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A Directly Readable Halftone Multifunctional Color QR Code

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Abstract — Color quick response (QR) code is an important direction for the future development of QR code, which has become a research hotspot due to the additional functional characteristics of its colors as the wide application of QR code technology. The existing color QR code has solved the problem of information storage capacity, but it requires an enormous hardware and software support system, making how to achieve its direct readability an urgent issue. This paper proposes a novel color QR code that combines multiple types of different identification information. This code combines multiplexing and color-coding technology to present the publicly encoded information (such as advertisements, public query information) as plain code, and traceability, blockchain, anti-counterfeiting authentication and other information concealed in the form of hidden code. We elaborate the basic principle of this code, construct its mathematical model and supply a set of algorithm design processes, which breakthrough key technology of halftone printout. The experimental results show that the proposed color quick response code realizes the multi-code integration and can be read directly without special scanning equipment, which has unique advantages in the field of printing anti-counterfeiting labels.

Key words — Color QR code, Information hiding, Multi-code integration, Halftone, Anti-counterfeiting.

I. Introduction

Despite the quick response (QR) code application has been greatly popularized, it is still showing a fission-type development tense constantly stimulated by various emerging factors (such as COVID-19). The prospective development trend of QR codes should be driven by application requirements and is nothing more than towards the direction of multi-functional, high-capacity color QR code development [1]. Due to the limitation of the reading conditions, the actual advance of the technical system from monochrome QR codes to color QR codes is not smooth. Color QR codes have consistently been the focus of researchers owing to their unique appearance. At present, the current research on this kind of code mainly directs against beautification and information capacity, namely artQR codes and high-capacity QR codes.

The most common approach to beautify QR codes is to enhance the aesthetic feeling of visual art through additional colors [2]. Without affecting the scannability of QR codes, beautification by embedding color images [3]–[5] is more eye-catching than altering the color of modules. Chen *et al.* [6], Lin *et al.* [7], and Xu *et al.* [8] embedded color images in monochrome QR codes to achieve the beautification effect, which to a certain extent solved the problems limited by the size of embedded images, visual distortion and poor robustness, etc. Nevertheless, the essence of this category of QR codes is still a simple code with a beautification effect, and their recognition speed is even lower than ordinary QR codes.

In addition, expanding the data capacity of QR codes by increasing colors [9], [10] is also the mainstream of current research. The added colors to QR codes are prone to cause color distortion [11], color confusion [12] and other problems, which bring great challenges to the decoding. Color-coding [13] and multiplexing [14] are pervasively used technical approaches to study color QR codes. Taveerad *et al.* [15] and Melgar *et al.* [16] improved the data capacity of black and white QR codes by using additional colors based on the concept of color-coding. But affected by environmental conditions, the change of its colors will affect the accuracy of decoding. Vongpradhip [17] and Galiyawala *et al.* [18] combine multiple standard black and white QR codes into a color QR code through multiplexing technology [19], which can increase the data capacity of the

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QR code by 24 times. Meruga *et al.* [20] independently encoded the data in the CMY printing colorization channel, generated three QR codes with unique colors, merged them into a single color QR code, and decoded by separating the RGB images captured, achieving three times the data capacity [21], but this type of color QR code loses the direct readability. Masanori *et al.* [22] allocated three two-color QR codes to the YC_bC_r color space on this basis, so that the synthesized color QR code can be decoded by the standard decoder, but the rest of the hidden codes need to be read by the proprietary decoder.

From the overall research status of color QR codes, the relevant technology is still in the preliminary exploration stage. On the one hand, their reading is limited by specialized scanning equipment, which seriously restricts their application and promotion; on the other hand, the lack of in-depth research on the technical bottlenecks in the printout of color QR codes has severely affected their technical implementation in this field. Moreover, most of the researches are color matching through hue, using self-designed software to complete the coding and decoding of color QR codes, while the research field of developing directly readable color QR codes based on grayscale is almost blank. Founded on the RGB color space, we develop a directly readable halftone multi-function color QR (HMC-QR) code composed by multi-code utilizing the grayscale distinction of color, which settles the inevitable technical bottleneck problem caused by color reproduction distortion and halftone quantization distortion when printing such codes.

II. HMC-QR Code

1. Design principle

HMC-QR code is a color QR code generated by a combination of multiple QR codes with different functions, that is, a QR code with reproduction characteristics and color grayscale loading multi-code information. It is a QR code as the carrier (plain code), another 1 to 2 QR codes are used as the modulation information (hidden code).

Discretizing the grayscale information generated by the mixing of RGB: the values of RGB three channels are normalized through the equation (1) and set to the binary color information represented by 0 and 1.

$$\begin{cases} R = \dfrac{R'}{255} \\ G = \dfrac{G'}{255} \quad (R', G', B' \in [0, 255]) \\ B = \dfrac{B'}{255} \end{cases} \tag{1}$$

The three primary colors are mixed according to the binary combination to generate color information of $2^3 = 8$ gray levels, including color information of 8 levels of grayscale synthesized by converting RGB to CMYK printing colors. Based on the grayscale equation of RGB, as shown in (2), color and grayscale coding are performed for plain and hidden codes.

$$Y = \alpha R + \beta G + \gamma B, \quad R, G, B \in [0, 1] \tag{2}$$

where $\alpha = 0.3,\ \beta = 0.59,\ \gamma = 0.11$; $R,\ G,\ B$ are the normalized values of red, green and blue channels respectively; Y is the normalized gray value, and its true gray value is calculated by (3) and denoted as G_r:

$$G_r = Y \times 255, \quad Y \in [0, 1] \tag{3}$$

Using QR matrix codes of version 4 as plain and hidden codes, namely: $V = 4$, with a size of 33×33 modules, which are combined into the whole by the above information modulation to generate the directly readable HMC-QR code with light and dark information, and its structure is shown in Fig.1. Under visible light and optical color filters, the HMC-QR code can display multiple different effective QR codes.

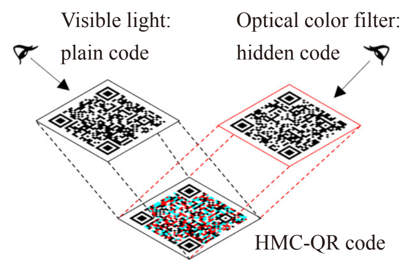


Fig. 1. Schematic diagram of HMC-QR structure.

2. Grayscale segmentation model

Traditional black and white QR codes are read by grayscale. To maintain its machine readability, the HMC-QR code configures color parameters based on a grayscale segmentation model to realize the direct reading of color QR codes. At the same time, it adds the function of loading hidden code information and readability.

Assuming that the number of multiplexed QR codes is n, at least 2^n color modules are required, that is, 2^n grayscale intervals: including $2^{n/2}$ dark intervals, $2^{n/2}$ light intervals. Taking n color modules as an example to illustrate. The grayscale segmentation model of the HMC-QR code is shown in Fig.2.

The n color modules in Fig.2 are used to characterize the plain code under visible light, whose grayscale can be expressed by $Y = \{Y_1, Y_2, \dots, Y_{n-1}, Y_n\}$. After optical color filtering, n new grayscales are obtained as $Y' = \{{Y_1}', {Y_2}', \dots, {Y_{n-1}}', {Y_n}'\}$. ${Y_1}'$ and ${Y_i}'$ are respect-

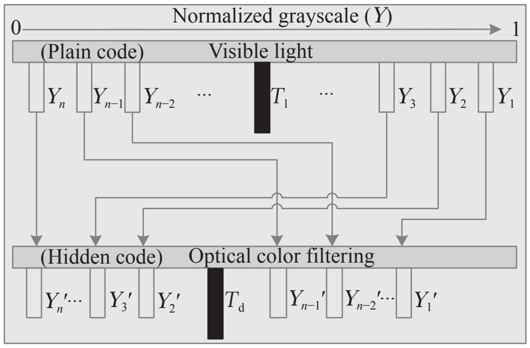


Fig. 2. Grayscale segmentation model of HMC-QR code.

ively the gray value of the ith color module of plain and hidden codes respectively ($i = 1, 2, \dots, n$). And $\{Y_1, Y_2, \dots, Y_{n/2}\}$ as light color, $\{Y_{n/2+1}, \dots, Y_{n-1}, Y_n\}$ as the dark color, between them satisfies

$$Y_n \le Y_{n-1} \le \cdots \le Y_2 \le Y_1, \quad Y_i \in [0, 1] \tag{4}$$

To realize that HMC-QR code can characterize its hidden code after optical color filtering, $\{Y_2, Y_3, \dots, Y_{n-2}, Y_{n-1}\}$ needs to perform "color reversal," its principle is to use the optical properties of colors to make a certain color represented by RGB appear light/dark color under visible light (at the read discriminant for 1/0), and part of the color components can be filtered out after color filtering, which shows the dark/light color (when read by discriminant is 0/1). The color modules carry on the inversion of the dark-light state under the visible light and optical color filter, namely, this process is called color reversal. Therefore, $\{Y_2, Y_3, \dots, Y_{n/2}\}$ as a light color module is flipped into dark $\{Y_2{}', Y_3{}', \dots, Y_{n/2}{}'\}$; $\{Y_{n/2+1}, Y_{n/2+2}, \dots, Y_{n-1}\}$ as a dark module is flipped to the light $\{Y_{n/2+1}{}', Y_{n/2+2}{}', \dots, Y_{n-1}{}'\}$; Y_1 and Y_n still retain the original color interval, recorded as $Y_1{}'$ and $Y_n{}'$. Therefore, the n color modules used to represent the hidden code are satisfied between them:

$$Y_n{}' \le Y_{n/2}{}' \le \cdots \le Y_2{}' \le Y_{n-1}{}' \le \cdots \le Y_{n/2+1}{}' \le Y_1{}', \quad Y_i{}' \in [0, 1] \tag{5}$$

Calculating the judgment thresholds T_l and T_d of plain and hidden codes by (6) respectively.

$$\begin{cases} T_l = \dfrac{Y_{\max} + Y_{\min}}{2} \\ Y_{\max} = \max\{Y_1, Y_2, \dots, Y_{n-1}, Y_n\} \\ Y_{\min} = \min\{Y_1, Y_2, \dots, Y_{n-1}, Y_n\} \end{cases}$$
$$\begin{cases} T_d = \dfrac{Y_{\max}{}' + Y_{\min}{}'}{2} \\ Y_{\max}{}' = \max\{Y_1{}', Y_2{}', \dots, Y_{n-1}{}', Y_n{}'\} \\ Y_{\min}{}' = \min\{Y_1{}', Y_2{}', \dots, Y_{n-1}{}', Y_n{}'\} \end{cases} \tag{6}$$

where $Y_{\max}$ and $Y_{\max}{}'$ represent the maximum grayscale of the n color modules in the plain code and hidden code, $Y_{\min}$ and $Y_{\min}{}'$ denote the minimum grayscale. Making use of the judgment threshold to distinguish the n color modules, as shown in Fig.3.

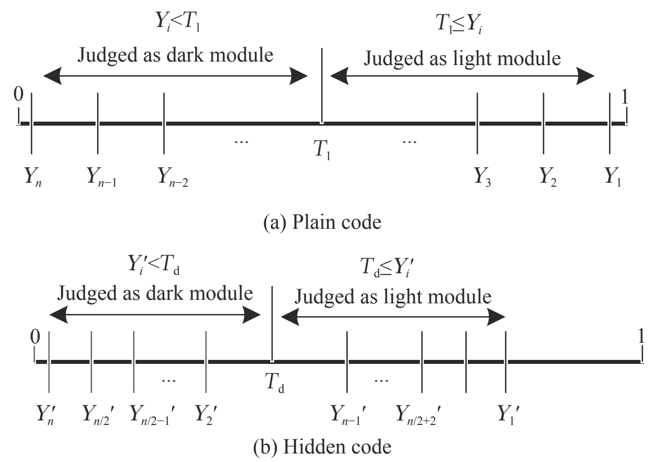


Fig. 3. Schematic diagram of grayscale judgment.

III. HMC-QR Code Generation

HMC-QR code takes ordinary black and white QR codes as the processing object and modulates the color information to realize the multiplexing of QR codes. After scanning test (simulation reading and printing reading) and parameter optimization, the HMC-QR code that can be read normally is finally obtained. The generation process is shown in Fig.4.

The HMC-QR code generated according to the process in Fig.4 ensures that the plain code under visible light and the hidden code under the optical color filter can be normally read (simulation reading and printing reading), that is, the two reach a state of relative balance, and solves the compatibility problem of plain and hidden codes.

1. Color coding

Taking into account the impact of realistic printing, the values of RGB are impossible to take 0 or 255, and assigning weight distribution to the RGB gray equation, as shown in (7).

$$Y = k_1 \times 0.3R + k_2 \times 0.59G + k_3 \times 0.11B \tag{7}$$

where k_1, k_2, k_3 respectively represent the weight of color components red, greenand blue, the grayscale of each color module of the plain code is calculated according to (7). Color filters can absorb colors that are not in their wavelength range, and colors within the wavelength range can pass through, for example, the red filter only allows R through, filtering out G and B, that is, R sets 1, G and B set 0, the same applies to the green and blue filters. The optical color filters with

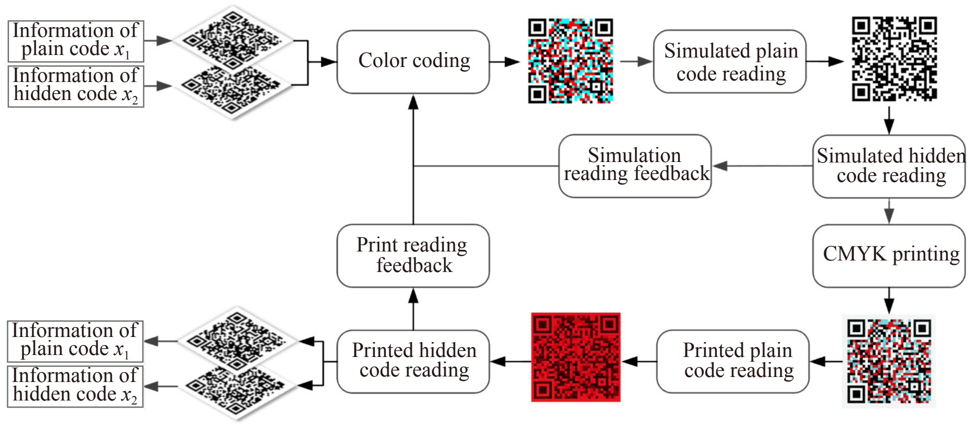


Fig. 4. Block diagram of the HMC-QR generation process.

band-pass (narrowband) filtering characteristics are used to study the three colors of red, green and blue. The relevant parameters of the color filters are shown in Table 1. Based on different optical color filters, the grayscale equation used by the hidden code is

$$\begin{cases} Y_r = k_1 \times 0.3R \\ Y_g = k_2 \times 0.59G \\ Y_b = k_3 \times 0.11B \end{cases} \tag{8}$$

Table 1. Related parameters of optical color filter

Optical color filter	Red	Green	Blue
Central wavelength(nm)	635	532	470
Wavelength range (nm)	[605,655]	[500,565]	[455,490]
Passed color	Red	Green	Blue
Absorbed color	Green/Blue	Red/Blue	Red/Green

With λ_R, λ_G, and λ_B respectively denoting the central wavelengths of the three RGB optical filters, it can be seen from Table 1 that they satisfy the following requirements:

$$\lambda_B < \lambda_G < \lambda_R \tag{9}$$

When designing the parameters of the color module later, this wavelength relationship can simplify the experiment.

Both plain and hidden codes are ordinary binary images before being combined. Dark color modules are represented by "0" and "1" are light color modules. According to the grayscale segmentation model, encoding the grayscale information presented by the three RGB primary colors and their mixed colors. With plain and hidden codes as input variables, and R, G, B as output variables of the coding table, represented by "1" and "0" whether color components are used. The designed grayscale code table is shown in Table 2:

As can be seen from Table 2, there are altogether 8 color modules, whose mapping relationship between their colors and attribute values is shown in Fig.5.

Table 2. Grayscale coding table

Plain code	Hidden code	Color filter(R/G/B)								
		Red			Green			Blue		
0	0	0	0	0	0	0	0	0	0	0
0	1	1	0	0	0	1	0	0	0	1
1	0	0	1	1	1	0	1	1	1	0
1	1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0	0	0	0
0	1	1	0	0	0	1	0	0	0	1

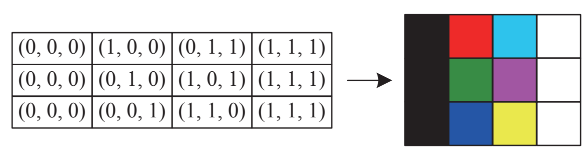


Fig. 5. Schematic diagram of the mapping relationship between colors and attribute values.

2. Algorithm design

The grayscale value of color modules is calculated by (1) and (2). Assuming that the pixel value of the plain code module is $P(i,j)$ and the pixel value of the hidden code module is $H(i,j)$, $(1 \le i \le N,\ 1 \le j \le N)$, the pixel values of the four selected color modules are respectively denoted as $Y_1(i,j)$, $Y_2(i,j)$, $Y_3(i,j)$, $Y_4(i,j)$, $1 \le i \le N$, $1 \le j \le N$. Taking the red color filter as an example: let $C_r(i,j)$ be the pixel value of the generated HMC-QR code, then it can be expressed as

$$C_r(i,j) = \begin{cases} Y_4(i,j), & P(i,j) == 0 \&\& H(i,j) == 0 \\ Y_3(i,j), & P(i,j) == 0 \&\& H(i,j) == 1 \\ Y_2(i,j), & P(i,j) == 1 \&\& H(i,j) == 0 \\ Y_1(i,j), & P(i,j) == 1 \&\& H(i,j) == 1 \end{cases} \tag{10}$$

The pixel values of color modules of HMC-QR code generated are determined jointly by the pixel values $P(i,j)$ and $H(i,j)$ of plain and hidden codes: $C_r(i,j)$, $C_g(i,j)$ and $C_b(i,j)$. The algorithm process is shown in Fig.6.

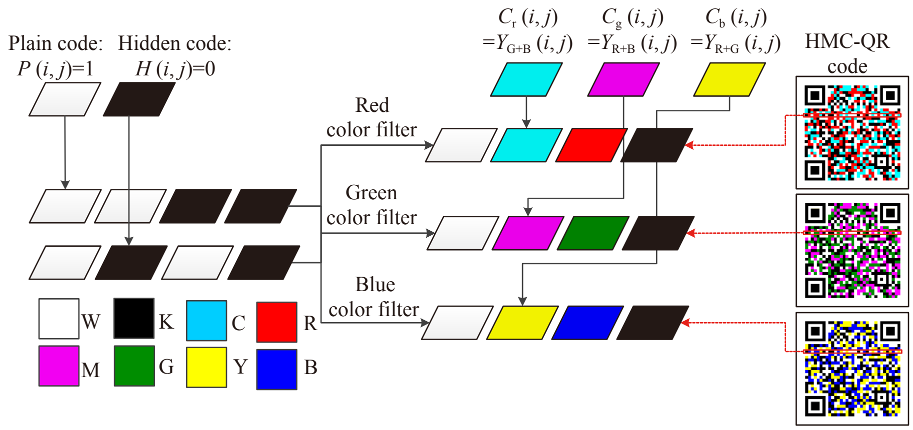


Fig. 6. Schematic diagram of HMC-QR code algorithm.

IV. Experimentation

1. Simulation test

Combining the grayscale segmentation model and coding table, we devise the theoretical data of four-color modules according to the following two criteria, and their grayscale is tested as it changes with the RGB value.

- Improving grayscale distinction between dark and light modules: making $Y_2 - T_l$ and $T_l - Y_3$, $T_d - Y_2'$ and $Y_3' - T_d$ as large as possible, i.e., increasing $Y_2 - Y_3$ and $Y_3' - Y_2'$ as much as possible.
- Equidistant distribution: ensuring that Y_2 and Y_3, Y_2' and Y_3' are evenly distributed on both ends of T_l and T_d, that is, $Y_2 - T_l$ and $T_l - Y_3$, $T_d - Y_2'$ and $Y_3' - T_d$ are as equal as possible.

Cleaning the test data through the relationship between the center wavelength of optical color filters in (9). Since $\lambda_R - \lambda_B \geq \lambda_R - \lambda_G$, the red color filter has a better effect of absorbing blue. When testing the cyan module, fixing the color component $B = 255$ and using 5 as the step size to test the influence of the numerical change of G on its grayscale. The parameters of the remaining color modules follow the same design principles. The specific test parameters are shown in Table 3. And Table 4 shows the simulated grayscale comparison of the four-color modules used in plain and hidden codes.

Table 3. Test parameters of each color module

Color module	Parameters to be measured	Grayscale	
		Visible light	After filtering processing
W-K	$R = G = B \in [0, 255]$	$Y_{W\text{-}K}$	$Y_{W\text{-}K}'$
R	$R \in [0, 255], G = 0, B = 0$	Y_R	Y_R'
G	$R = 0, G \in [0, 255], B = 0$	Y_G	Y_G'
B	$R = 0, G = 0, B \in [0, 255]$	Y_B	Y_B'
C	$R = 0, G \in [0, 255], B = 255$	Y_{G+B}	Y_{G+B}'
M	$R = 255, G = 0, B \in [0, 255]$	Y_{R+B}	Y_{R+B}'
Y	$R = 255, G \in [0, 255], B = 0$	Y_{R+G}	Y_{R+G}'

According to the simulation grayscale test results in Table 4, selecting four groups of RGB color ratios based on the above two design criteria to generate HMC-QR code by MATLAB programming. Performing a simulation reading test of plain and hidden codes on this code: directly scanning HMC-QR code under visible light with ordinary QR code reading equipment to record the reading results of the plain code; simulating optical color filtering with computer image processing software (such as Photoshop), and recording the reading result of the hidden code. If plain and hidden codes of the generated HMC-QR code cannot be read normally at the same time, it is necessary to adjust the color matching parameters of the corresponding color modules, and regenerates the HMC-QR code with the new parameters and test again. In this way, iteratively modify the parameters until plain and hidden codes can be read normally. The HMC-QR code generated by simulationis shown in Table 5.

2. Printing test

Printing with “Ricoh Pro C7100X” printer: the images in RGB format are called from the “sRGB (PC)” color source, converted to CMYK format with the “Fiery Pro C7100-C7110 flame-matte v1RF” output feature, finally, we choose 1200 dpi and 200 dots for printing out. The actual printed HMC-QR code is more difficult to read than the stimulated HMC-QR code, mainly owing to the following factors:

- Due to the limitation of color gamut mapping, CMYK four-color printing suffers from color loss when copying RGB originals, which makes it difficult to reproduce all RGB mixed colors.
- The restricted precision of printing equipment leads to uneven color and irregular size of ink spots after printing, making it difficult to restore the color of theoretical design with high fidelity.
- The color filter effect of the optical color filter is difficult to achieve an ideal state, and cannot com-

Table 4. Grayscale comparison of four-color modules (Simulation)

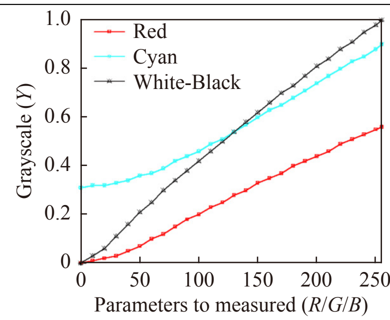
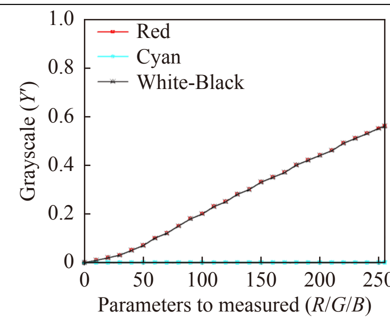
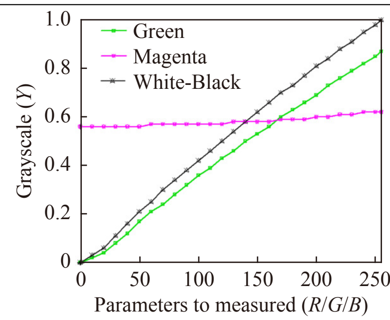
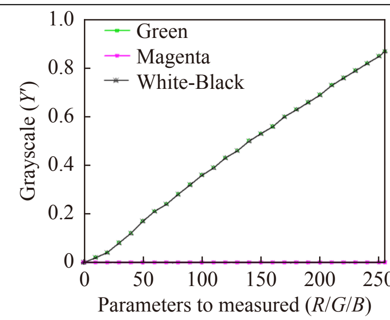
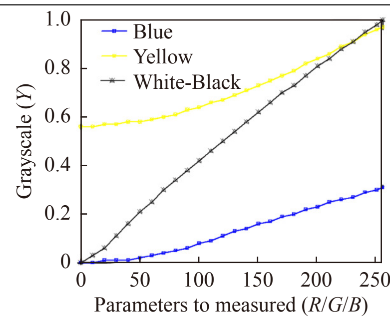
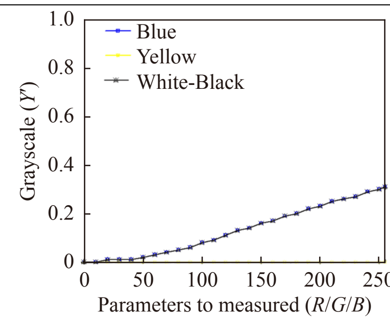
Optical colorfilter	Plain code	Hidden code
Red color filter		
Green color filter		
Blue color filter		

Table 5. HMC-QR based on different optical color filters (Simulation)

Optical color filter	Y_1, Y_4	Y_2	Y_3	Plain code	Hidden code
Red color filter					
Green color filter					
Blue color filter					

pletely absorb the colors beyond its wavelength range.

Therefore, the experiment pays more attention to the research of actual printed HMC-QR code.

Performing printing grayscale test for color modules to reduce the experimental error from simulation to printing and design more accurate color data. Generating grayscale gradual test images according to the parameters in Table 4, the ambient light source and shooting position are fixed, we use the same device to shoot the printed test images, then the images are imported into the Photoshop software to measure actual grayscale under visible light and optical color filter.

Table 6 shows the grayscale comparison of the four-color modules used for different optical color filters in the plain and hidden codes. It can be seen from Table 6 that based on the magenta module in the green filter (as a light color module), when $Y > 0.4$, there are $Y_{\mathrm{R+B}} < Y_{\mathrm{G}}$ and $Y_{\mathrm{R+B}} - Y_{\mathrm{R+B}}{}' < 0.15$, which makes it difficult to realize the "color reversal" from light to dark; Similarly, although the grayscale of the blue module (as a dark module) is smaller than that of the other three modules under visible light, the grayscale after color filtering $Y_{\mathrm{B}}{}' \leq 0.24$, which can hardly be flipped from dark to light.

According to (2), G is the color component that has the greatest impact on grayscale, and magenta and blue modules of the theoretical design are adjusted as follows:

- The magenta module consisting of R+B adds a part of G to raise the grayscale, i.e., R+G+B or R+G.
- Adding G can also increase the grayscale of the blue module (composed of B), i.e., G+B.

The results of the grayscale test and comparison are shown in Table 7.

As can be seen from Table 7, the grayscale of color modules with G added significantly increases under visible light and after color filter processing, and:

- When $Y \leq 0.5$, there are $Y_{\mathrm{R+G+B}} \approx Y_{\mathrm{R+G}}$, and $Y_{\mathrm{R+G}}{}' \leq Y_{\mathrm{R+G+B}}{}'$. Therefore, when the same grayscale is displayed under visible light, the grayscale of the module composed of R+G is significantly smaller than the grayscale of the R+G+B module after filter color processing, which is more easily flipped to a dark color.
- When $Y \leq 0.5$, $Y_{\mathrm{B}}{}' < Y_{\mathrm{B}}$, and $0.05 \leq Y_{\mathrm{G+B}}{}' - Y_{\mathrm{G+B}}$,

Table 6. Grayscale comparison of four-color modules (Printing)

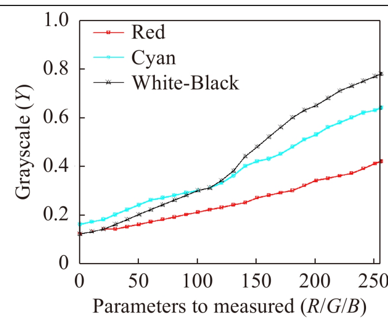
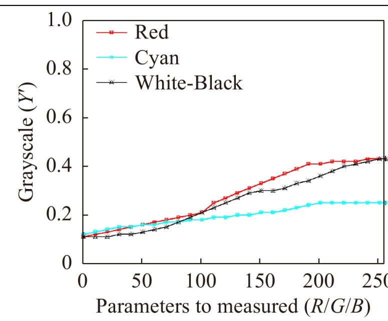
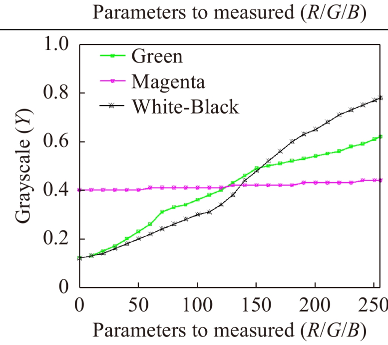
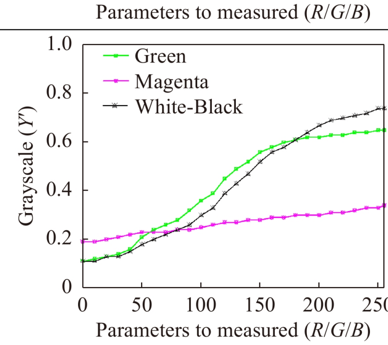
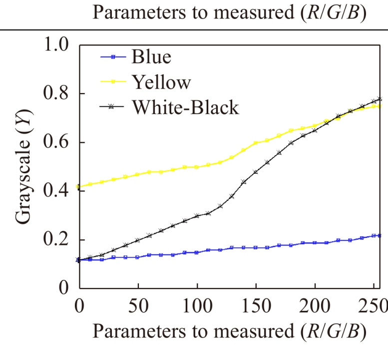
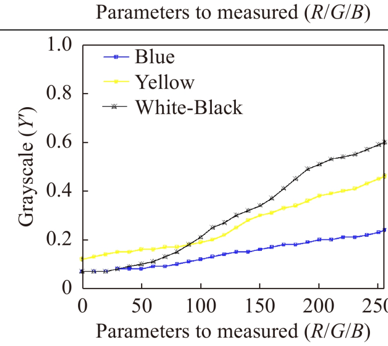
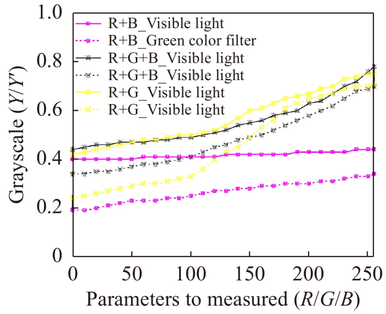
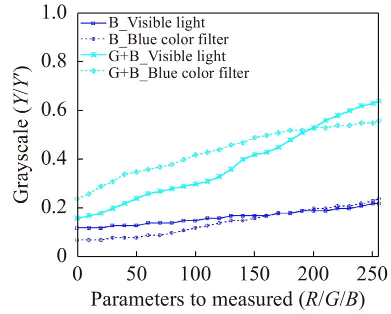
Optical color filter	Plain code	Hidden code
Red color filter		
Green color filter		
Blue colorfilter		

Table 7. Grayscale test comparison (Printing)

Magenta modules



Blue modules



so that the module composed of G+B can solve the problem of turning from dark module to light module after optical color filtering.

In the subsequent experiments, the green color filter uses R+G as the light module, and the blue color filter uses G+B as the dark module.

V. Experimental Results

Scanning the printed HMC-QR code under visible light to get the reading results of the plain code, with the help of optical color filters (install it on the lens of the ordinary QR code reading device) to complete the reading of the hidden code. If plain and hidden codes of the HMC-QR code cannot be read normally at the same time, taking a picture of the printed HMC-QR code with a mobile phone to measure the grayscale of each module, and correcting the relevant parameters according to their grayscale difference until the printed HMC-QR code can read both the plain and hidden codes normally.

After extensive experiments, these situations exist in the reading of the HMC-QR code mainly: unable to read, read slowly and read normally. Taking the red filter as an example, different reading results of the HMC-QR code are shown in Table 8.

It can be seen from Table 8 that when the reading of the printed HMC-QR code is slow or unreadable, the simulated image reading is normal, which indicates that the simulated HMC-QR code has a larger readable range and verifies the idea that simulated reading is easier than printed reading. In addition, judging from the reading situation of the printed HMC-QR code, the reading of plain and hidden codes is contradictory relationship: improving the reading effect of the plain code may result in a reduction in the reading performance of the hidden code; improving the reading coding effect of the hidden code requires sacrificing the reading speed of the plain code. Taking the intersection of normal reading in the reading effect of plain and hidden codes, that is, the intersection where the reading of plain and hidden codes reaches a relatively balanced state.

According to the same process, green and blue color filters were studied to obtain HMC-QR code with the normal reading of both plain and hidden codes, the results are shown in Table 9.

The experimental results in Table 9 prove the feasibility of the method to generate this code. The HMC-QR code designed by the given algorithm and the grayscale segmentation model can read plain and hidden information directly.

VI. Evaluation

The reliability of QR code reading is limited by external factors, such as the light environment, the printing size of QR codes and the reading angle. For color QR codes, the influence caused by these factors may increase exponentially, therefore, we discuss the recognition reliability of the HMC-QR code based on these three factors.

We use the control variable method to keep the same printing size and reading angle, only change the light environment when reading to test the reading reliability under different light environments. Similarly, testing the other two factors in turn. Five different models of mobile phones are used to read the printed HMC-QR code(“S” for reliable, “U” for unreliable). The test results are shown in Table 10. In addition, we also compared the research results of HMC-QR code and other color QR codes, mainly for its capacity, decoding conditions, decoding speed, multi-code compatibility, etc. The results are shown in Table 11.

We can see from Table 10 that the reading results of the HMC-QR code are the same with mobile phones of different models. Under different light environments and reading angles, both plain and hidden codes can be read normally. For different printing sizes, when the size is less than 1 cm, the reading of the plain code is affected to a certain extent. This is because the printing size is too small, and the printing accuracy of the printing equipment is not enough, which causes the color module to be greatly affected by dot diffusion, and

Table 8. Reading results of HMC-QR code (Printing)

Plain code (Simulation)	Plain code (Printing)	Reading results		Hidden code (Simulation)	Hidden code (Printing)	Reading results	
		Simulation	Printing			Simulation	Printing
		Read normally	Unableto read			Read normally	Read normally
		Read normally	Readslowly			Read normally	Read normally
		Read normally	Read normally			Read normally	Read normally
		Read normally	Read normally			Read normally	Read slowly
		Read normally	Read normally			Read normally	Unable to read

Table 9. Reading normal HMC-QR code (Printing)

Optical color filter	HMC-QR code	Plain code	Hidden code
Red color filter			
Green color filter			
Blue color filter			

Table 10. Reading stability test based on different factors

Reading results (Plain code/Hidden code)	Light environment		Printing size		Reading angle			
	Weak light	Strong light	Size < 1 cm	Size ≥ 1 cm	0°	90°	180°	270°
Huawei	S/S	S/S	U/S	S/S	S/S	S/S	S/S	S/S
Xiaomi	S/S	S/S	U/S	S/S	S/S	S/S	S/S	S/S
Vivo	S/S	S/S	U/S	S/S	S/S	S/S	S/S	S/S
Samsung	S/S	S/S	U/S	S/S	S/S	S/S	S/S	S/S
Apple	S/S	S/S	U/S	S/S	S/S	S/S	S/S	S/S

Table 11. Comparison of HMC-QR code and other color QR codes

Color QR codes	Capacity (times)	Decoding conditions		Decoding speed	Multi-code compatibility
		Standard decoder	Special decoder		
Meruga *et al.* [20]	3	×	√	Slow	×
Bhardwaj *et al.* [21]	3	×	√	Slow	×
Masanori *et al.*[22]	3	√	√	Slow	×
Ours	≥ 2	√	×	Fast	√

the color interference phenomenon is more obvious. Fortunately, this problem can be easily solved by using more accurate printing equipment. According to the QR code standard released by the national public service platform for standards information, it stipulates that the minimum module size of QR codes should not be less than 0.254 mm. For QR codes with 39×39 modules (including six static areas onboth sides), the minimum size should not be less than: $0.254 \text{ mm} \times 39 = 0.9906 \text{ cm} \approx 1 \text{ cm}$. Therefore, printing sizes can be almost disregarded in practical applications. According to the experimental results of different light environments, printing sizes reading angles, it is proved that the reading of this HMC-QR code has strong reliability.

As can be seen from Table 11, the capacity of the HMC-QR code is not lower than that of other color QR codes (in order to ensure the direct readability and decoding speed, it is best to multiplex 2 to 3 QR codes). And the HMC-QR code has good compatibility withplain and hidden codes, they can be directly read by standard decoders; because no third-party decoding tools are required, the decoding speed is significantly faster than other color QR codes.

In order to study the anti-noise and anti-distortion performance of the HMC-QR code, the scanned image and printed image are discussed. During the scanning process, affected by the resolution of the scanning equipment and the environment, jitter distortion and noise will inevitably occur. Due to the limitation of color gamut and the limited accuracy of printing equipment, color errors caused by the inaccurate ink control, ink, ink diffusion, flying ink and other factors are unavoidable during the printing process, so that the printed halftone image is mixed with a certain noise. Compare the electronic, scanned and printed images of the HMC-QR code and perform a reading test. The results are shown in Table 12 (taking the red color filter as an example).

It can be seen from Table 12 that the scanned image has a certain distortion, the ink dots of the printed image are chaotic and unevenly distributed, and both have relatively large noise, but they still maintain the direct readability of plain and hidden codes. Therefore, it is proved that the HMC-QR code has good anti-noise and anti-distortion ability according to the reading resultsof the scanned and printed images, and this code can be printed by ordinary color printing process, which is beneficial to its practical application.

Table 12. Image comparison of the three states of HMC-QR code

HMC-QR code		**Readable**	
		Plaincode	Hiddencode
Electronic image		Read normally	Read normally
Scanned image		Read normally	Read normally
Printed image		Read normally	Read normally

VII. Conclusions

This paper provides a directly readable HMC-QR code of multi-code composite with plain and hidden information and establishes a mathematical model for generating this code by using multiplexing and color-coding technique. The HMC-QR code solves the problems of the compatibility of multiple codes, direct reading, halftone printout, etc., which makes the application of this code very promising. Users can use ordinary reading equipment to select the required QR code for modulation reading. Experiments have proved that the HMC-QR code is more superior and innovative to existing color QR codes. In the future, the maximum dynamic grayscale interval that can be read of the HMC-QR code can be further studied, and the method is combined with beautification and anti-counterfeiting technology to be extended to different application scenarios.

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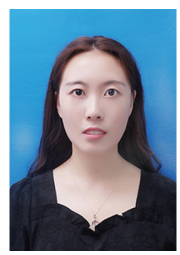

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