DESIGN OF A MONOCHROMATIC PATTERN FOR A ROBUST STRUCTURED LIGHT CODING

Chadi ALBITAR, Pierre GRAEBLING and Christophe DOIGNON

Laboratoire des Sciences de l'Image, de l'Informatique et de la Télédétection (UMR ULP-CNRS 7005)
Boulevard Sébastien Brant, BP 10413, F-67412 Illkirch, France
Tel: (+33) (0) 3 90 24 44 95, fax: (+33) (0) 3 90 24 44 97,
{albitar, graebling, doignon}@lsiit.u-strasbg.fr

ABSTRACT

In this paper we present a new pattern for the robust coding of the structured light based on the spatial neighborhood scheme and by means of the M-array approach. The pattern is robust as it allows a high error rate characterized by a Hamming distance higher than 3. We tackle the design problem with the definition of a small set of symbols associated to geometrical features with simple shapes. We benefit from the stripe, as it is one of the considered primitives, to embed the local orientation of the pattern. This is helpful while performing the search for the relevant neighborhood during the decoding process. The aim of this work is to use this pattern for the 3-D reconstruction of dynamic scenes with fast and reliable detection and decoding stages. Ongoing results are presented to assess both the capabilities of the proposed pattern and the decoding algorithm with projections onto simple 3-D scenes.

Index Terms**—** Structured light, Hamming distance, M-array, 3-D reconstruction

1. INTRODUCTION

The 3-D reconstruction of the environment in which we work is a major problem for many applications using computer vision. It is particularly the case for medical applications for which the use of imagery devices is increasing. Right now, the use of imagery in that field remains limited because of the nature, generally two-dimensional, of the information provided by the most of acquisition devices. Thus, a device providing, possibly in real time, the 3-D information of the environment would open new prospects. For example, within the framework of the use of robots in interventional radiology, it would be possible to register a planned gesture using preoperative images, or to compensate the physiological movements of the patient during the operation with intra-operative images. That would also be helpful to foresee and to achieve robotized surgical acts. The objective of our work is to estimate the 3-D surfaces of body parts or internal structures of the abdomen in order to integrate this information in robotic medical systems. Among all the techniques usually used for surface reconstruction, we propose a solution based on structured light projection, which consists in illuminating a scene with a known pattern, and then interpreting its deformations to locally reconstruct the 3-D scene. The main problems of such systems are related to the choice of the pattern and to the associated coding. In this article, we focus on the design and the use of a new robust pattern based on the "M-array" approach. It will be employed to recover the 3D structure of dynamic scenes, for vision-based control of robots in surgery or for other medical applications.

2. STRUCTURED LIGHT CODIFICATION

Structured light techniques can be classified into three categories [1] according to the coding of the projected pattern: time multiplexing, direct coding and spatial neighborhood. The main drawback of the time multiplexing based methods is their weakness to deal with dynamic scenes since they require multiple patterns projections. The methods adopting direct coding provide a good spatial resolution but their applicability is limited due to their sensitivity to noise and to light variations. Methods of the last category adopt the projection of a unique pattern including all the code. The code of each component of the pattern depends on its neighbors. That is why these methods can treat dynamic scenes if we are able to take into account some errors during the decoding stage. For our application, a technique related to the latter category seems to be the most suitable. Difficulties then lie in the choice of the pattern to be projected and in the choice of a new associated decoding algorithm.

2.1. Spatial neighborhood strategy

The methods based on the spatial neighborhood technique tend to integrate the entire coding scheme in a unique pattern. The coding must alleviate any ambiguity while identifying the components (uniqueness of code words) and must also increase the robustness of decoding, even in the presence of occlusions. Some authors ([2]-[4]) have proposed simple patterns with non-formal coding, without any mathematical background, which are consequently neither optimal nor robust. This can cause ambiguity because we may encounter identical regions within the pattern. Other strategies used a well-defined coding based on a De Bruijn sequence ([5]-[7]). The drawback in this case is that occlusions or shadows may cause deletions and disorders among the pattern primitives, thus it is difficult to decode the observed pattern. To solve these problems, some authors adopted the theory of perfect maps to encode a unique pattern ([8]-[12]). The M-array is a matrix of dimensions $n \times m$ where each element is taken from an alphabet of k symbols so as every submatrix appears exactly once except the one filled with 0's. The robustness of techniques using projections of such patterns is due to their capability to decode the visible parts of the observed pattern thanks to the properties of M-array's. Moreover, we can distinguish between the proposed patterns according to the size of the considered matrices, to the use of color or not, and to the size of the considered alphabet.

2.2. Constraints of M-array based pattern

Since we are interested in non-controlled scenes which is the case of the images of the internal structures of the abdomen, we have to face the classical problems of dealing with shadows and occlusions. In such situations, a key factor is to elaborate a pattern with a significant Hamming distance between the code words, that is very helpful to correct the errors raised in the decoding stage. It was shown in [9] that we can obtain better results with a Hamming distance higher than 3. However, most of referenced methods suggest obtaining such a distance with a significant number of symbols as it is in [9] and [12] where, respectively, 7 and 8 symbols were used. But in order to simplify the decoding stage, it would be more efficient to handle fewer symbols. To represent them, we can use color dots where each color is associated to a symbol, or geometrical primitives. However, in practice, monochromatic patterns are more robust than colored ones. Firstly, it is much easier to treat an image having only two intensity levels. Secondly, if the scenes are very colored, the choice of colors to be used in the pattern can be very tricky. Moreover, the realization of patterns with a monochromatic light is much simpler. Finally, since the code of a primitive depends on its neighborhood, it is necessary to detect this neighborhood easily and without imposing constraints on the acquisition device. Following this way, the primitives can be linked as proposed in [11]. Unfortunately, this can raise new difficulties in the detection and segmentation stages. So, it would be more convenient to consider an alphabet with a minimum number of symbols to build an M-array while being able to guarantee the correct detection of the neighborhood.

3. THE PROPOSED PATTERN

The pattern we present is designed to solve the mentioned problems taking into account the constraints imposed by the desired application. The proposed pattern is based on M-array theory with respect to the following properties:

1- Monochromatic light,
2- Central symmetry,
3- Uniqueness of the code of each window (3×3),
4- Hamming distance > 3,

Considering the choice of using a monochromatic light, the symbols cannot be coded with different colors, so we propose an alphabet of three symbols where symbols are associated to geometrical shapes as shown in Figure 1.

Figure 1: The proposed primitives: disc, circle and stripe.

The choice of circle and disc was motivated by simplifying the image processing during the segmentation stage. The third symbol is the stripe which will allow us, thanks to the directional information it carries, to rotate the window of observation correctly during the stage of neighborhood detection. The Hamming distance quantifies the differences between code words. If this distance is higher or equal to 1, it quantifies the capability to correct the errors that can occur in the detection and segmentation stages. In our case, the length of codeword associated to each primitive is 9 since we consider a 3×3 window centered on this primitive. The uniqueness constraint of each window corresponds to a Hamming distance of 1. To increase this value, we imposed an additional constraint so that each window must remain unique even if the upper corners elements are missing. Since the matrix which we search for is central symmetric, each window will remain unique even if the lower corners elements are also missing. Consequently, the Hamming distance is higher than 3 since each codeword will be different from the other code words in at least three symbols. We have implemented an algorithm to generate the matrix respecting the above mentioned constraints. In order to project the pattern onto a surface of significant size, we focus on maximizing the matrix dimensions. Finally, we obtained a matrix having the dimensions of 27×29 verifying all the desired criteria and using the three primitives (see Figure 2).

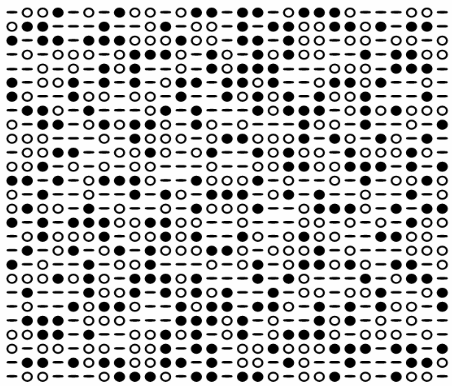
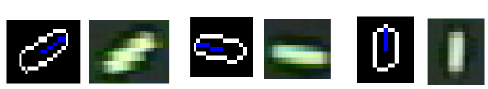


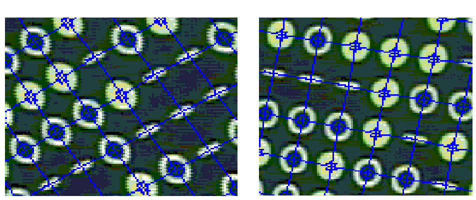
Figure 2: The proposed pattern.

3.1. Pattern segmentation and decoding

The segmentation is based on an approach using contours for detecting the symbols. First, the contours are detected and only those having a minimal length are considered and classified. The classification must lead to label a contour by one of the three pattern symbols, if not it is rejected. The classification of the primitives (circle, disc or stripe) is based on first-order statistics for the circle and of second- order for the two other primitives. In practice, the centers of contours are estimated, and then distances between pixels of each contour and its center are computed in order to determine the closest pixel and the farthest one. If the minimal distance is lower than an experimentally defined threshold, the primitive corresponds to a stripe; otherwise it corresponds to a disc. As for the stripe, the direction of the line passing by the center and the most distant pixel on the contour gives its local orientation (Figure 3-a). Then we can, thanks to this information, predict the directions to initiate the search for the neighbors of each symbol. Since the surfaces are locally smooth, their orientation varies slowly in a small neighborhood. This drastically simplifies the search of the neighbors for each symbol while being reduced to a coarse estimated orientation (Figure 3-b).



(a)



(b)

Figure 3: a) Stripe local orientation b) Searching the neighbors with respect to the local orientation.

The result of the contour detection for the symbol represented by a circle corresponds to two concentric circles. Consequently, to recognize this primitive, we have simply to search for two confused centers, or in practice, those that are very close to each other.

Once the neighbors of each primitive are detected, its code is determined as illustrated in Figure 4. Therefore, an exhaustive search is carried out to decode the primitives (finding its location in the matrix) taking advantage of the robustness of our pattern. We used also the method of votes which considers the decoding results of each primitive neighbor to determine the correct code of the primitive. Finally, we used a projective reconstruction to highlight the results on the observed images.

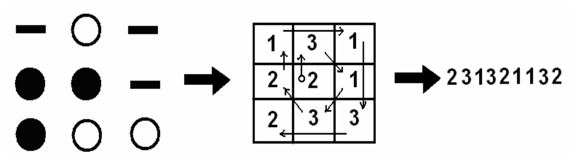


Figure 4: Determining the code of each window.

4. EXPERIMENTAL RESULTS

The system of validation is composed of a camera (JAI CV-S3200) which provides images of dimensions (568×760), and a video-projector (Sony VPL-CS6). The application of interest consists of acquiring images of internal structures of the abdomen. So we undertook a study on light-organs interaction under the conditions of the laparoscopic vision, which led us to choose a source of light whose wavelength corresponds to the green color. The first results we communicate are intended to validate the proposed method and to evaluate the choice of the pattern. After having projected the pattern on a plan (Figure 5-a), we applied the detection and decoding algorithms previously described. Figure (5-b) shows the detected primitives, and Figure (5-c) those which were decoded correctly (attribution of correct row-column indices), which corresponds here to 99% of the whole detected primitives.

We have also tested our pattern on other surfaces. For this purpose, we projected the pattern on a cylindrical surface (Figure 6-a). In spite of several deteriorations of the detection near strong discontinuities of surface; the large majority of the detected primitives (95 %) were decoded (Figure 6-b and Figure 6-c). The projective reconstruction of this surface is shown in Figure (6-d). In table 1 below, we gather the results obtained for various conditions of projection.

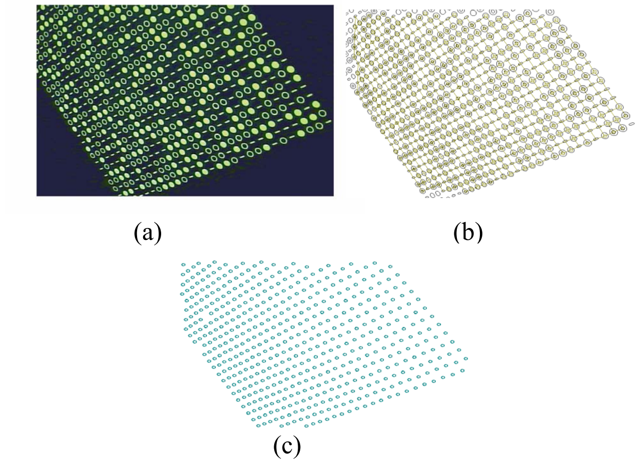


Figure 5: a) The pattern projected on a plan b) Detection c) Decoding

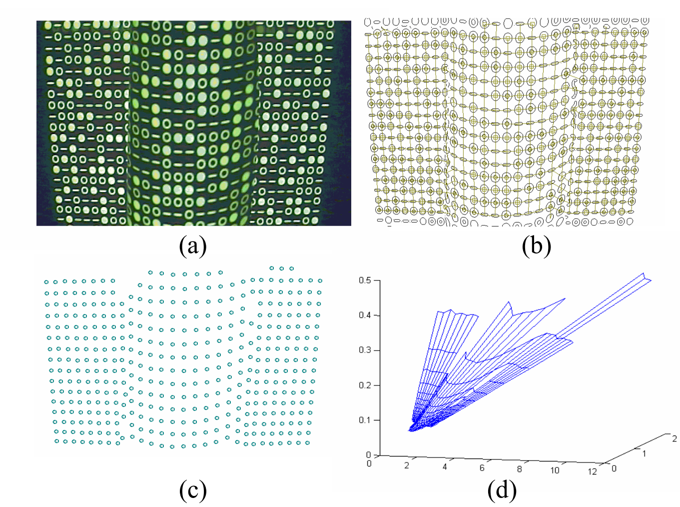


Figure 6: a) The pattern projected on a cylinder b) Detection c) Decoding d) 3-D Reconstruction.

Scene structure	detected primitives	decoded primitives	%
Plan1	756	754	99.7
Plan2	753	751	99.7
Cylinder	675	642	95.1

Table 1.

5. CONCLUSION

In order to code the structured light using the strategy of spatial neighborhood, we presented in this article a new pattern using monochromatic light with three symbols based on the M-array theory. The final objective, which exceeds the framework of paper, is to reconstruct moving surfaces in real time. To this end, we adopted a method which models the patterns with simple geometrical primitives instead of color coding. The code words were of length 9 with a Hamming distance higher than 3. We considered three simple primitives; one of them carries the directional information which simplifies the detection and speeds up the decoding. A traditional system of structured light was used to project our pattern on planar and cylindrical surfaces and the common projective reconstruction was employed to highlight the results. The first results show that more than 95 % of the detected primitives are decoded correctly, even in the presence of partial occlusions. These results must thereafter be followed by other experiments on non-uniform and textured surfaces before tackling the abdominal scenes.

6. REFERENCES

[1] J. Salvi, J. Pagès and J. Batlle, "Pattern codifications strategies in structured light systems", Pattern Recognition, Vol. 37, pp. 827-849, 2004.

[2] M. Ito and A. Ishii, "A three-level checkerboard pattern (tcp) projection method for curved surface measurement", Pattern Recognition, 28(1), pp. 27-40, 1995.

[3] C. Chen, Y. Hung, C. Chiang and J. Wu. "Range data acquisition using color structured lighting and stereo vision", Image and Vision Computing, Vol. 15, pp. 445-456, 1997.

[4] N. Durdle, J. Thayyoor, and V. Raso, "An improved structured light technique for surface reconstruction of the human trunk", In IEEE Canadian Conference on Electrical and Computer Engineering, Vol. 2, pp. 874-877, 1998.

[5] J. Salvi, J. Batlle and E. Mouaddib, "A robust coded pattern projection for dynamic 3d scene measurement", Int. Journal of Pattern Recognition Letters, Vol. 19, pp. 1055-1065, 1998.

[6] P. Lavoie, D. Ionescu and E. Petriu, "3D reconstruction using an uncalibrated stereo pair of encoded images", In Proceedings of the Int. Conf. on Image Processing, Vol. 2, pp. 859-862, 1996.

[7] L. Zhang, B. Curless and S. Seitz, "Rapid shape acquisition using color structured light and multipass dynamic programming", In Int. Symposium on 3D Data Processing Visualization and Transmission, Padova, Italy, June 2002.

[8] E. M. Petriu, Z. Sakr, H. Spoelder and A. Moica, "Object recognition using pseudo-random color encoded structured light.", In Proceedings of the 17th IEEE Instrumentation and Measurement technology Conference, Vol. 3, pp. 1237-1241, 2000.

[9] R. Morano, C. Ozturk, R. Conn, S. Dubin, S. Zietz, and J. Nissanov, "Structured Light Using Pseudo-random Codes", IEEE Trans. on Pattern Analysis and Machine Intelligence, Vol.(20)3, pp. 322 – 327, 1998.

[10] J. Pagès, Ch. Collewet, F. Chaumette and J. Salvi, "An approach to visual servoing based on coded light", In IEEE Int. Conference on Robotics and Automation, pp. 4118- 4123, 2006.

[11] S. Yee and P. Griffin, "Three-dimensional Imaging System", Optical Engineering 33(6), 2070–2075, 1994.

[12] A. Adan, F. Molina, and L. Morena, "Disordered patterns projection for 3D motion recovering", In Proceedings of the 2nd Int. Symp. on 3D Data Processing, Visualization, and Transmission, 3DPVT'04, Vol. 00, pp. 262- 269, 2004.