An M-array Technique for Generating Random Binary Pattern Based on a Connectivity Constraint

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Abstract

Much research has been conducted so far to find a perfect structured light coding system. One of the main problems of those introduced structured light systems is keeping a simple decoding method even for the larger pattern resolutions. Our main concern of this research is to introduce a new encoding strategy to solve the above problem based on M-arrays theories. We define two constraints: use only one pattern symbol, no connected symbols within the pattern to create simple binary pattern. Using this algorithm, we successfully generate a (200×200) pattern with (9×9) window property and even higher resolution with larger window sizes. But these patterns still can have a simple decoding algorithm, thanks to the constraints we applied to the pattern.

1. Introduction

With the improvement of computer capabilities and control theories, application areas of Computer Vision and Robotics have been increased largely in past few decades. 3D object modeling, automatic vehicle driving, biometrics and environments building are such few applications. One of the important problems of these applications is how to measure a 3D surface correctly.

In past years there have been introduced several 3D measuring techniques and among all these techniques, one of the famous techniques is stereo vision. The stereo vision is based on imaging the scene from two or more views points and then finding the correspondence between each view and applying the triangulation theories to correctly measure the 3D position. However, this method has the problem of finding corresponding points between different views accurately. To simplify this correspondence problem, structured light techniques have been introduced by replacing one camera of the stereo vision system with a light pattern projector.

2. Structured light coding

Coded structured light systems are based on projection of single or multiple patterns to a target scene and measure the surface of the scene by imaging the illuminated scene with a single camera or set of cameras. The pattern is designed so that code-words are assigned to a set of pixels, and thus there is a direct mapping from every code-word to their corresponding coordinates of the pixel in the pattern. There are different methods to represent the code-word in the pattern, such as using gray levels, colors or geometrical representations. In addition, there are many strategies to assign a code-word to a set of pixels. Therefor the structured light pattern projection techniques can be classified into three categories according to the coding of the projected pattern: time multiplexing, neighborhood codification and direct codification [2].

Time multiplexing methods project a sequence of simple patterns over time and generate the code word by combining all the patterns. The main drawback of this method is the weakness in capturing a dynamic scene as they use multiple patterns. Direct codification techniques provide a good spatial resolution, because it defines a code-word for every pixel, which is equal to its gray level or color. But their applicability is limited due to their sensitivity to noise and light variation. The neighborhood techniques tend to concentrate the entire coding scheme in a unique pattern so that a code-word for a certain point is obtained from a neighborhood of the points around it. The property of having a unique pattern, leads this technique to use in dynamic scene capturing. However, the decoding stage of the neighborhood codification will be more difficult since spatial neighborhood cannot always be recovered. So this technique needs a good encoding method that also increases the robustness of the decoding algorithm.

2.1 M-array based pattern coding

Some authors have invented several spatial neighborhood codification systems based on non-formal coding [3][4][5] and De Bruijn sequences [6][7][8]. Apart from these two techniques some authors have adopted the theory of Perfect Maps to encode unique patterns [1][11][12][13]. The perfect map is a matrix of dimension

$(m \times n)$ where each element is taken from an alphabet of k symbols and has the window property, i.e. each different sub-matrix of dimension $(p \times q)$ appears exactly once. If the matrix contains all the sub-matrices except the one filled with 0's, then it is called M-array or pseudo random array [9][10]. Perfect sub-map is a $(m \times n)$ matrix where all the $(p \times q)$ sub-matrices are unique within the matrix, but does not necessarily contain all the possible $(p \times q)$ sub-matrices.

All the methods previously implemented for generating M-arrays or perfect sub-maps have one drawback of low pattern resolution. It is mainly because increasing the pattern size will leads to huge difficulties in decoding as their encoding methods does not support for the robustness of the decoding algorithm. So the main goal of our research is to achieve larger pattern resolution using perfect sub-maps techniques, while simplifying the decoding stage.

3. Proposed Pattern Encoding Method

Here we propose a pattern encoding method that solves the above discussed problems. The proposed pattern is based on the M-array theory and has following constraints to address the above problems.

1. Only one pattern symbol
2. No connected pattern symbols
3. No repeated code-word within the pattern

The ultimate goal of this research is to create a high resolution structured light pattern. When we are creating larger patterns, having more pattern symbols will be problematic in a pattern decoding stage. It will takes more time to decode the each pattern symbol separately. And another problem of having more symbols is we have to use different colors or shapes to represent them. It will limit the usage of the pattern as the colored pattern cannot use to illuminate the scenes that have more colors. In addition shapes can be changed when it projected to a complex scene.

By concerning these issues and also to simplify the image processing during pattern segmentation in the decoding stage, we use a simple white square as the only symbol. We define the alphabet $A = \{0,1\}$ with two elements and these two elements are representing by the presence and the absence of the white square.

1 – Small filled white square
0 – No white square

The second constraint is also to simplify the pattern segmentation process in the decoding stage. As this research is about creating a dense structured light pattern with only one type of symbol, having connected symbols will lead to huge difficulties when identifying each white circle separately within the captured image. Thus in our pattern encoding method we avoid any code-word with connected symbols. Then in the decoding stage we can easily apply a contour detection or blob detection algorithm to segment the pattern.

The third constraint is to simplify the correspondence problem of stereo matching. The code-word for a given point is identified by analyzing its neighbors within a given window, and if it is unique we can easily match that point with the projected pattern image.

3.1 Algorithm

In 1998 Morano et al. [1] introduce an algorithm based on a brute-force approach to generate a perfect sub-map of size $(m \times n)$, in which each element of the pattern is taken from an alphabet of k symbols. It has the window property so that each $(p \times q)$ sub matrix appears exactly once within the whole pattern and keeps the Hamming distance h between every window.

1	0	1				
0	0	0				
0	0	0				

(a) Step 1

1	0	1	0			
0	0	0	0			
0	0	0	1			

(b) Step 2

1	0	1	0	1	0	0
0	0	0	0	0	0	1
0	0	0	1	0	0	0
0	0	0				

(c) Step 3

1	0	1	0	1	0	0
0	0	0	0	0	0	1
0	0	0	1	0	0	0
0	0	0				
0	0	1				

(d) Step 4

1	0	1	0	1	0	0
0	0	0	0	0	0	1
0	0	0	1	0	0	0
0	0	0	0			
0	0	1				

(e) Step 5

1	0	1	0	1	0	0
0	0	0	0	0	0	1
0	0	0	1	0	0	0
0	0	0	0	0	0	1
0	0	1	0	1	0	0

(f) Completed pattern

Figure 1: Steps to generate a 5 by 7 pattern with 3 by 3 window property where k=2.

For an example, to generate a pattern using three symbols with a window property of 3×3, the algorithm starts by seeding the top left 3×3 window with random letter assignment. Then consecutive (3×1) columns with random letter assignment are added to the right of the initial window, maintaining window property and Hamming distance between windows. That followed by adding random (1×3) rows beneath the initial window in a similar way. Then the both horizontal and vertical processes are repeated by incrementing the starting position by one in both directions, until whole pattern is filled. In this last step it has to add only a single point to the pattern and check the constraints. Whenever the process reaches a position where no possible symbol can be placed, whole pattern is cleared and starts again with another initial window.

For our pattern encoding method, we have used a similar algorithm with some modifications to imposed additional constraints. In our encoding method, the number of elements in the alphabet is $k=2$. But we use only one symbol and presence of the symbol represents the two elements of the alphabet. So instead of checking the Hamming distance between each window, we check for the connected symbols within each added window. If it has connected symbols we change the added (3×1) column or (1×3) row or a single point to another possible one and check again for the constraints. If a newly added window passes the connectivity constraint then we check for the uniqueness of the window. We continue these steps until it fills the whole array. If there is any state that there is no any possible way to place the symbol we follow the Morano's algorithm.

Figure 1 explains how to fill a (5×7) perfect sub-map with a (3×3) window.

4. Experiment and Results

We test our proposed pattern encoding method with different pattern resolutions and window sizes. For keeping the simplicity we always use a square window. So the possible window sizes are (3×3), (5×5), (9×9) and likewise. If the pattern resolution is $(m\times n)$ and window size is w, then $(m-\lfloor w/2\rfloor)(n-\lfloor w/2\rfloor)$ number of total code-words needs to fill the full pattern array. In our proposed encoding method we always choose k as two, so there are $2^{w\times w}$ distinct code-words. But when we applied the connectivity constraint we have to eliminate large number of code-words from it. As an example, when $w=3$ we have $2^9=512$ different code-words and after eliminating the code-words with connected symbols only 34 will remain.

As the experiment, the implemented algorithm was executed for 1000 times for different combinations of pattern resolution and window size. Table 1 shows the results for (5×5) window size, Table 2 shows the results for (7×7) window size and Table 3 shows the results for (7×7) window size. In both tables parameters summarized the 1000 searches for a given resolution: Total Code-words, Average, Maximum completed and Number completed. Total code-words means number of total code-words need to fill the pattern with the given resolution. Number completed gives the number of times out of 1000 trials, which successfully finds the full pattern. Maximum completed will be 100% if the full pattern is generated in any trial. Otherwise it gives maximum percentage filled by the algorithm. The average of the filling percentage of the full pattern in all of the 1000 trials is given by Average.

The results of the experiment show that, to achieve larger pattern resolution we need larger window size. Within 1000 trials we cannot achieve more than (20×20) resolution with (5×5) window, and more than (60×80) resolution with (7×7) window. But, with (9×9) window we achieve (200×200) resolution with larger probability. By further experiment we find out that even (300×300) resolution is possible with (9×9) window. Figure 2, 3 and 4 shows three pattern images with different resolutions and window sizes generated by our proposed pattern encoding method.

Table 1: The results of the pattern encoding algorithm with (5 × 5) window and different pattern resolutions

Resolution	15×15	18×18	16×24	20×20	30×40	45×45
Total Codewords	121	196	240	256	936	1681
Average	58.4	38.6	31.5	30.4	9.5	6.0
Maximum completed	100	100	100	100	27.1	15.5
Number Completed	129	8	2	2	0	0

Table 2: The results of the pattern encoding algorithm with (7 × 7) window and different pattern resolutions

Resolution	20×20	30×40	45×45	60×80	100×100
Total Codewords	196	816	1521	3996	8836
Average	99.4	91.9	75.2	36.3	17.1
Maximum completed	100	100	100	100	50.1
Number Completed	982	763	390	7	0

Table 3: The results of the pattern encoding algorithm with (9 × 9) window and different pattern resolutions

Resolution	45×45	60×80	100×100	150×150	200×200
Total Codewords	1369	3744	8464	20164	36864
Average	100	100	99.8	96.3	92.7
Maximum completed	100	100	100	100	100
Number Completed	1000	1000	994	907	795

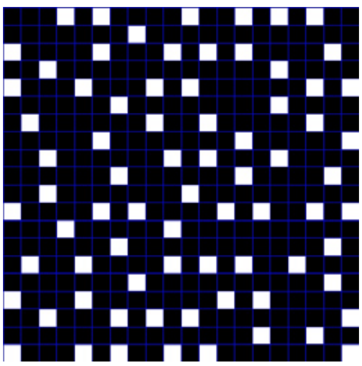

Figure 2: (20×20) pattern image generated with (5×5) window property

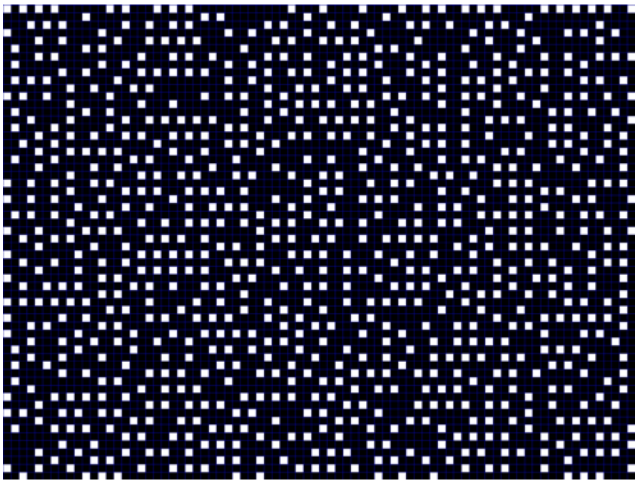

Figure 3: (60×80) pattern image generated with (7×7) window property

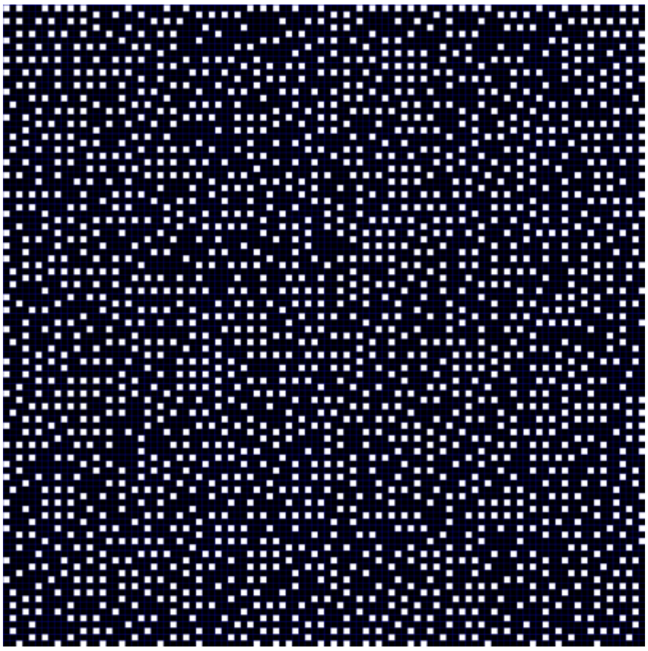

Figure 4: (100×100) pattern image generated with (9×9) window property

5. Conclusion

We have introduced a new structured light codification method based on pseudorandom arrays that can achieve larger pattern resolutions. We only used one type of symbol and represent the binary alphabet by the presence of that symbol. We introduced an algorithm to generate pseudorandom arrays with no connected symbols, to simplify the decoding stage. In our experiments we show that when the pattern resolution increased, the probability of generating a pattern will reduce largely. But by increasing the window size we were able to improve the probability of generating a larger resolution.

As a future work we are going to implement a robust decoding method for our proposed pattern. Furthermore we are planning for a calibrated 3D imaging device that can capture 3D scenes in real-time.

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