

Recent Progress in Structured Light in order to Solve the Correspondence Problem in StereoVision

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ABSTRACT

We present a summary of the most significant techniques, used in the last few years, concerning the coded structured light methods employed to get 3D information. In fact, depth perception is one of the most important subjects in computer vision. Stereovision is an attractive and widely used method, but, rather limited to make 3D surface maps, due to the correspondence problem. The correspondence problem can be improved using a method based on structured light concept, projecting a given pattern on the measuring surfaces, although some relations between the projected pattern and the reflected one must be solved. This relationship can be directly found codifying the projected light, so that, each imaged region of the projected pattern carries the necessary information to solve the correspondence problem. We do not need to mention the numerous advantages that presents an accurate obtention of 3D information for many research subjects, such as: robotics, autonomous navigation, shape analysis, and so on.

INTRODUCTION

It is already known that a stereoscopic system is made by the relationship between two cameras or frames imaged from different views of the scene^(1,2). Each camera can be modelled, with a translation matrix, as a pinhole model^(3,4). Then, an object point position can be calculated from both projections, although we have to make sure that both projections are projections of the same object point. This problem is known as the correspondence problem.

It is also known that the projection on the second image plane must lie on the epipolar line⁽⁵⁾, but it could be occluded by any other surface of the scene, or it might be projected out of the scope of the camera.

We can alleviate the correspondence problem using an active method based on the structured light concept^(6,7,8). Here, the second camera is replaced

by a light source, which projects a known pattern of light on the scene. The first camera images the illuminated scene, and the wished 3D information can be obtained analysing the deformations of the imaged pattern with respect to the projected one. Of course, depending on the chosen pattern, some correspondences between the projected pattern and the imaged one must be solved^(9,10).

The correspondence can be directly solved, codifying the projected pattern, so that each projected light point carries information from where it has been emitted. This technique is known as Coded Structured Light⁽¹¹⁾, and it is the main subject of the paper.

Note that we can obtain the object point knowing only one of the two projected point co-ordinates⁽³⁾. This idea allows us to code the projected pattern along only one co-ordinate axis, so that the captured light carries information from the emitted row or from the column. Firstly, we present a new classification about coded structured light techniques. In the second section we survey the different techniques which code the pattern projected on the scene. Their advantages and disadvantages have been discussed. The survey ends with a brief chronological summary of the related techniques. Conclusions are presented in the last section.

A NEW CLASSIFICATION

In this paper we propose a classification of the different techniques which codify the projected pattern.

I. Based on the temporal dependence, the technique can be classified into:

- **Static:** The technique is limited to static scenes, made by moveless objects. This is always due to the constraint of projecting a set of different codified patterns to obtain the label for each column (or row) of the pattern.

- **Dynamic:** The technique is not limited to static scenes. If the objects of the scene can move,

the column or row of the projected image must be coded with a single pattern projection.

II. Based on the light projected, the technique can be classified into:

- **Binary:** Each projecting point of the pattern can only take one of the two binary values. The codified value usually represents opacity and transparency against the emitted light.

- **Grey Level:** Each pattern's point can have an associated value, which represents the transparency (or opacity) level of the point against the projected light. As the information is coded in a grey light level, it is necessary to obtain another image of the scene lighted with the same intensity for each pattern point (without coding). In this way, we can obtain the needed reference light in order to cancel the surface reflection effect, which depends on the kind of the surfaces where the light is reflected. This limitation leads us to classify also the pattern as static.

- **Colour:** Each pattern point can have an associated hue value. The hue values are quite different among them, in order to obtain a more efficient and accurate segmentation. Obviously, scene colours must be pale or neutral, as highly saturated colour objects can produce lost pattern regions in the segmentation step and posterior decodification.

III. Another classification, from surface depth discontinuities dependence, can be proposed. Based on this dependence, the technique can be classified as:

- **Periodical:** The codification is periodically repeated along the pattern. The method allows us to reduce the number of bits which codifies the pattern, but produces a limitation of the depth discontinuity, which can not be larger than the period length.

- **Absolute:** Each column or row of the projected pattern has an unique codification. So, it does not have any depth discontinuity dependence.

Hereafter, a survey about the coded patterns presented in the last years is related.

OVERVIEW: CODED STRUCTURED LIGHT TECHNIQUES

Method proposed by Posdamer-Altschuler. The system^(12,13) is based on the use of a pattern as a dot matrix of $n \times n$ binary light beams. Each n_i column of the pattern can be independently controlled, so it can be turned on or off. Then, several masks can be made, as they permit to code any pattern dot in a temporal way, as a sequential

projection of different patterns. The number of patterns to be projected is determined by the number of columns to be coded.

The system usually works as follows. Firstly, a whole illuminated dot pattern is projected on the scene. The camera images all the dots reflected from the surfaces of the scene and keeps their positions in a datum structure. In the following steps, each coded pattern is projected and the system can ask for the light information in the stored positions. After all the patterns have been projected, each detected point has a code that permits to determine from which beam column it has been projected.

The Posdamer and Altschuler idea has been widely studied. Basically, some different codification techniques, such a Gray code method⁽¹⁴⁾, have been tried. Computational time has been improved as well. In order to improve towards a more analogical and accurate pattern, a Liquid Crystal Device, which permits to increase the number of projecting columns, is proposed^(15,16). The system also improves the computational time against a slide projector, as the LCD can be electronically controlled⁽¹⁷⁾. Another complementary method of segmentation based on the projection for each coded pattern of its positive and negative representation^(15,16) has also been proposed.

The same temporary codification described by Posdamer and Altschuler in 1982, was again proposed by Müller⁽¹⁸⁾ in 1995.

Method proposed by Carrihill-Hummel. The system⁽¹⁹⁾, proposed in 1985, is based on the 3D information obtention of any scene from the analysis of two captured images. The first image is captured with a constant illuminated projection on the scene. A linear wedge filter is used to project on the scene a pattern brightly illuminated in one side, and half brightly in the other. This wedge filter is used to light the scene for the second image capturing step.

For the first projection it is supposed that the intensity of the light is constant along both x-axis and y-axis of the projector, and, for the second projection along the y-axis. Then, for each obtained pixel, the intensity subtraction, of the two images can be calculated. This difference allows us to obtain the column of the projector from which the dot has been emitted. This intensity ratio permits to cancel potential surface reflections or highlights, because a projected light variation

always produces a change of the illumination ratio.

In order to improve the accuracy in the measuring without increasing the bit depth of the captured image, a new method based on a sawtooth pattern could be proposed. Obviously, the maximum surface depth discontinuity that could be measured is limited to the chosen period.

Method proposed by Boyer-Kak. A single pattern, coded by vertical coloured slits⁽²⁰⁾, was proposed in 1987. In this case the correspondence problem is limited to the obtention of the relationship between the imaged slit and the projected one. This relationship can be solved by slit codification.

It has been proposed to code the pattern using the three basic colour components: Red, Green and Blue. White can also be used. Optionally, between each slit, a black gap can be placed. This gap can be used as a slit separator. Note that white can be easily obtained and identified as a colour which has approximately the same red, green and blue intensity values.

The pattern proposed by Boyer et al. is made by n vertical slits. They proposed to divide this pattern in m sub-patterns, where each sub-pattern is made by k vertical slits, as $n = m * k$. K is a value as big as necessary to code the m patterns in a unique way. From the captured image, it seems hard to find out beginnings and endings of the projected sub-patterns. In fact, multiple matchings can be obtained as we do not know where a sub-pattern ends to start the next one. Furthermore, the slits have been reordered as a function of the measured surface discontinuities.

Concerning the colour slit detection, Boyer et al. proposed a hardware which detects red, green and blue peaks in the RGB signal given by the camera. The slit position can be obtained from the camera synchronism. Obviously, as the three RGB signals do not have the same gain, the hardware has to equalise them.

A software algorithm is used which can obtain in three steps the sub-patterns from the index and position given by the hardware. The software is based on a heuristic region growing algorithm to obtain the best matchings. When the third step is completed, a datum structure which associates captured and projected sub-patterns, has been obtained. Then, the 3D information of the scene can be determined by triangulation.

Although the proposed pattern is limited to measure predominantly neutral colour surfaces, it is

especially recommended in dynamic environments, as a single projection is used.

Method proposed by Le Moigne-Waxman. Many different patterns can be made based on the grid pattern concept. When a grid pattern is chosen, the number of crossing points to be projected has to be chosen, as well as the line thickness, as it depends directly of the smoothness of the imaged surface texture. A very thick line will give a low resolution and a very thin one will give a lot of discontinuities, which will complicate the matching process. Obviously, the thickness of the line has to be chosen knowing the kind of the scenes to be measured.

Le Moigne and Waxman⁽²¹⁾ proposed to add dots on the grid used as landmarks to initiate the decodification or labelling of the projected pattern.

The configuration used for the system, that locates the projector at a determined distance along the y-axis of the camera, implicates that vertical lines are imaged nearly without deformation, keeping its naturally parallelism and continuity, so they will be easily detectable.

A square neighbourhood operator is computed in each imaged pixel to reduce the albedo or highlight effect. The system uses the known position of the vertical lines as guides to search the dots and horizontal line intersections. Then, the horizontal lines are explored to join their discontinuities. Note that, if a lot of discontinuities are found, this is due to the fact that the chosen thickness of the line is too thin. Finally, two different edge labelling processes are used for each landmark dot. Then, a merging algorithm is used to label the whole pattern.

Although someone could think that the labelling algorithm is rather complicated, note that horizontal lines can be highly broken due to depth discontinuities of the measuring surfaces. They can also be partially disappeared. So, easily matching errors could be obtained using a single labelling process.

The proposed pattern is especially indicated to work in dynamic environments, as a single projection is needed to obtain 3D information of the scene. But, it is true that the resolution given by the pattern is rather limited, basically for two reasons. Firstly, vertical lines do not give any depth information, as they are only used as searching guides. Secondly, the matching process might be rather slow in density grids, so, dynamic high resolution is not permitted.

Its use on mobile robot navigation in structured indoor environments is perfectly recommended, as the surfaces do not have high contrast textures which can deform the pattern, and the scene is quite regular, so that small differences do not give interesting information.

Method proposed by Morita-Yakima-Sakata. In 1988 Morita et al.⁽²²⁾ proposed a binary pattern of light dots as an M-array. The M-array has the coding window feature since any sub-pattern only exists within a window and at a unique place in a pattern period.

Morita et al. placed the camera and projector so that Δ_y and Δ_z distances between them are zero, simplifying the correspondence problem. Then, the dot identification process is quite simple, as the dot position on the image plane can only move horizontally.

Firstly, this method has to project an entire illuminated dot matrix to obtain the image coordinates of each dot. Then, a binary (bright and dark) dot matrix is projected, so that each window with a fixed size determines the column index from where the imaged point has been projected.

The proposed system is quite simple, as 3D information can be obtained without much computing time. However, since two projections are needed, the system is limited to static scenes. As the system projects isolated light dots, little textural information can be obtained. If the dot size is reduced to get more resolution, then high contrast textural surfaces could modify the dot shape, which makes its localisation more difficult.

Method proposed by Vuylsteke-Oosterlinck. In this case, a dynamic column coded pattern is proposed⁽²³⁾. The basic structure of the pattern is like a regular chess-board alternating bright and dark squares. The pattern is modulated overlapping a bright or dark spot at every square vertex. Any square of the regular chess-board pattern carries an additional information bit which, together with the neighbours bits, will be used to code each column.

A code of 6 bits length is needed to codify the 63 different columns of the pattern. Consequently, any window of 2x3 squares permits to code any column index. In fact any window with 6 squares size can be used but a compact window is obviously less affected to surface discontinuities than an elongated one. The code assignment can not be chosen independently due to the fact that the identification windows overlap. Then, a kind of recursive code

generation sequence, with an initial birth polymony has been used, which permits to obtain a desired length period to code all the columns of the pattern, in an unique way.

Basically, the presented pattern has two limitations. The first one is based on the difficulty of measuring high textural surfaces which produce partial lost regions of the pattern. The second one is based on the surface orientation. If these orientations are not perpendicular to the projector optical axis, a deformation of the projected pattern is presented, which beyond a determined angle orientation, does not allow us to identify the pattern. Nevertheless, the pattern is well recommended in order to measure dynamic surfaces where a single projection is permitted.

A reimplementation of the same pattern was proposed in 1995⁽²⁴⁾. As an improvement, a hexagonal codification instead of a square one is proposed. In this case, the window size is reduced. As a result of that, the number of not indexed columns due to depth discontinuities, is also reduced. However, the identification step is more complicated.

Method proposed by Tajima-Iwakawa. The system proposed in 1990, is based on the vertical slit coding technique⁽²⁵⁾. Each slit is emitted with a different wavelength. The pattern looks like a Rainbow, as the whole colour spectre, from violet up to red, is projected. The Rainbow can be obtained diffracting white light.

The slit emission angle can be determined from its slit wavelength.

The objects illuminated by the Rainbow pattern are imaged with a single monochromatic camera instead of a colour one. Two different colour filters, placed in front of the camera, are used and two images of the scene are captured. For the same point, the intensity relation between the two images does not depend on the illumination, neither on the colour object. Tajima et al. have proved that this intensity relation depends directly on the wavelength slit.

As the system needs to capture two images for each measure, it is limited to static scenes. Obviously the system could measure dynamic scenes using a colour camera.

In 1996, Geng⁽²⁶⁾, proposed again the same Rainbow pattern to obtain 3D information of the measuring surface. The idea is the same as the one proposed by Tajima, but it has been improved by using a CCD colour camera and a Linear Variable

Wavelength Filter (LVWF). In this case, the projector emits a white light plane, which using a cylindrical lens, generates a continuous fan of planes. From the natural design of the LVWF, a continuous colour spectre is obtained, so that there are not two light planes projected on the scene with the same wavelength. Obviously, the system resolution depends on the resolution of the camera to distinguish one colour, or wavelength, from another.

The same method has been recently reimplemented by Smutny et al.⁽²⁷⁾ Regarding limitations of the Rainbow pattern, they said that the surface can have any colour but it must be opaque. Obviously, another wavelength, which does not come from the projector can not be emitted on the scene. Therefore, the scene has to be light controlled. The objects can not be fluorescent, nor phosphorescent.

Method proposed by Wust-Capson. The system proposed in 1991, is based on the projection of a sinusoidal intensity pattern⁽²⁸⁾. The proposed pattern is made by the overlapping of three sinusoids, one for each red, green and blue primary colour of n periods along the x -axis. The green sinusoid is shifted 90° with respect to the red, and the blue is shifted 90° with respect to the green. The pattern is column coded. So, all the rows are identical, obtaining a colour vertical fringe pattern.

Instead of obtaining the column index by decoding the imaged pattern, Wust et al. proposed to obtain the depth directly from the wave phase shifting. This technique is widely used in order to measure continuous surfaces in Moiré methods.

Some limitations of the method can be described: As any system which projects colour, the scene has to be predominantly neutral. As the pattern is made by periodical fringes, it is limited to measure surfaces without discontinuities longer than a fringe period. According to Wust et al., camera response depends on the frequency of the emitted fringes. The histogram equalisation used in order to compensate the non-linear intensity response, also produces some measuring errors. Improving these aspects the system can obtain a better resolution and robustness.

In 1993, a grey level sinusoidal pattern⁽²⁹⁾ was proposed. The phase can be obtained approximately from its light intensity.

Method proposed by Griffin-Narasimhan-Yee. In 1992, a mathematical study⁽³⁰⁾ which should

be the largest size of a coded matrix dot pattern, has been realized. It is supposed that: 1.- A dot position is coded by the information from itself and its four neighbours (North, South, East and West). 2.- It is impossible that two different dot positions have the same code. 3.- The information is determined using a fixed basis, which gives the symbols used to code the matrix. 4.- The biggest matrix is wanted, that is, the matrix which gives a better resolution.

Given a basis b , the maximal matrix (the biggest $n \times m$ matrix) can be obtained from its maximal horizontal vector (V_{hm}), and its maximal vertical vector (V_{vm}). V_{hm} is a vector made by the sequence of all the triplets of numbers that can be made without repetition using a b basis. V_{vm} is a vector made by the sequence of all the pairs of numbers that can be made without repetition. Then, the first row of the matrix, is given directly by V_{hm} , and the other matrix elements can be determined from the precedents and from the V_{vm} vector.

After the coded matrix is obtained, a different projection can be associated for each value, that is, for each number which belongs to the interval $\{1, b\}$.

The resolution of the pattern can be improved simply by increasing the basis value. Depending on the discrimination capability of the system employed to image the scene, almost every degree of resolution can be obtained.

The proposed method is the unique method studied that, from the decodification of each image point of the pattern captured by the camera, can give both projector point co-ordinates, from which it has been emitted. As it has been explained, it is not necessary to know both projector co-ordinates. Therefore, the method can be obviously simplified in order to obtain a single row or column coded pattern.

Method proposed by Maruyama-Abe. The method⁽³¹⁾, described in 1993, is based on the projection of multiple vertical slits. Slits are coded from the position of some random cuts. All the random cuts are placed to obtain short lines, keeping their length in the interval $[L_0 + \Delta, L_0 - \Delta]$, where L_0 is a determined length and Δ is given by a random number.

Segment matching is based on the correspondence of the short line end points along the epipolar lines. As the cuts are randomly distributed, more than one pattern line can be

matched with a given image segment. To remove erroneous matching, the information of neighbour segments is consulted. Finally, in the aim to obtain the correspondence of all the segments, a region growing algorithm, matching from adjacency constraints, is used.

To improve the system, we could think in using a pattern with an intelligent distribution of the cuts. Then, a bijection between captured image and projected pattern is determined. But if adjacency constraints are used, the matching can be done through a region growing algorithm. Furthermore, a region growing algorithm has to be used in order to match the segments which do not have a matching line, due to the noise on the image, or to a surface depth discontinuity.

The method is suitable for measuring 3D objects with relatively smooth surfaces. It will not work on objects with a lot of discontinuities and with highly textured surfaces, as line discontinuities complicate the matching process. However, the pattern can be perfectly used to measure dynamic scenes, as only one projection is required.

SUMMARY

In order to provide an overview of the presented techniques, we summarise them in the following chronological list and classification table:

- 1982 Posdamer-Altschuler. A temporal space-encoded projected beam system^(12,13).
- 1985 Carrihill-Hummel. An intensity ratio pattern projection⁽¹⁹⁾.
- 1987 Boyer-Kak. A colour encoded pattern⁽²⁰⁾.
- 1988 Le Moigne-Waxman. A grid pattern with some landmark dots⁽²¹⁾.
- 1988 Morita-Yakima-Sakata. An M-array pattern projection system⁽²²⁾.
- 1990 Vuylsteke-Oosterlinck. A single binary-encoded chess board pattern⁽²³⁾.
- 1990 Tajima-Iwakawa. A rainbow pattern⁽²⁵⁾.
- 1991 Wust-Capson. A colour sinusoidal pattern⁽²⁸⁾.
- 1992 Griffin-Narasimhan-Yee. A mathematical study about uniquely encoded patterns⁽³⁰⁾.
- 1993 Maruyama-Abe. A multiple slits with random cuts pattern projection⁽³¹⁾.

Authors' method	Pattern type		Dependencies	
	Light	Shape	Temp.	Surface
PoAl ^(12,13)	Binary	Slits	Static	-
Carr ⁽¹⁹⁾	Grey	Slits	Static	-
BoKa ⁽²⁰⁾	Colour	Slits	Dynamic	White/Pale
Moig ⁽²¹⁾	Binary	Grid	Dynamic	-
MYS ⁽²²⁾	Binary	Dots	Static	-
Vuyl ⁽²³⁾	Binary	Dots	Dynamic	Smooth
Taji ⁽²⁵⁾	Colour	Slits	Static	-
Wust ⁽²⁸⁾	Colour	Slits	Dynamic	Continuous
Grif ⁽³⁰⁾	Bn/Col	Dots	Dynamic	-
Maru ⁽³¹⁾	Binary	Slits	Dynamic	Smooth

CONCLUSIONS

The accuracy of the surface measurement depends highly on the vision system used. It is widely known that a vision system based on stereoscopy is useful to measure surfaces with well defined boundary edges. An algorithm to recognise singular points can be used to solve the problem of correspondence between points on both image planes. But the system becomes rather inefficient to measure continuous surfaces where there are few reference points, or to measure highly depth discontinuous or textural surfaces where the abundance of reference points can produce matching errors. In these cases, an active system based on the structured light concept will be useful.

In structured light, a correspondence between the captured pattern imaged by the camera and the pattern projected on the scene, has to be solved. The correspondence problem can be highly time computing and sometimes unproductive using only the geometric constraints between camera and projector. Along the past few years, several coded structured light techniques have been proposed, in which the emitted light carries information of the position, with respects to the projector co-ordinate system where it comes from. This information allows us to solve directly the camera-projector correspondence.

This work surveys the different techniques which code the pattern projected on the scene. Their advantages and disadvantages have been discussed:

- a) To measure dynamic scenes, where just one pattern can be projected to find out the correspondence, or static scenes, where the sequential projection of several patterns is allowed.
- b) To measure scenes made by highly saturated colour objects, on which basically binary patterns can be projected, or to measure scenes with a predominantly neutral colour content, where the

emission of colour is possible using an easier pattern codification. c) To measure scenes with a lot of discontinuities with different depths, where only an absolute codification is allowed, or to measure predominantly continuous scenes, where very easy periodical patterns can be projected.

Although we have described and compared several coded structured light methods, we propose to study them in depth to obtain a relationship of their computational time. But one still has to work a lot to obtain a generic vision system which permits to get an instantaneous measure of an unknown scene. There is not any doubt that the electronic integration and the improvement of the computation power of the new processors lead us in the correct direction.

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