ICEM12- 12th International Conference on Experimental Mechanics
29 August - 2 September, 2004 Politecnico di Bari, Italy

COLOR N-ARY GRAY CODE FOR 3-D SHAPE MEASUREMENT

Jiahui Pan, Peisen S. Huang, Song Zhang, Fu-Pen Chiang

Department of Mechanical Engineering, Stony Brook University, Stony Brook, 11794, NY, USA, Jiahui_new@yahoo.com or Peisen.huang@sunysb.edu

ABSTRACT

A fringe projection method that uses a novel color N-ary Gray code has been developed for high-speed 3-D shape measurement. In this method, more than two graylevels in each color channel are used to create a color-coded pattern. The code is designed to be self-normalizing so that an adaptive threshold method can be used to reduce decoding error and therefore increase measurement resolution and accuracy. Two example N-ary codes, a ternary code ($N = 3$) and a sextanary code ($N = 6$), were examined. Their effectiveness was tested in two systems, one consisting of a LCD projector and a color 3-CCD camera while the other, a high-speed fringe projection system, consisting of a DLP projector and a black-and-white CCD camera. In the latter system, the color pattern is projected in gray scale, one color channel at a time and at a high switching speed (80 Hz). Therefore, it is less sensitive to the imbalance problem of the three color channels and the measurement result is also not affected by the surface color of the object. The feasibility and effectiveness of the two coding methods were confirmed by experiments. The results showed that the ternary coding method produced better and more reliable measurement results than the sextanary coding method. The proposed technique has various potential applications in high-speed 3-D shape measurements, especially in on-line inspection or dynamic measurement of moving objects.

1. INTRODUCTION

Fringe projection techniques are being widely used today for 3-D shape measurement because of the ubiquitous availability of video projectors. One frequently used such technique is the binary fringe projection technique, which has the merits of being significantly less sensitive to system noise and nonlinearity error [1, 2]. However, one drawback of this technique is that it usually requires several fringe patterns for measuring the 3-D shape of an object, which reduces the measurement speed. As a result, this technique is not suitable for dynamic or real-time measurements. To reduce the number of required fringe patterns, some techniques that use more intensity levels to code the patterns have been proposed [3]. In these techniques, a new concept, N-ary code, which is a generalization of binary code, was introduced. In the N-ary code, N intensity levels are used for coding. Binary code is then just a special case of N-ary code when N equals to 2. Caspi *et al.* developed a color N-ary Gray code for range sensing in which the number of fringe patterns M and the number of intensity levels N_i in each individual color channel are automatically adapted to the environment [4]. Horn and Kiryati provided an optimal design for generating the N-ary code with the smallest set of projection patterns that meets the application-specific accuracy requirements given the noise level in the system [5]. The above two techniques significantly reduced the number of fringe patterns by adopting N-ary codes. However, they required one or two additional uniform illumination references to generate the individual threshold for each pixel to achieve high resolution.

In this paper, we develop a technique that requires only a single fringe projection for high-speed 3-D shape measurement. A novel color N-ary Gray code is designed for this purpose.

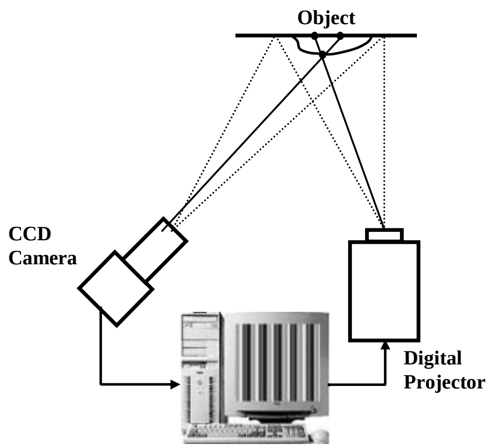


Fig. 1 Layout of the 3-D shape measurement system

The threshold for binarization at each pixel can be obtained from the coded pattern itself without additional uniform illumination references. The coding and decoding schemes, system setup and implementation, and experimental results are presented.

2. SYSTEM SETUP

The system layout of the fringe projection technique that uses the proposed color N-ary Gray code is shown in Fig. 1. This system consists of an LCD projector (EPSON PowerLite 8000i; 2000 ANSI lumens; 1024 × 768 resolution), a 3-CCD color camera (Duncantech MS2100; 656 × 494 resolution), a frame grabber (Matrox Corona), and a PC (Pentium III 866 MHz). A color fringe pattern is created by software in the computer and projected onto the object by the projector connected to the computer. The fringe image of the object is captured by the camera positioned at a certain angle with respect to the projector. The captured image is then digitized and the intensity in each color channel of each pixel is determined. Finally, each pixel is decoded and the corresponding height information of the object at the pixel is calculated based on a triangulation algorithm [1].

3. CODING

A code is composed of many codewords, which are unambiguous identifiers for the combination of a set of code digits. Proper design of the code or the combination of the codewords is critical for the measurement system to achieve higher resolution and accuracy.

3.1 N-ary Gray Code

To reduce decoding errors and increase the margin of noise, a Gray code scheme is employed in coding the pattern. Gray code is originally used in the areas of telecommunication and circuit design and has been widely used for pattern coding recently. In a Gray code, the number of different code digits between any two adjacent codewords, called Hamming-distance, is one. Due to this feature, those pixels with mixed colors will be determined to have either one of the two participant colors rather than a third color. Therefore the decoding error due to mixed colors can be minimized to just 1 pixel, which results in higher spatial resolution. In an N-ary Gray code, each digit may have any value ranging from 0 to N-1 based on radix of N. The number of available codewords is N^M if M fringe patterns are used.

There are many ways to generate the N-ary Gray code. Table 1 shows the two typical number systems representing such a code as well as their corresponding decimal and triple expressions for a 3-digit number system. The first system is a cyclic number system. By cyclic, we mean that the Gray code is circular. In other words, the first codeword is the successor of the last codeword. Therefore, the cyclic number system produces a circular Gray code that can be repeatedly used in order to increase the length of the code [6, 7]. However, one drawback of the cyclic number system is that the value of the changing digit can differ by more than one between the neighbouring codewords. This will significantly increase the ambiguity of decoding. Another system, a reflected number system, uses a different approach to organize the number so that the value of the changing digit will only change one from one codeword to another. In the reflected number system, the value of each digit changes from 0 to N - 1 first and then from N - 1 back to 0 as if reflected from a mirror [8, 9]. By organizing the code as a reflected number system, the difference between any adjacent codewords will be minimized. However, the reflected number system can not always produce a circular Gray code. Only when N is even can the code be a circular Gray code. In this paper, we propose a coding scheme that has the advantages of both the cyclic and the reflected systems, which will be introduced in the next sub-section.

3.2 Color N-ary Gray Code

In this sub-section, we describe a color N-ary Gray code that has both the advantages of the cyclic and reflected systems as well as some other features that can benefit our application. The purpose of designing this code is to be able to measure the 3-D shape of an object with a single fringe pattern, so that dynamic or real-time measurement can be achieved. To design such a code, the following strategies need to be used:

- To obtain more codewords with one fringe pattern, all the three color channels should be used. Therefore, the number of fringe patterns M can be regarded as three.
- Because of the limited number of unique codewords, the available codewords need to be used periodically. Therefore, the code should be cyclic.
- To reduce decoding errors, the values of the changing digit should only differ by one between any adjacent codewords, which means that the code should be reflected
- To make the system more tolerable to nonuniform illumination and surface reflectivity, a self-normalizing scheme should be used in coding [2]. This requires at least one digit with the maximum value of N - 1 and another with the minimum value of 0 in any codeword. Once so coded, each pixel will have its own maximum and minimum intensity values appearing at least once. As a result, an appropriate threshold value can be set for each pixel for digitization. This is called the adaptive threshold method.

It can be proven that the number of unique codewords for the proposed color N-ary Gray code is $6 \times (N - 1)$. Table 2 shows two examples of the color N-ary Gray code when $N = 3$ and $N = 6$, which are called ternary code and sextanary code respectively. The number of available codewords are $6 \times (3 - 1) = 12$ and $6 \times (6 - 1) = 30$ respectively. The formation of the color N-ary Gray codes is illustrated in Fig. 2. It can be seen that to satisfy all the requirements listed above, the three color channels are coded to have T/3 shifts between each other, where T is the length of the code using all the available unique codewords. The larger the value of N is, the larger the value of *T* will be. With a larger *T* value, there will be more unique codewords available, which makes the system more tolerable to the discontinuity problem. An extreme extension of the color N-ary Gray code is shown in Fig. 2(c) with *N* being 256 in an 8-bit system. This is the so called intensity ratio method which provides higher resolution compared to our proposed method. However, the intensity ratio method is highly sensitive to system noise and projector nonlinearity. In this work, the ternary and sextanary codes, which are used periodically for improved resolution, are tested to demonstrate the feasibility of the proposed technique.

Table 1 A comparison of different number systems

Decimal	Triple	N-ary Gray Code	
		Cyclic Triple	Reflected Triple
0	000	000	000
1	001	001	001
2	002	002	002
3	010	012	012
4	011	010	011
5	012	011	010
6	020	021	020
7	021	022	021
8	022	020	022
9	100	120	122
10	101	121	121
11	102	122	120
12	110	102	110
13	111	100	111
14	112	101	112
15	120	111	102
16	121	112	101
17	122	110	100
18	200	210	200
19	201	211	201
20	202	212	202
21	210	222	212
22	211	220	211
23	212	221	210
24	220	201	220
25	221	202	221
26	222	200	222

Table 2 Codewords of the color N-ary Gray codes

No.	Ternary	Sextanary
	RGB	RGB
0	020	050
1	021	051
2	022	052
3	012	053
4	002	054
5	102	055
6	202	045
7	201	035
8	200	025
9	210	015
10	220	005
11	120	105
12		205
13		305
14		405
15		505
16		504
17		503
18		502
19		501
20		500
21		510
22		520
23		530
24		540
25		550
26		450
27		350
28		250
29		150

4. DECODING

The decoding procedure includes calculating the codeword value for each pixel and generating a continuous codeword map. These two steps are very similar to the phase wrapping and unwrapping procedures used in the phase shifting methods [10].

In the first step, the intensity value of each pixel is digitized into *N* different levels according to the maximum and minimum intensity values at the pixel. The codeword value of each pixel is then obtained based on the digitized values. Since the codewords are defined periodically along the decoding direction, they appear like a sawtooth shape and discontinuities occur periodically.

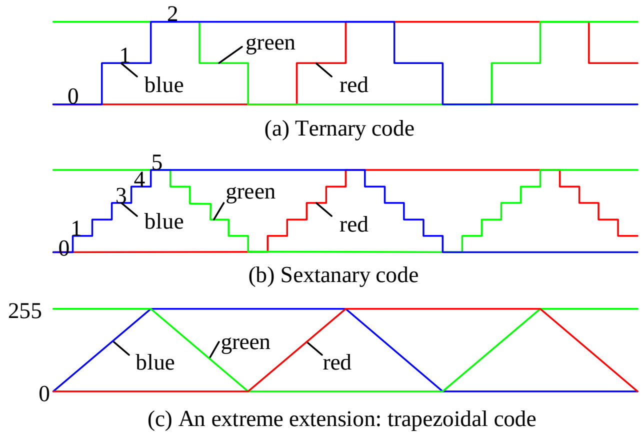


Fig. 2. The color N-ary Gray Codes

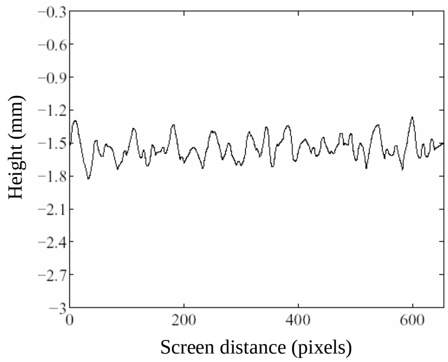
To generate a continuous codeword map, the discontinuities need to be removed in the second step. Since the codewords are not unique along the decoding direction, any holes or bad points on the image can prevent decoding from tracing back the previous codeword. Therefore, decoding of one row can not be done without taking into account its adjacent rows. In this work, we developed an iterative algorithm to reconstruct the continuous codeword map. With this algorithm, the value of each codeword is retrieved according to its own calculated value together with the value of the pixel in the previous row or previous column along the decoding direction. If the variation of the codeword values between neighboring pixels is greater than $6 \times (N - 1) / 2$, the value of the codeword should be increased or decreased by $6 \times (N - 1)$ depending on whether the variation is negative or positive.

5. EXPERIMENTS

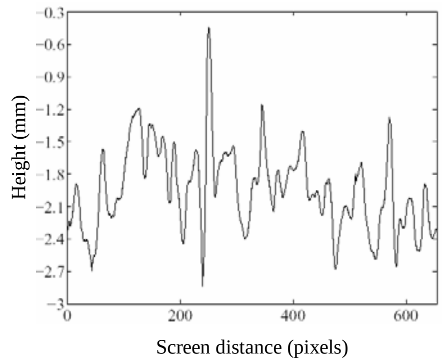
A flat board with a smooth surface was measured to verify the uncertainty of the measurement system. The measured area was 220 × 165 mm. Both the ternary and sextanary coding methods were used. The cross sections of the 300th row of the 3-D results are shown in Fig. 3. The noise of the ternary coding method is RMS 0.1 mm while the noise of the sextanary coding method is much larger. This is because the more graylevels used for coding, the more decoding errors will be introduced due to image noise.

A more complex object, a plaster head, was also measured with both of the two coding methods. Since the code is self-normalizing, the texture of the object could be extracted from the maximum intensity of each pixel. The 3-D results with and without texture mapping reconstructed by the ternary coding method are shown in Fig. 4. The result of the sextanary coding method showed much larger decoding errors and is not shown here.

From the experimental results, it can be seen that some stripes appear on the reconstructed surface of the object. It is even clearer on the surface with texture mapping. These errors were caused by the imbalance of the three channels. Since the texture image is acquired by extracting the maximum value of the three channels, the imbalance of the three color channels shows up as intensity variations on the reconstructed surface.

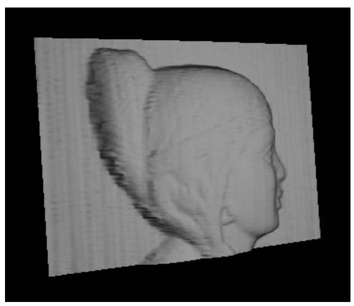


(a) With the ternary code (RMS = 0.1022 mm)



(b) With the sextanary code (RMS = 0.3813 mm)

Fig. 3 Cross-sectional profiles of a measured plate



(a) 3-D result

(b) 3-D result with texture mapping

Fig. 4 3-D results of a plaster head measured by using the ternary code

6. IMPLEMENTATION IN A HIGH-SPEED FRINGE PROJECTION SYSTEM

6.1 Principle

The color N-ary Gray code technique described in previous sections requires only one image for 3-D reconstruction. Therefore, it has the advantage of high potential measurement speed. However, it has two main problems. First, during the decoding process, the threshold at each pixel is calculated based on the maximum and minimum intensity values from any two of the three color channels. This requires that the three color channels be well balanced, which is difficult to achieve in practice through either adjustment or compensation. Therefore, the calculated threshold can not accurately represent the threshold for each individual channel. The second problem is associated with the properties of the object surface being measured. If the object surface contains large variations of color, the proposed method is not able to measure it because the fringe pattern itself contains color. Although an adaptive threshold method is used, the threshold obtained is not based on values from a single color channel. Thus, this method is limited to measurement of objects with a neutral surface color.

To solve the above problems, we implemented this method in a high-speed 3-D shape measurement system developed by Huang *et al*. [11]. In this system, a DLP (digital light processing) projector and a black-and-white CCD camera are used instead of an LCD projector and a color 3-CCD camera. This DLP projector has one DMD (Digital Micromirror

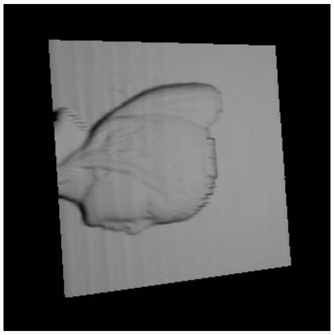
Device) chip and uses a unique color channel switching principle to generate 24-bit color images. It produces a color image by projecting its three component images one by one at a high speed. To form the three component images, a color wheel with three segments, red, green, and blue, is inserted between the light source and the DMD chip. As the color wheel spins, red, green, and blue light beams illuminate the DMD chip sequentially and periodically. A photo diode placed behind the color wheel picks up a tiny portion of the scattered light to produce a timing signal. This timing signal controls the timing of the projection for each color component. Since the sequential projection of color components is done at a high speed, human eyes see only an integrated color image, instead of three red, green, and blue monochromatic images.

In Huang's method, a one-chip DLP projector is used to project a color fringe pattern with the color filter removed. The purpose of removing the color filter is to make the projected fringe patterns in grayscale so that the color of the object will not affect the accuracy of measurement. With an externally provided timing signal to control the projection and synchronize the CCD camera with the DLP projector, 3-D shape measurement could be realized at a potential speed of 80 Hz or 80 frames/sec.

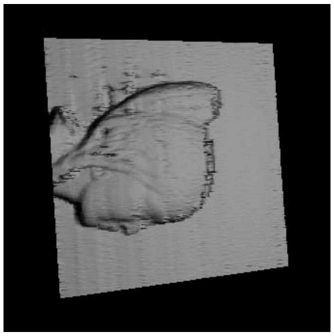
In this research, we use this system to implement our color N-ary Gray code for 3-D shape measurement. The image sent to the projector is still the same color fringe pattern, but what are actually projected are three grayscale fringe patterns projected in sequence and at a speed of 12.5 ms/cycle. The potential speed of the 3-D shape measures can be as high as 80 Hz, but in the current system, the actual speed is 40 Hz due to hardware limitations. Since the fringe patterns projected onto the object are in grayscale, this system does not have the potential problems associated with color. In addition, since a one-chip DLP projector and a one-CCD camera are used, the imbalance between the three color channels can be easily compensated for.

6.2 Experimental Results

To demonstrate the effectiveness of the N-ary Gray coding method implemented with this new system, the same plaster head was measured. The results are shown in Fig. 6. It can be seen from Fig. 6(a) that proper measurement result was obtained with the ternary code. However, the result of the sextanary coding method shows larger errors for the same reason as that discussed in Section 5.



(a) With the ternary code



(b) With the sextanary code

Fig. 6 3-D results of a plaster head with the new measurement system

7. CONCLUSION

In this paper, we proposed a novel 3-D shape measurement technique that uses a single color fringe pattern. This fringe pattern is coded with the newly developed color N-ary Gray code, which was designed based on the features of the cyclic and reflected Gray codes. This code was also designed to be self-normalizing so that the adaptive threshold method can be used to reduce decoding errors and therefore improve measurement accuracy. An algorithm was developed to decode the periodical codewords. In experiments, we implemented two example codes, the ternary and sextanary codes, in our current system and also a high-speed fringe projection system. The latter is more tolerable to the imbalance of the three channels and the color variations of the object surface. The feasibility and effectiveness of the technique have been confirmed by the experimental results. When implemented in our current system, the ternary code showed a noise level of RMS 0.1 mm over an area of 220 × 165 mm while the sextanary code showed a noise level three times larger. The results of the codes implemented in the high-speed fringe projection system were similar. As a conclusion, the ternary code produces better and more reliable measurement results than the sextanary code. However, the sextanary code has more unique codewords and therefore should be more tolerable to the discontinuity problem. The proposed color N-ary Gray coding technique can be applied where high-speed dynamic 3-D shape measurements are needed.

BIBLIOGRAPHY

[1] Weiyi Liu, Zhaoqi Wang, Guoguang Mu and Zhiliang Fang, "Color-coded projection grating method for shape measurement with a single exposure," *Appl. Opt.*, Vol. 39(20), 2000, pp.3504-3508

[2] Jiahui Pan, Peisen S. Huang and Fu-Pen Chiang, "3D shape measurement based on a color-coded binary fringe projection technique," in *5th International Conference on Computer Vision, Pattern Recognition and Image Processing (CVPRIP'2003), Proc. of 7th Joint Conference on Information Sciences*, Sept., 2003, pp.704-707

[3] Joaquim Salvi, Jordi Pages and Joan Batlle, "Pattern codification strategies in structured light systems", *Pattern Recognition*, Vol. 37(4), 2004, pp.827-849

[4] Dalit Caspi, Nahum Kiryati and Joseph Shamir, "Range imaging with adaptive color structured light", *Pattern IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 20(5), 1998, pp.470-480

[5] Eli Horn and Nahum Kiryati, "Toward optimal structured light patterns", *Image and Vision Computing*, Vol. 17(2), 1999, pp.87-97

[6] Martin Cohn, "Affine m-ary gray codes", *Information and Control*, Vol. 6, 1963, pp.70-78

[7] Bhu Dev Sharma and Ravinder Kumar Khanna, "On m-ary gray codes", *Information Sciences*, Vol. 15, 1978, pp.31-43

[8] M. C. Er, "On generating the n-ary reflected Gray codes", *IEEE Transactions on Computers*, Vol. 33, 1984, 739-741

[9] Ivan Flores, "Reflected number systems", *IRE Transactions on Electronic Computers*, Vol. EC-5, 1956, pp.79-82

[10] J. E. Greivenkamp and J. H. Bruning, Optical Shop Testing, Chapter 14 Phase shifting interferometry, pp.501-598. Wiley, New York, 2nd edition, 1992 (Book)

[11] Peisen S. Huang, Chengping Zhang and Fu-Pen Chiang, "High-speed 3-D shape measurement based on digital fringe projection", *Opt. Eng.*, Vol. 42(1), 2003, pp.163-168