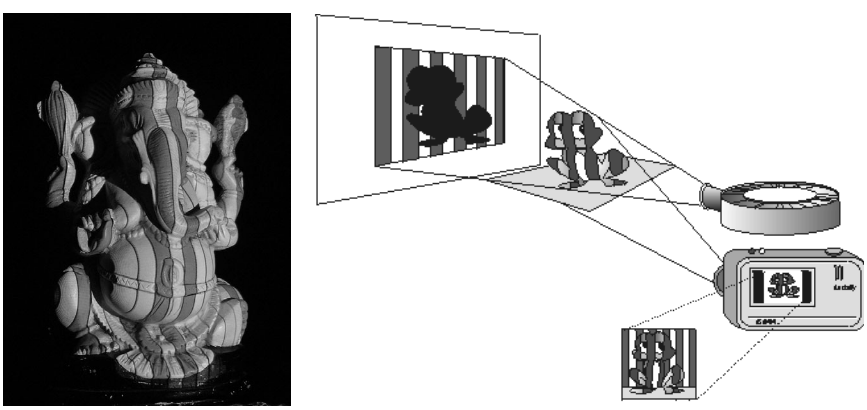
Figure 2: Laser beam projected on an object and its captured image.

position as shown in Figure 2.

In order to get dense range information, the laser plane has to be moved in the scene (or, equivalently, the object has to be rotated). Structured light methods improve the speed of the capturing process by projecting a slide containing multiple stripes onto the scene, as depicted in Figure 3. To distinguish between different stripes, they must be coded appropriately, in such a way that the correspondence problem is solved without ambiguity.

In summary, the basic steps in recovering shape employing structured light are the following:

- Camera and projector calibration;



(a) ganesh statue (b) schematic view of a scanner device

Figure 3: Example of structured light projected on a statue and an illustration of the scanner device.

- Establishing correspondences between points in the image and projected stripes;
- Reconstruction of 3D co-ordinates of the points in the scene.

In this survey, we concentrate on the second step. For more on the techniques related to the other two steps, we direct the reader to [Boug, Cla98] for the calibration step and [Ber00] for a description on processing acquired data.

3. Early approaches(the 80's)

In the 80's, pioneer tests with light coding were made and the main concepts were conceived. At the time, the methods were limited by restrictions imposed by existing hardware and software. Here we outline some of the main ideas in coding during that period. We have based our overview on [Bat98]; we do not intend to reproduce their careful description of several different patterns.

3.1 Temporal coding

An idea to code projector position is project sequentially a binary signal corresponding to the binary digits of a code.

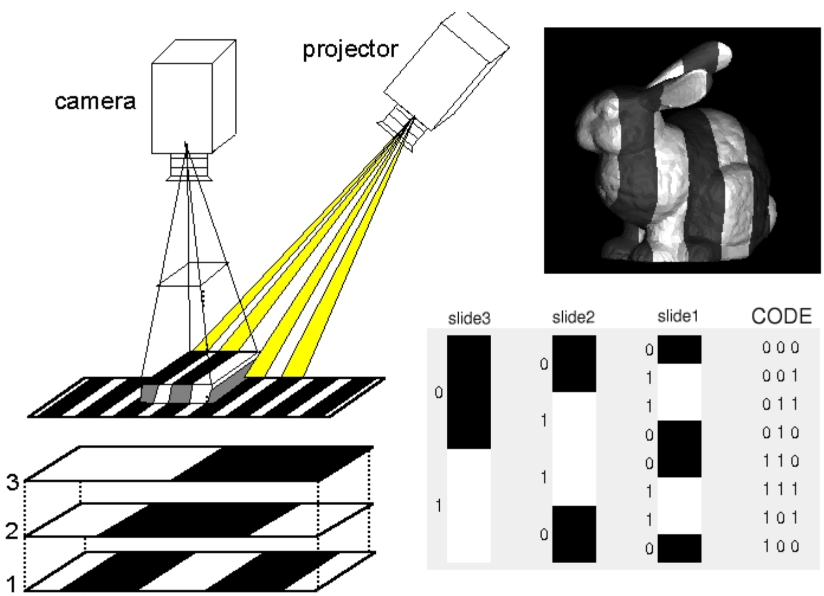


Figure 4: Temporal coding (Gray Code)

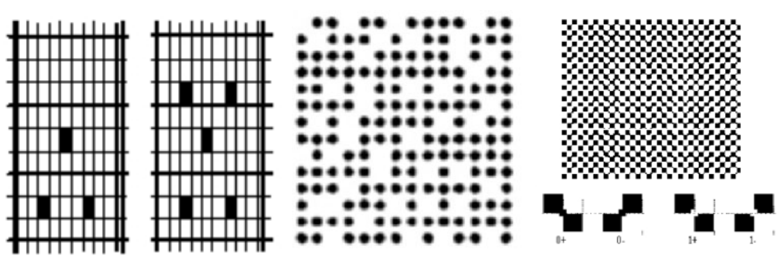
In figure 4 the binary signal is translated into black or white stripes. Projecting a sequence of n slides produce 2^n coded stripes and the resolution increases as the number of slides increases.

To decode the position of a projector pixel, the main task is to recover the projected binary intensity in a sequence of patterns. Image processing is needed to detect shadow areas. In practice, a binary signal is transmitted analogically, and suffers interference from the object's surface. In addition, it is captured by a camera and has to be redigitized.

In 1982, [Pos82] proposed a binary temporal coding, while in 1984 [Ino84] proposed to replace it by a more robust Gray binary code. This code was revisited, re-implemented, refined and analysed many times, and still it is a robust geometry acquisition technique for static scenes. The main problem of binary temporal code is the large number of slides that have to be projected to achieve the desired resolution and its restriction to static scenes.

3.2 Spatial coding

The desire to acquire dynamic scenes and to reduce the number of projected slides leads to codes conveyed by a single slide. The only way to code position in a single slide is by increasing the number of distinct projected patterns, in such a way that there are enough patterns to achieve the desired resolution. The common way to do so is to use the neighborhood of a pixel, known as spatial coding, or to modulate the projected light as a function of projector position (to be discussed in subsequent sections).



(a) grid pattern (b) M-array code (c) 2×3 pixels code

Figure 5: Examples of spatial codes (from [Sal]).

In figure 5 we show some schemes for spatial coding. The main challenge is to recover projected patterns deformed by the object's surface. We have choosen three codes to describe as representative of the main approaches:

- Grid patterns: there are a lot of different patterns that can be made based on this concept, that consists in using stripes as guidelines for the code. An exemple is given in figure 5(a), where the grid is partially coded by dots used as landmarks [Moig88]. A limitation of this approach is that, if some discontinuity on object surface produces a discontinuity on imaged guidelines, the decoder can get lost.

- Coded array: in [Mori88] light dots as an M-array – figure 5(b) – are simply coded as codewords written horizontally as arrays of constant size. Dot size influences resolution and is critical in recovering phase, while dot shape can be modified by the surface's texture, complicating dot detection.

- Coded window: in [Vuy90], windows of 2×3 pixels are used to code projector position – figure 5(c) – based on 4 different digits (also shown in figure). The details of the code will not be given here, but an important caracteristic of this approach is that the identification of projected pattern is dependent on the preservation of its geometry.

Spatial coding imposes limitations on object discontinuities: the code array/window cannot include discontinuity regions in order to be decoded. But these are local restrictions, while for grid patterns the restriction is global.

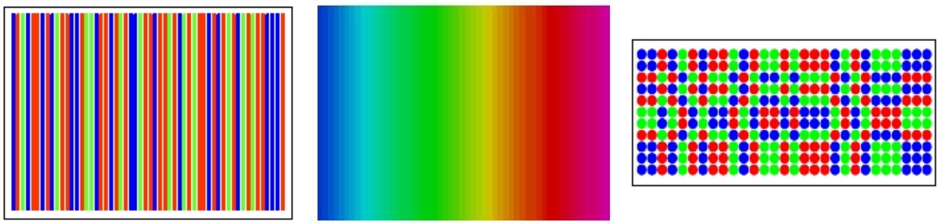
3.3 Modulating projected intensity

In order to code a pixel in an unique slide without neighborhood information one can modulate light intensity as a function of the projector pixel. This approach is sensitive to noise and surface properties such as texture can interfere in the signal in such a way that decoding is not robust. To alleviate this problem a white pattern is projected – which implies in restricting the application to static scenes – and the difference of projected intensities is used to recover code. This method was proposed in [Carr85].

3.4 Introducing the usage of colors

The usage of color was introduced in the late 80's due to technological advances in capturing colored images. The basic improvement was the possibility to use 3 channels in codes rather than one, but colored light in colored surfaces was not well behaved, thus restricting this kind of code to neutral colored scenes.

Colored codes are shown in figure 6 . Vertical slits are coded by its sequence of colors in [Boy87] – figure 6(a)– , while modulation of wavelength in a rainbow pattern – figure 6(b) – was proposed in [Taj90]. The main challenge of color usage is its recovery.



(a) horizontal codeword (b) wavelength modulation (c) cardeal neighbors

Figure 6: Examples of color based codes (from [Sal]).

4. Structuring the problem (the 90's)

In the 90's, the great improvement in hardware and software permitted a more accurate and extensive research in coding light. More analytic papers were published, establishing a theoretical basis and comparing the accuracy of different methods.

4.1 Improvements in coding

Several works were published in this decade attempting to explore the main ideas of coding in their full potential. New codes, improving the known ones, were proposed. Also, existing codes were re-implemented and had their results enhanced. Some of the representative works are [Bat98, Pad95, Smu96, Mon94].

[Grif92] developed a theoretical study to determine the largest size allowed for a coded matrix dot pattern. A large matrix is desired, in order to provide high resolution; see figure 6 (c).

In the late 90's [Hsi98, Hsi01] pointed out that although much work had been done in coding and accurately processing acquired images, the problem of decoding projected light position (without using brute force) had been ignored. The author proposed an efficient decoding algorithm suitable for being applied in a set of codes with an underlying graph structure.

In 1999 [Horn99] proposed a criterion to search for optimal design of structured light patterns, exploring the similarity between projections of patterns and transmission of signals in a communication system. He claimed that the design of K projection patterns for a structured light system with L distinct planes is equivalent to the placement of L points in a K-dimensional space subject to certain constraints.

4.2 Image processing and accuracy

The crucial steps for range image accuracy are the calibration of the system and the detection of projected patterns. Poorly calibrated cameras or projectors cause error propagation in depth measurements. Unappropriate camera models (for instance, using a pin-hole model when lens distortion is relevant) can also generate systematic errors. Several works were published in this period about this subject, which is beyond the scope of the present survey. Therefore, we will restrict attention to the discussion of accuracy in the pattern detection process.

The hardware used to project slides and capture images has a direct influence on measurement accuracy. In a more subtle way, scene illumination conditions and the object's surface features also play an important role. Detection of shadow regions – viewed by the camera, but not illuminated by the projector – is also important, these areas are characterized by having a very small brightness compared to illuminated areas.

The projection of spatially defined patterns leads to the problem of defining a central point or some important feature to represent the pattern. When projecting stripes, it is desirable to determine the stripe edge position and this is the most widely studied problem in terms of accuracy.

A method to obtain sub-pixel accuracy on boundary position, consists of projecting positive and the negative slides with the same pattern. In this methodology, the position of the stripe edge P is computed as the intersection between line AB and line EF of the positive and negative patterns, respectively (see Figure 7).

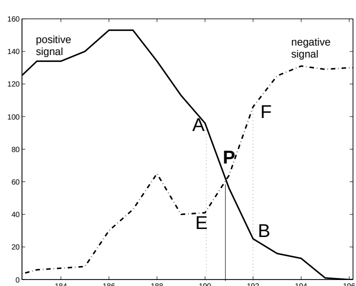


Figure 7: Boundary from complementary patterns.

This technique assumes that the considered sampling points lie in the linear part of the edge profile. This is true in general, except for very narrow edges whose width is less than two pixels.

Trobina [Tro95] did a comparison of the techniques for detecting stripe position and concluded that the method described above – linear interpolation with inverse pattern – is more accurate and robust. In his work, noise dependence on the object's surface orientation is also studied. The study considers only black and white patterns.

5. Taxonomy

As seen in the previous two sections, a large number of methods for coding structured light were proposed. In order to better understand how they relate to each other, it is useful to establish classification schemes for the methods. In the subsections below, we examine two such classification schemes. First, we look at the more usual taxonomy, based on object restrictions. After that, we propose a new classification scheme, based on coding concepts.

5.1 Usual Taxonomy - based on object restrictions

As we saw in previous sections, the three ways to code projected light are the use of chromatic, spatial or temporal modulation in the illumination intensity pattern. A taxonomy of CSL proposed in [Holt01] considering differences between patterns and the restrictions that they impose on the scene to be scanned.

Chromatic modulation imposes restrictions on the allowable colors in the scene. When spatial coding is used, local continuity of the scene is necessary for recovering the transmitted code. Conversely, temporal coding restricts motion of the scene. This discussion is summarized in the table below.

Assumptions	Methods	Restrictions
spatial coherence	neighborhood-based methods	discontinuities on object's surface are not allowed
temporal coherence	many slides vs. one slide	restricted to static scenes vs. permits dynamic(moving) scenes.
reflectivity	binary/grey level vs. color coding	no assumptions on object colors vs. neutral colored objects.

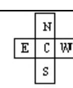
5.2 Taxonomy based on code

There is a natural analogy between CSL and a digital communication system. The projector coordinates are encoded by the slide patterns and transmitted to the scene. At each point of the camera image, a noisy transmission is received and needs to be decoded. The transmission channel is the object's surface and the transmitted message is the encoded position of the projector pixel. Considering this analogy, two main issues have to be studied:

1. Limitations of the transmission channel, related to surface reflectance properties.

2. How to encode projector pixels, which will restrict the class of objects suitable to be scanned.

We can classify CSL methods by observing the code design. This is better than the previous taxonomy in the sense that is the code design that imposes restrictions on the scene (or transmission channel). That is, if we use spatial coding, the scene has to preserve the spatial structure; otherwise, there will be loss of information. In the scene this can be translated as local continuity. The principal caracteristics of code design are the number of distinct symbols (basic signals), the size of the word made by symbols and, in the case of spatial coding, the geometry used.

method	num. slides (codeword size)	intensity modulation/channel (no. of characters)	neighborhood (character's region)	resolution (alphabet size)
Gray Code (fig.4)	n	binary(2) monochromatic	single pixel	2^n per line
colored Gray (fig.8)	n	binary(2)/ RGB	single pixel	$2^{3\times n}$ per line
rainbow pattern (fig.6(b))	2	2^8/ RGB	single pixel	$(2^8)^3$ per line
dot matrix (fig.6(c))	1	3 (R, G or B)		3^5
coded window fig.5(c)	1	binary	4 pixels 2×3 window	4^6

From this point of view it is clear that code design imposes restrictions on objects. Spatial structure of coding will be lost if discontinuities are present on projected surface area. Also, it is necessary to recover accurately intensity modulations, which requires that the surface does not distort intensities or chroma too much. Finally, the size of the codeword imposes that movement is not allowed while the codeword is not completed.

6. Recent trends

In recent years CSL systems have been revisited by many researchers with the motivation to find a theoretical basis that could provide a better understanding of known methods, as well as make it possible to develop new improved systems [Holt02, Sco01, Zha02].

Such a shift of paradigm can be seen in [Holt01], where a CSL scheme based on stripe boundaries is proposed. The codes are associated with pairs of stripes, instead of with the stripes themselves as in traditional methods. Boundary coding has several advantages: it gives higher spatial precision and requires less slides (that is, features better temporal coherence).

In order to allow the greatest possible variations in scene reflectance, the scheme of [Holt01] is based on black and white stripes. This option leads to an undesirable problem: "ghost" boundaries (i.e., black to black and white to white transitions) must be allowed. Their scheme is also complicated by restrictions on boundary transitions because of the decoding algorithm, which is augmented by an additional step that solves the matching problem.

Recentlly, [Zha02] proposed using dynamic programming techniques to compute an optimal surface given a projected pattern and the observed image. The camera and projector correspondence is obtained up to one pixel resolution and a post-processing step is carried out to achieve sub-pixel accuracy.

The concept of using a colored boundary code is present in [Zha02] but the option to use a one-shot code implies in considering a subsequence of consecutive stripes to guarantee uniqueness of codewords with the desired resolution. Increasing the size of the basis used in coding complicates the decoding step. The price of adopting a one-shot code is that requirements on spatial coherence cannot be minimized, and some information will be lost due to discontinuities in the scene. Some considerations to reduce color misalignment and ato ccount for color crosstalk are done in designing and processing correspondences, but the problem is not robustly solved, as shown in their results. To increase resolution and robustness, the same pattern is shifted and projected, leading to a spacetime analysis of the color stripe pattern.

7. Going back to colors

The traditional use of color in coding restricts the object surface reflectivity, because we would not want to modify the projected colors in acquired images. By projecting complementary slides, however, the reflectivity restrictions are eliminated [Sa02].

The intensity p of a projector light beam is scattered from the object surface into a camera pixel. If the camera characteristic is linear, the sensor clips intensity at a maximum value. The digitized intensity per channel is given by:

$$
\begin{aligned}
I_R &= \min(u_R + r_R p_R, I_{R_{\max}}) \\
I_G &= \min(u_G + r_G p_G, I_{G_{\max}}) \\
I_B &= \min(u_B + r_B p_B, I_{B_{\max}})
\end{aligned}
$$

where (u_R, u_G, u_B) is the ambient light component, (r_R, r_G, r_B) is the local intensity transfer factor mainly determined by local surface properties and (p_R, p_G, p_B) is the projector intensity for each channel [Malz99]. Supposing that $I_{R_{\max}}$, $I_{G_{\max}}$ and $I_{B_{\max}}$ are never achieved we have: $(I_R, I_G, I_B) = (u_R + r_R p_R, u_G + r_G p_G, u_B + r_B p_B)$.

We can estimate parameters u and r if we fix projector, sensor and object in relative positions, and produce sequential projected patterns varying p. As mentioned previously, two complementary slides are projected, that is, if $p_i = 0$ on first slide then $p_i = 1$ on second. Then we have:

$$
I_i = \begin{cases} u_i & \text{when } p_i = 0 \\ u_i + r_i & \text{when } p_i = 1 \end{cases}
$$

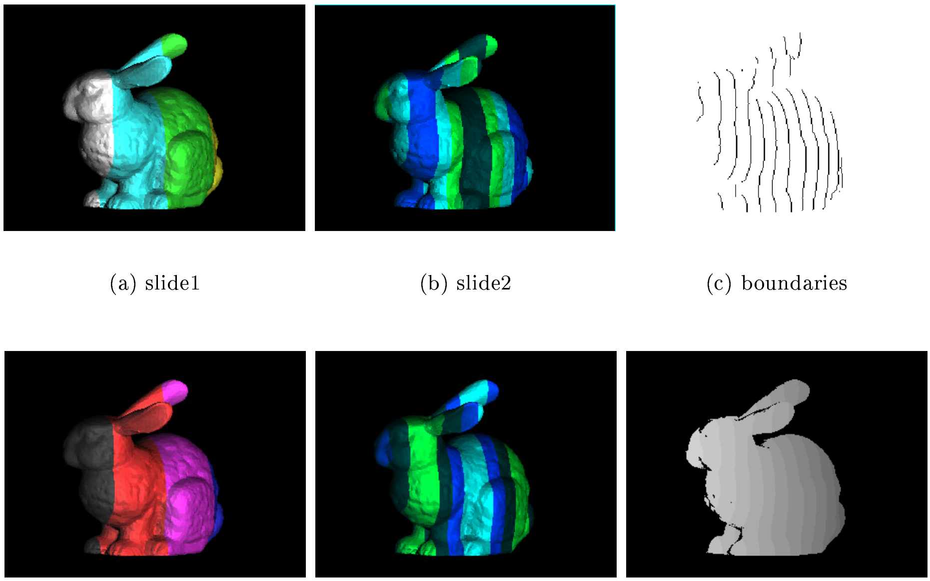
If we just take the maximum value per pixel for each channel between the complementary slides, it will be equivalent to recovering the value of each pixel as if it were illuminated with white light coming from the projector, that is , $p = (1, 1, 1)$. Equivalently, if we take the minimum value per pixel for each channel, we are recovering the ambient light, that is, $p = (0, 0, 0)$. In addition, the color of the projected light can be recovered if we treat channels separately.

One problem in the use of color coding is the cross-talk between the RGB sensors [Cas98]. In that respect, color fidelity can be improved by a color correction pre-processing step that takes into account the response of the projector-camera system.

To give an example of the validity of this approach we propose the usage of a colored Gray code, where each channel of a colored slide corresponds to one slide of the black and white Gray pattern. This approach divides by three the number slides required to achieve the same resolution required by classic Gray pattern. We have tested this code in our virtual ambient [Visgraf] and the results are shown in figure 8.

8. Conclusion

In this survey we described the evolution of structured light codes for methods that use active stereo for shape recovery. We pointed out that this evolution was in great part determined by hardware and software performance. We also described a new taxonomy of the coding methods, based on a signal processing analogy, which helps categorizing the methods and understand their capabilities and limitations. Finally, we discussed trends observed in recent work in the area, that try to eliminate



(a) slide1 (b) slide2 (c) boundaries

(d) slide1-neg (e) slide2-neg (f) decoding

Figure 8: Two slides showing colored Gray code (a,b) and their respective negatives (d,e) projected on bunny. The recovered boundaries are shown in (c). The number of recovered stripes after decoding is represented in (f) as gray levels.

restrictions imposed by previous techniques. The most important recent developments discussed are the search for methods that allow real-time acquisition and new schemes using color codes.

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