An Overview of the Advantages and Constraints of Coded Pattern Projection Techniques for Autonomous Navigation.

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Abstract

The absolute necessity of obtaining 3D information of structured and unknown environments in autonomous navigation reduce considerably the set of sensors that can be used. The necessity to know, at each time, the position of the mobile robot with respect to the scene its indispensable. Furthermore, this information must be obtained in the least computing time. Stereo vision is an attractive and widely used method, but, it is rather limited to make fast 3D surface maps, due to the correspondence problem. The spatial and temporal correspondence among images can be alleviated using a method based on structured light. This relationship can be directly found codifying the projected light; then each imaged region of the projected pattern carries the needed information to solve the correspondence problem. We present the most significant techniques, used in recent years, concerning the coded structured light method.

1. Introduction

When 3D information of a given unknown scene is needed, we have to choose between a passive method and an active one. The most widely known passive method is stereovision which can be achieved by two different ways. In the first way, an optical sensor is moved to known relative positions in the scene. In the second way, two or more optical sensors are previously fixed in known positions. The surface to be measured is projected on the image plane of each sensor through each focal point. The 3D co-ordinates of the object point can be obtained by trigonometry [1,2] from the known projections of an object point and, furthermore, from the relationship between the optical sensors. But we have to know, with correctness, for each object point, its projections on the optical sensor image planes. In fact, in order to obtain the 3D co-ordinates of a given point from n given projections (one from each sensor), these projections have to be necessarily from the same object point. This problem is known as the correspondence problem.

The correspondence problem can be considerably alleviated by an active method [3]. One of the most widely used active methods is based on structured light projection [4]. Normally, only one camera is used to image the projection of a given pattern on the measuring surface. 3D information manifests itself in the apparent deformations of the imaged pattern from the projected one. Analysing these deformations we can get information about the position, the orientation, and the texture of the surface on which the pattern has been projected. The 3D analysis can be also quite alleviated using Coded Structured Light. This technique allows us to know for each imaged point, its original point on the emitted projector plane. Then, the correspondence problem can be directly obtained, so it is not necessary to use geometrical constraints to get it. This technique is the main subject of the paper.

The paper is structured as follows: In order to obtain the 3D co-ordinates of the measuring object from its projections, mathematical equations and geometrical constraints of a structured light system are analysed. Then, the coded structured light method is presented as a

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technique to solve the correspondence problem easily and quickly. Finally, several coded structured light techniques are presented and discussed. The advantages and constraints are explained. The paper ends with the conclusions.

2. Coded structured light

Assume a general stereoscopic system made by the relationship between two cameras, where the A_i matrix, which models the C_i camera as a pinhole camera can be obtained in the calibration process.

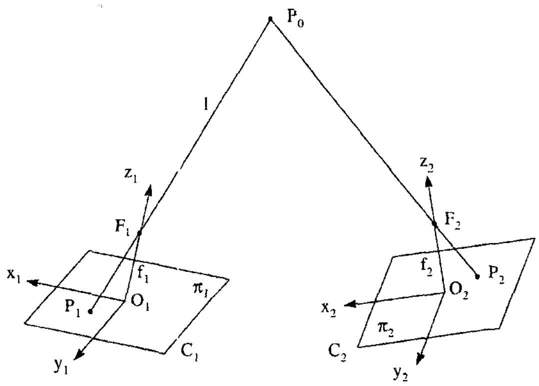

Figure 1. A general stereoscopic vision system

$$\begin{bmatrix} w_1 x_{p1} \\ w_1 y_{p1} \\ w_1 \end{bmatrix} = \begin{bmatrix} A_{111} & A_{112} & A_{113} & A_{114} \\ A_{121} & A_{122} & A_{123} & A_{124} \\ A_{131} & A_{132} & A_{133} & A_{134} \end{bmatrix} \begin{bmatrix} x_{p0} \\ y_{p0} \\ z_{p0} \\ 1 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} w_2 x_{p2} \\ w_2 y_{p2} \\ w_2 \end{bmatrix} = \begin{bmatrix} A_{211} & A_{212} & A_{213} & A_{214} \\ A_{221} & A_{222} & A_{223} & A_{224} \\ A_{231} & A_{232} & A_{233} & A_{234} \end{bmatrix} \begin{bmatrix} x_{p0} \\ y_{p0} \\ z_{p0} \\ 1 \end{bmatrix} \quad (2)$$

Suppose that P_0 is an object point, then, its position (x_{p0},y_{p0},z_{p0}) from a world co-ordinate system, can be calculated from its projections P_1 (x_{p1},y_{p1}) and P_2 (x_{p2},y_{p2}), on the two image planes by trigonometry. But, before the calculation of P_0 co-ordinates, we do not have to consider only the P_1 and P_2 positions, the most important is to be sure that both P_1 and P_2 are projections of the same object point P_0. As the object co-ordinates depend on the corrected association of the captured image point P_1 (x_{p1},y_{p1}) and the projected point P_2 (x_{p2},y_{p2}), any mistake in the correspondence establishment lead to an error in the object point co-ordinates determination.

If we select an image point P_1 on π_1, as the projection of an object point P_0 along the **l** line, defined from F_1 and P_0. As P_0 can be placed at any point on the **l** line, there is no unique position of P_2 on π_2, if we only want to apply geometrical constraints. However, we can affirm that the projection P_2 on π_2 has to lie on the segment made by the intersection between the plane defined by the points F_1, F_2 and P_1 and the image plane π_2. This constraint is known as the epipolar constraint.

If the projection point P_1 on π_1 is known, the epipolar constraint allows us to find the projection point P_2 on π_2 in only one direction. Of course, we can not know if the P_0 projection has been imaged on the π_2 image plane. It may be occluded by any other surface of the scene, or it may be projected out of the scope of the camera.

We can considerably alleviate the correspondence problem leaving out passive methods such as stereo, and going to an active method based on the structured light concept. Here, the second stereo camera is replaced by a light source, which projects a known pattern of light on the measuring scene. A single camera images the illuminated scene. The required 3D information can be obtained by analysing the deformations of the imaged pattern with respect to the projected one. Of course, some correspondences between the projected pattern and the imaged one should be solved.

If a single light dot or a slit line is projected on the scene, then, there is no correspondence problem to be solved, but all the scene has to be scanned to obtain the 3D map. Shirai et al., in 1971, proposed a slit line projection to recognise polihedric objects [5]. In 1973, Agin et al. generalised this idea to recognise curvilinear objects [6]. Two years later, Popplestone et al. proposed a more general system which recognises either polihedrics or curvilinear objects [7]. In 1986, Yamamoto et al.[8] proposed a half plane illumination system instead of a slit line. In fact, binarizing an image of a scene illuminated by a half plane pattern corresponds to the boundary edge detection between the illuminated and the obscured area. There are also some authors, as Sato et al. [9], who project two slit lines with different orientation and position in the 3D co-ordinates system. In a similar way, Kemmotsu and Kanade [10] chose to project three lines on the measuring scene.

In order to improve the accuracy of the system, an alternative way is to project a grid of dots or lines on the scene to cover all the scope of the camera. Asada et al. proposed to use a pattern made by a set of vertical, parallel and equidistant, stripe lines [11]. Wang et al., have extended Asada's idea with the sequential projection of two orthogonal stripe patterns [12]. Furthermore, in order to obtain 3D surface properties, Gu and Stockman [13] have proposed the widely known projection of a grid. Other authors also use the information given by an intensity image to obtain, with a better accuracy, the boundary edges of the scene. Then, an easier correspondence has to be solved, we have to identify, for each point of the imaged pattern, the corresponding point of the projected pattern.

All these methods allow us to find out 3D information from the geometric constraint propagation. However, in order to solve the correspondence problem, many of these patterns have quite a few constraints. For any kind of object, and surface, there is also the problem due to the lost projected points that do not have a projection on the image plane. This issue can be due to a low surface reflection, to a surface occlusion, or simply because dots are reflected out of the camera scope. All these troubles can be solved if the projected pattern is conveniently coded [14], so that, the projected light carries information about the point (x_{p2},y_{p2}) from which it has been emitted. When the point is imaged on π_1, this information can be used to determine its co-ordinates on π_2, from where it has been emitted.

As it can be deduced from (1) and (2) we can use four equations to calculate the three variables that determine the object point (x_{p0},y_{p0},z_{p0}). In fact, one of the four equations is linearly dependent on the other ones, so, with the aim to determine the three variables, only three of the four equations have to be used. As an image of the scene has to be captured to deduce depth scene information, the image points co-ordinates (x_{p1},y_{p1}) are known, as is the projection of the object point with co-ordinates (x_{p0},y_{p0},z_{p0}). Therefore, only one of the two co-ordinates (x_{p2},y_{p2}) of the projected point has to be known. This idea allows the projected pattern to be codified just along one component co-ordinate, so the captured light, at the point (x_{p1},y_{p1}) on the image plane, carries information of row x_{p2}, or column y_{p2}, from which it has been emitted.

3. Overview : coded structured light techniques

Several coded structured light methods have been proposed in recent years. In the following, these methods will be described, analysing their advantages and constraints. The overview is structured as a sequence of several methods presented in recent years, going from easy methods to more complicated in a non-chronological order.

There are a lot of different patterns that 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, but the line thickness has to be also chosen, as it depends directly on the smoothness of the imaged surface texture. A very thick line will give a low resolution, and, with a very thin one, we will obtain a lot of discontinuities, which will complicate the matching process. Obviously, the thickness of the line has to be chosen knowing the kind of scenes to be measured.

Le Moigne and Waxman [15] proposed to add dots on the grid which can be used as landmarks to initiate the decodification or labelling of the projected pattern. In figure 2 some grid patterns coded with dots are shown.

The configuration used for the system locates the projector at a fixed distance from the camera, along the y-axis. This means that vertical lines are imaged nearly without deformation, keeping its natural parallelism and continuity, so they will be easily detectable. The system uses the known location of the vertical lines as guides to search the dot and horizontal line intersections. Then the horizontal lines are explored to join their discontinuities. Note that, if lot of discontinuities are found, it is due to the line thickness chosen is too thin. Finally, for each landmark dot, a edge labelling process, using a greedy algorithm, is used.

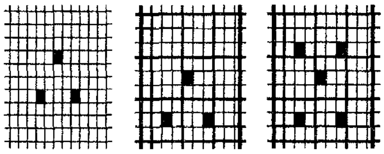

Figure 2. Grid patterns partially coded by the position of some dots.

The pattern proposed by Le Moigne et al. is specially 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. And finally, the matching process may be rather slow in density grids, so, dynamic high resolution is not permitted. But its utilisation as a vision sensor for mobile robot navigation in structured indoor environments is highly recommended. In such environments, the surfaces do not usually have high contrast textures, which can deform the pattern, and the scene is quite regular, and small differences do not give interesting information.

Altschuler et al. [16] and Posdamer et al. [17] proposed a temporal binary codification of a stripe pattern. The same principle is also proposed by Mundy and Porter [18] and Minou et al. [19]. The system is based on the utilisation of a pattern structured as a dot matrix of nxn binary light beams. Each n_i column of the pattern can be independently controlled, so it can be lighted or obscured. Then, several masks can be made to allow coding 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. An exemple, of five projection patterns, is shown in figure 3.

The system proposed by Posdamer et al. and Altschuler et al. is limited to static scenes as it has to capture an image from each projected pattern. But, as proposed by Altschuler et al. [16], the system can be improved to be used in dynamic scenes. In this case, all the patterns are projected with a different frequency wave and n cameras are used, one for each projected pattern. Each camera should have an optical filter, as each camera will image only one pattern frequency. Then, all the patterns can be projected at the same time. The cameras should be located as close as possible. Even so, we could also obtain some points that can not be decoded as they are not imaged from all the cameras.

Figure 3. The temporary codification proposed by Altschuler et al. and Posdamer et al.

Posdamer and Altschuler's idea has been widely studied. Basically, the codification and the speed measurement have been improved. For example, Inokuchi et al. [20] in 1984 proposed changing the binary codification to a Gray codification which is more error robust. Later, in 1986, Sato et al. [21], and in 1987, Sato and Inokuchi [22], proposed to use a Liquid Crystal Device, already studied by Inokuchi et al. [23] in 1972, which allows an increased number of columns to be projected with a high accuracy. The system also improves the coded speed, against a slide projector, so the LCD can be electronically controlled.

If an object has a high textural contrast or any high reflected surface regions, then, some pattern segmentation errors can be produced. Normally, this problem can be solved capturing the first image without pattern projection (or with the same light projection for each dot) to obtain a reference light intensity. This intensity gives a dynamic threshold for each pixel. Sato et al. [21], in 1986, and Sato and Inokuchi [22], in 1987, proposed a complementary method of segmentation based on the projection for each coded pattern, of its positive and negative representation. Then, comparing the intensity image with both representations, a better segmentation of the projected pattern can be obtained.

The problem of a light projector is sometimes a result of heat irradiation onto the scene, and of its big size and weight. In 1995, Hattori et al.[24] proposed to replace the light projector with a semiconductor laser, which gives a high power illumination with low heat irradiation.

In 1995, the same temporary codification described by Posdamer et al. and Altschuler et al. in 1982 is again proposed by Müller [25]. In 1996, Sato [26] proposed a new moving modulated pattern light and spatio-temporal image processing.

The method described by Maruyama et al. [27], in 1993, is based on the projection of multiple vertical slits. Slits are coded from the position of some random cuts, as shown in figure 4. Segment matching is performed only 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.

Maruyama et al. consider that the epipolar lines can always be horizontally computed, so that only the x-axis has to be examined to find out all the lines on the pattern which match with the imaged segment. This is not always true, as epipolar lines depend on the projector position and orientation, with respect to the camera axis, and Maruyama et al. do not impose any restriction. But, it is true that the image can always be transformed to get horizontal epipolar lines, as they said in their work.

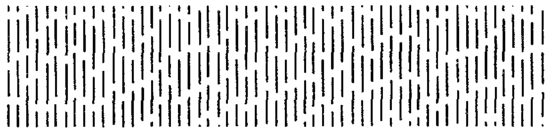

Figure 4. A detail of the pattern proposed by Maruyama et al.

To improve the system, we could think of using a pattern with an intelligent cut distribution which matches the same imaged segment, along its epipolar lines (in order to not obtain more than one matching). So, a bijection between captured image and projected pattern is determined. But, as Maruyama et al. said, if the adjacency constraints are used, the matching can be done using a region growing algorithm. However, surface depth discontinuity or noise problems in the image could provide segments which do not have a matching line. In this case, a region growing algorithm has to be also used to match them.

The method is suitable for measuring 3D objects with relatively smooth surfaces. For objects with a lot of discontinuities and with highly textured surfaces, the method will have some difficulties. Obviously, line discontinuities produced in the captured segments complicate the matching process. However, the pattern is perfectly used to measure dynamic scenes, as only one projection is required.

The system proposed by Carrihill et al. [28], in 1985, is based on getting 3D information of any scene from two frame images. The first image is captured with a constant illumination projection on the scene. A linear wedge filter is used to project on the scene a pattern brightly illuminated on one side, and half brightly on the other. This pattern is shown in figure 5. This wedge filter is used to illuminate the scene for the second image capturing step.

For the first projection, it is supposed that the illumination intensity is constant along the x-axis and the y-axis of the projector. For the second projection, illumination has to be a constant along the y-axis. Then, for each obtained pixel, the intensity subtraction of the two images, can be calculated. This difference allows obtaining the column of the projector from which the dot has been emitted.

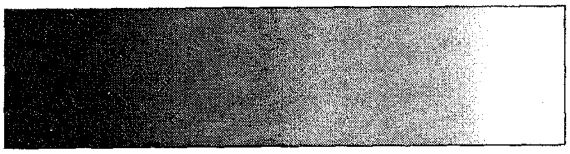

Figure 5. The pattern proposed by Carrihill.

Using a difference ratio for each pixel makes easier to cancel possible surface reflections or highlights as an illumination ratio change is always produced by a change in the projected illumination.

In order to improve the accuracy measurement 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 to be measured is limited to the chosen period. In 1993, Hung [29] proposed a grey level sinusoidal pattern. The period of the captured pattern depends on the depth of the surface where it is reflected. However, computation demands to much time. Hung proposed, to triangulate from the column phase of the imaged point. For each pixel point, this phase can be approximately obtained from the light intensity.

In 1988 Morita et al. [30] proposed a binary pattern of light dots as an M-array. The M-array has property of the *coding window* as any subpattern into a window exists only once and at one place within a period.

Firstly, this method has to project an all illuminated dot matrix to obtain the image co-ordinates of each dot. Then, a binary (bright and dark) dot matrix is projected, as, each window with a fixed size, determine the column index from where the imaged point has been projected.

The proposed system is quite simple, so that 3D information can be obtained without a lot of computing time. However, the system is limited to static scenes because they need two projections. As the system projects isolated light dots, not a lot of textural information can be obtained, and, if the dot size is reduced to get more resolution, then, high contrast textural surfaces could modify the dot shape, making its localisation difficult.

Recently, in 1996, Lavoie et al. [31] has proposed a binary grid pattern with a pseudo-random dot codification at each grid vertex.

A model with a dynamic pattern, column coded, is proposed by Vuylsteke and Oosterlinck [32]. The basic structure of the pattern is like a regular chess-board alternating bright and dark squares, as it is shown in figure 6. Then, the pattern is modulated overlapping a bright or dark spot at every square vertex, so that, any square of the regular chess-board pattern carries an additional information bit, which together with the neighbouring bits, will be used to code each column.

A 6 bits length code is needed to codify the 63 different columns of the pattern. Then any window of 2x3 squares allow coding any column index. In fact, any window with 6 squares size can be used, but obviously, a compact window is less affected by surface discontinuities that an elongated one.

The pattern presented has basically two limitations. The first one is based on the difficulty to measure high textural surfaces, which produce partial lost regions of the pattern. And the second one is associated with the surface orientation. If these are not perpendicular to the optical axis of the projector, a deformation of the projected pattern is presented, which from a determined angle orientation, does not allow the identification of the pattern. However, the pattern is well recommended to measure dynamic surfaces where only one projection is permitted.

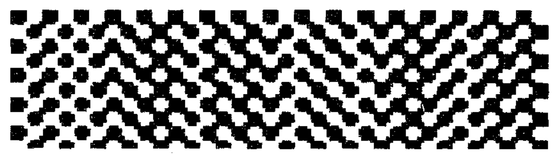

Figure 6. A detail of the pattern propossed by Vuylsteke and Oosterlinck.

In 1995, Pajdla [33] has reimplemented the same pattern. Pajdla has proposed, as an improvement, to use a hexagonal codification instead of a square one. In this case, the window's size is reduced and as a result, the number of not indexed columns due to depth discontinuities is decreased. However, the identification step is more complicated..

Griffin et al. [34], in 1992, have carried out a mathematical study about which should be the largest size allowed for a coded matrix dot pattern. It is supposed that: 1.- A dot position is coded with information emitted by itself and the information of its four neighbours (North, South, East and West). 2.- There can not be two different dot positions with the same code. 3.- The information is determined using a fixed basis, which determines the symbols used to code the matrix. 4.- The biggest matrix is desired, that is, the matrix which gives a better resolution.

Griffin et al. have proved that, given a basis b, the largest matrix (the biggest nxm matrix) can be obtained from its largest horizontal vector (Vhm), and its largest vertical vector (Vvm). Vhm is a vector made by the sequence of all the triplets of numbers that can be made without repetition using a b basis. Vvm 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 Vhm (equation 3), and, the other matrix elements can be determined applying the equation (4) where 'i' is the row index and varies from 0 to the Vhm length, and 'j' is the column index and varies from 0 to the Vvm length.

$$f_{0i} = Vhm_i \tag{3}$$

$$f_{ij} = 1 + ((f_{i-1j} + Vvm_j) \bmod b) \tag{4}$$

After the coded matrix is found out, 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 increased by simply increasing the basis value. Depending on the colour discriminating capability of the system employed to image the scene, almost any degree of resolution can be obtained. In many applications, the scene is not made by colour neutral surfaces. Then, monochromatic light has to be projected on the scene. In this case, the coloured association projected of each number can be changed for a geometric association.

The method proposed by Griffin et al. is a method that from the decodification of the pattern captured by the camera, it can be known, for each image point (x_{p1},y_{p1}), the projector position point (x_{p2},y_{p2}) from which it has been emitted. As shown in the second section of this paper, it is not necessary to know both projector co-ordinates. Then, the pattern can be obviously simplified to obtain a single row coded or column coded pattern.

Some recent examples about dot projection are the work of Ito et al. [35] and Davies et al. [36] In 1995, Ito and Ishii [35] have proposed a three-level checkerboard pattern. Each 3D object point or node is surrounded by four projected dots which can be coded using only three different grey levels. Ito et al. defined a subcode of a node as the clockwise combination of the codes of the four adjacent nodes. They assert that the quantity of codes is large enough to avoid false matchings between two spatially coded patterns. However pattern generation without repeated appearance of the same feature code values is a further research subject, it is not a problem because the correspondence constraint eliminates confusion. In 1996, Davies et al. [36] have implemented a coloured dot projection system. A specially developed formulation of the Hough Transform is used to extract each imaged spot, the imaged ellipse is described by only three implicit parameters instead of the conventional five. The parameters are the centre position along its epipolar line and two which describe the variation in shape.

In 1987, Boyer and Kak [37] proposed to illuminate the scene using a single pattern projection. The pattern will be made by a sequence of vertical slits coloured with any of the three basic components: red, green and blue.

If it is supposed that the pattern is made by n vertical slits, Boyer et al. proposed to divide this pattern in m subpatterns, each one made by k vertical slits, as n = m * k. In order to code the m patterns in a unique way, k is a value as large as necessary. As each subpattern is emitted without any beginning and ending code, multiple matchings can be obtained in reception. Actually, we do not know where a subpattern ends and the next begins, and moreover, the slits have been reordered as a function of the measured surface discontinuities.

In 1992 Monks et al.[38] assert that the matching process proposed by Boyer it is not optimal, because if the matches for the first vertical slit contain errors, these will be propagated through the rest of the data. Monks et al. have developed a new technique which eliminates this problem and has the advantage of being non-iterative, encoding the topology of the entire set of stripes as a directed acyclic graph.

The pattern proposed by Boyer et al. [37] and Monks et al. [38], is limited to measuring predominantly neutral colour surfaces, as highly saturated hues could produce slit identification errors. Even so, it is specially recommended in dynamic environments as only one projection is needed.

The system proposed by Tajima [39] in 1990 is based on the vertical slit coding technique, where each slit is emitted with a different wavelength. The projected pattern is like a rainbow pattern, as the whole colour spectrum, from the violet up to the red, is projected. This can be obtained diffracting white light.

Depth can be obtained using the triangulation principle, but first the slit angle (the x_{p2} co-ordinate) which has produced the colour pixel imaged on the image plane, has to be known. In fact, the slit emission angle can also be determined knowing the slit wavelength.

The objects illuminated by the rainbow pattern are imaged with a single monochromatic camera instead of a colour camera. 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, nor on the colour object. Tajima et al. have proved that this intensity relation depends directly on the wavelength slit.

As the system needs two frames for each measurement, it is limited to static scenes, but obviously the system can measure dynamic scenes using a colour camera. In 1996, Geng [40], seemingly without knowing the work already done by Tajima et al., proposed the same rainbow pattern in order to obtain 3D information from the measuring surface. However, the initial idea proposed by Tajima et al. have been improved by Geng using a CCD colour camera and using a Linear Variable Wavelength Filter (LVWF).

Recently, Smutny and Pajdla [41] have reimplemented the system proposed by Tajima et al. Regarding limitations of the rainbow pattern, they said that the surface can have any colour, but this has to be opaque. Obviously, no other wavelength which do not come from the projector, can be emitted on the scene. The scene has to be light controlled and the measuring objects can not be fluorescent, nor phosphorescent.

In 1991, Wust and Capson [42] proposed the projection of a sinusoidal intensity pattern on the measuring surfaces. The proposed pattern is made by the overlapping of three sinusoids, of n periods along the x-axis. Each sinusoid is associated with each primary colour (red, green and blue). The green's 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, resulting a colour vertical fringe pattern.

Instead of obtaining the column index by decoding the imaged pattern, Wust and Capson proposed to obtain the depth directly from the wave phase shifting. This technique is widely used in Moiré methods to measure continuous surfaces [43].

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

4. Conclusions

There are some essential problems which difficult to match points in both image planes. However some geometrical constraints as the epipolar line and the disparity gradient can be used, they always lead us to hard computational systems which can not be used in autonomous navigation. We can considerably alleviate the correspondence problem using a method based on structured light.

In recent years a new structured light technique has increased in importance. This technique is based on an unique codification of each token of light projected on the scene. When the token is imaged by the camera this codification allows us to obtain the correspondence, i.e. to know from where it comes, reducing considerably the computing time to solve the matching.

This work surveys several techniques which codify the pattern projected on the scene. The advantages and disadvantages have been discussed analysing the following capabilities: a) to measure dynamic scenes, where only one pattern can be projected [15, 27, 31-38, 40-42], and static scenes, where the sequential projection of several patterns is allowed [16-26, 28-30, 39], b) to measure scenes made by highly saturated colour objects, with basically only binary patterns can be projected [15-33]; or to measure scenes with a colour content predominantly neutral, where the emission of colour is permitted [34, 36-42]; specular or metallic surfaces should also be included, but they always lead to a specific system [44, 45]. The reflection of a pattern region on another surface, already illuminated, produces an evident identification error of the image captured by the camera; c) to measure scenes with a lot of discontinuities, of several different depths, where an absolute codification is only allowed [16-26, 28, 30-42]; or to measure scenes predominantly continuous [27], where very easy periodical patterns can be projected [29].

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