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DEVELOPMENT OF A HYBRID DYNAMIC FUZZY ENCODER AND DECODER MODEL FOR COLOUR QR CODE

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By

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A Quick Response (QR) code is a popular type of two-dimensional barcode that is widely used in various applications. There are two types of QR codes, namely, the normal black and white (B/W) QR code and the colour QR code. The colour QR code is a new generation of B/W QR code which is able to encode three times the data encoded by a B/W QR code. However, research into colour QR codes is still at the initial stage. Improving a colour QR code is a challenging research area as it involves both the colour QR code encoder and decoder. The problem with a colour QR code encoder is the limited size and static colours of the QR code. Current colour QR code encoders can encode data with a maximum size of only three kilobytes and generate QR codes that are limited to eight colours only. Three data layers, comprised of the colours red, green and blue, are required to form the eight colours. As such, the encoder is prevented from encoding a dynamic number of data layers, according to the size of the colour QR code. Furthermore, the disadvantages of QR code decoders are their success rate, speed and static colours. Current colour QR code decoders have a decoding success rate of up to 45% and speed of 3 seconds only. The success rate and speed of the decoders become an issue when larger files are involved, since none of the existing decoders are able to decode large QR codes. Moreover, current colour QR code decoders are static, meaning that they can only decode eight colours and are unable to handle a dynamic number of data layers. A new colour QR code algorithm known as a Fuzzy QR code (FQR code) was proposed to solve the problems faced by current colour QR codes. The proposed algorithm consisted of two parts, an encoder and decoder. The objectives of this research are to design a fuzzy encoder algorithm to handle the size limitation and static colour problems, to design a fuzzy decoder algorithm to cater for the success rate, speed and static colour issues and to test the algorithms using two different datasets from Yang et al. (2018) and the colour QR codes generated by the proposed FQR code encoder. The FQR code encoder algorithm provided a novel enhancement to the colour QR code by adding a colour reference to its structure. The encoder algorithm was designed based on dynamic fuzzy logic and it was able to encode up to four data layers to overcome the size limitation. With the fuzzy encoder algorithm, the number of layers required to overcome the static colour limitation could be selected. The proposed fuzzy encoder algorithm used dynamic membership functions, which were built according to the size of the file. Dynamic fuzzy membership functions were proposed because they give better results than the usual fuzzy static membership functions. The output of the fuzzy encoder algorithm would be the number of data chunks. The experiment showed that the FQR code encoder was able to encode files with a capacity that was 25% larger than current colour QR codes. In addition, it was able to encode files that were smaller by 50% than current colour QR codes. The FQR code decoder used a colour reference to select the number of colours needed to overcome the dynamic colour selection limitation. The FQR code decoder was based on fuzzy logic to overcome the limitations of the decoding success rate and decoding speed. The proposed fuzzy decoder algorithm was built on a dynamic fuzzy process for the colour recovery, where the membership functions were dynamically built according to the colour reference. The dynamic fuzzy membership algorithm could be adapted to any colour compared to the static fuzzy membership functions, which worked with specific colours only. The decoder significantly enhanced the decoding success rate by 67.66%, and the decoding speed was 200% faster compared to the existing colour QR code decoders. Experiments were carried out to test the FQR encoder and decoder using two different datasets (Yang, 2018 dataset, and FQR code generated dataset). The results showed significant enhancements by the proposed colour QR code encoder and decoder, where the encoder increased the minimum size for the current QR code by 25% and decreased the minimum size by 50%. Moreover, the decoder enhanced the decoding success rate by 67.66% and the decoding speed by 200% compared to the existing decoders.

Keywords: QR code, Fuzzy, Encoder, Decoder, Colour enhancement.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN MODEL EKODER DAN DEKODER DINAMIK DINAMIK HIBRID UNTUK KOD QR WARNA

Oleh

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Kod maklum balas pantas (QR) adalah sejenis kod bar dua dimensi popular yang digunakan secara meluas dalam pelbagai aplikasi. Dua jenis kod QR adalah kod QR hitam dan putih (B/W) biasa serta kod QR warna. Kod QR warna merupakan generasi baru kod QR B/W dan ia dapat mengkodkan data tiga kali lebih besar berbanding kod QR B/W. Namun demikian, penyelidikan mengenai kod QR warna masih lagi di peringkat awal. Penambahbaikan kod QR warna mewakili sebahagian penyelidikan yang mencabar kerana ia melibatkan kedua-duanya, pengekod dan penyahkod kod QR warna. Masalah dengan pengekod kod QR warna adalah had saiz serta warna statik. Pengekod kod QR warna semasa boleh mengekod data dengan saiz maksima sebanyak hanya tiga kilobait. Sebagai tambahan, kod QR warna semasa mempunyai bilangan warna statik yang hanya terhad kepada lapan warna sahaja. Untuk membentuk lapan warna tersebut, tiga lapisan data warna merah, hijau dan biru diperlukan. Ini menghalang pengekod untuk mengkodkan lapisan data dinamik yang bergantung kepada saiz kod QR warna. Selanjutnya, masalah dengan penyahkod kod QR adalah kadar kejayaan, kelajuan dan warna statik. Penyahkod kod QR warna semasa menghasilkan kadar kejayaan mencecah 45% dengan kelajuan hanya 3 saat. Masalah dengan kadar kejayaan dan kelajuan penyahkod merupakan masalah mengkodkan fail yang lebih besar kerana tiada penyahkod yang dapat menyahkod kod QR yang besar. Lebih-lebih lagi, penyahkod kod QR warna semasa adalah statik. Ini bermaksud ia hanya mampu menyahkod lapan warna sahaja serta tidak dapat menangani perubahan terhadap bilangan lapisan data yang dinamik. Algoritma baru untuk kod QR warna, yang dinamakan sebagai kod QR kabur (kod FQR), dicadangkan untuk menyelesaikan masalah dengan kod QR warna semasa. Algoritma yang dicadangkan terdiri daripada dua bahagian, pengekod dan penyahkod. Objektif kajian ini adalah untuk mereka bentuk algoritma pengekod kabur bagi mengendalikan masalah had saiz dan warna statik, merekabentuk algoritma penyahkod kabur bagi menyelesaikan masalah kadar kejayaan, kelajuan dan statik serta bagi menguji algoritma dengan menggunakan dua set data yang berbeza daripada Yang et al. (2018), dan menjana kod QR warna daripada pengekod kod FQR yang dicadangkan.

Algoritma pengekod kod FQR memberikan penambahbaikan baru kepada struktur kod QR warna dengan menambahkan rujukan warna pada strukturnya. Algoritma pengekod direka berdasarkan logik kabur dinamik dan dapat mengekod sehingga empat lapisan data bagi mengatasi had saiz. Algoritma pengekod kabur membolehkan pemilihan bilangan lapisan yang diperlukan untuk mengatasi had warna statik. Algoritma pengekod kabur yang dicadangkan menggunakan fungsi keahlian dinamik yang dibina secara dinamik berdasarkan saiz fail. Keanggotaan kabur dinamik dicadangkan kerana ia memberikan keputusan yang lebih baik berbanding dengan kabur biasa dengan fungsi keanggotaan statik. Hasil algoritma pengekodan kabur ialah jumlah potongan data. Eksperimen menunjukkan yang pengekod kod FQR dapat mengekod fail dengan kapasiti yang 25% lebih besar berbanding dengan kod QR warna semasa. Sebagai tambahan, ia mampu mengekodkan fail yang 50% lebih kecil berbanding dengan kod QR warna semasa. Penyahkod kod FQR menggunakan rujukan warna bagi memilih jumlah warna untuk mengatasi had pemilihan warna yang dinamik. Pengekod kod FQR adalah berdasarkan pada logik kabur bagi mengatasi had kadar kejayaan dan kelajuan penyahkodan. Algoritma kabur penyahkod yang dicadangkan dibina berdasarkan proses kabur dinamik untuk pemulihan warna, di mana fungsi keahlian akan dibina secara dinamik berdasarkan warna rujukan. Algoritma keahlian kabur dinamik bersifat adaptif dan boleh disesuaikan dengan sebarang warna berbanding dengan fungsi keahlian kabur statik, yang hanya dapat berfungsi dengan warna yang tertentu. Penyahkod telah meningkatkan kadar kejayaan penyahkodan secara signifikan sebanyak 67.66%, serta kelajuan penyahkodan adalah 200% lebih pantas berbanding dengan penyahkod kod QR warna yang sedia ada. Eksperimen bagi menguji pengekod dan penyahkod FQR telah dijalankan dengan menggunakan dua set data yang berbeza. Hasilnya menunjukkan peningkatan yang ketara berbanding dengan pengekod dan penyahkod kod QR warna semasa, di mana pengekod yang dicadangkan meningkatkan saiz minima kod QR semasa sebanyak 25%, serta menurunkan had saiz minima sebanyak 50%. Sebagai tambahan, penyahkod yang dicadangkan turut meningkatkan kadar kejayaan penyahkodan sebanyak 67.66%, di samping meningkatkan kelajuan penyahkodan sebanyak 200% berbanding penyahkod yang sedia ada.

Kata kunci: Kod QR, Kabur, Pengekod, Penyahkod, Peningkatan warna.

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LIST OF ABBREVIATIONS

EAN	European Article Number
UPS	Universal Product Code
FQR	Fuzzy QR code
1D Barcode	One-dimensional Barcode
2D Barcode	Two-dimensional Barcode
QR	Quick Response
3D Barcode	Three-dimensional Barcode
B/W	Black and White
RGB	Red, Green, Blue
CMYK	Cyan, Magenta, Yellow and Black
Level [L]	Low
Level [M]	Medium
Level [Q]	Quality
Level [H]	High
FL	Fuzzy Logic
AI	Artificial Intelligence
QDA	Quadratic Discriminant Analysis
SVMs	Support Vector Machines
NFC	Near-Field Communication
LSVM	linear support vector machine
FL	Fuzzy Logic
FIS	Fuzzy Inference System
FS	File Size
PS	Paper Size
DTX	Distance Top X axis
RS	Region Size
OC	Original Colour
CRC	Colour Reference Count

MS	Model Size
AC	Actual Colour
MR	Membership function of red colour
MG	Membership function of Green colour
MB	Membership function of Blue colour

CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

Barcodes are widely used in everyday life, and they are developed from simple visual codes such as the European Article Number (EAN) or Universal Product Code (UPC) (Pavlidis et al.,1990; Finkenzeller, et al.2010). These barcodes are well known as one-dimensional barcodes (1D barcodes). 1D barcodes can store data only in one dimension, which severely limits the data size of these barcodes. Due to the limited data size, these barcodes are only attached to systems that offer 1D barcodes, and they can be seen on products at supermarkets. These barcodes store the product identification, and the supermarket system is able to read this identification and obtain the product information from the system database. Figure 1.1 (A) shows an example of a 1D barcode.

Two-dimensional barcodes (2D barcodes) include the Quick Response (QR), Data Matrix, and Aztec codes (Denso, 1994; Gao et al., 2007). These were developed from the 1D barcode. As 2D barcodes can encode data in 2 dimensions, they are able to store data that are 10 times larger than normal 1D barcodes. A QR code is a special type of 2D barcode, and it is very popular in everyday life due to such features as its 360-degree reading, fast decoding speed and up to 30% error correction. Due to its popularity, many researchers have been working to extend the limitations of current QR codes. (Mahssa 2019; Yang, 2018; and Bhardwaj, 2016).

Current QR codes can only encode data of a limited size, and therefore, their applications are confined to online solutions (to store website links, purchase online bus tickets, or access secure websites). QR codes can rarely offer offline server applications such as storage of Word documents, PDF files, or identity images. Figure 1.1 B shows an example of a 2D barcode.

Three-dimensional barcodes (3D barcodes) or colour barcodes are the next generation of barcodes that can store data that are up to 3 times larger than existing 2D barcodes. 3D barcodes store the extra data in the same space on paper or on a screen. A visual code with a larger data capacity will have many additional uses. The issue with current colour QR codes is that their size in limited to only 3 kilobytes. A colour QR code uses a colour layer to increase the size and adding more colours to increase the size will create more challenges for decoding, since current colour QR code decoders have a low success rate (45%), and long processing time (3 seconds). Moreover, adding more colours will make it more challenging for colour QR code encoders to provide a dynamic number of colours to fit the data size. this will be explained on section 2.3.

Current colour QR code decoders use machine learning techniques such as quadratic discriminant analysis (QDA) and support vector machines (SVMs), which suffer from decoding processes that are quite time-consuming (Yang, 2018). Furthermore, large training datasets are needed to train the classifiers. As such, the researchers were motivated to find a way to overcome the limitations of current colour barcodes. Figure 1.1 C shows an example of a 3D barcode.

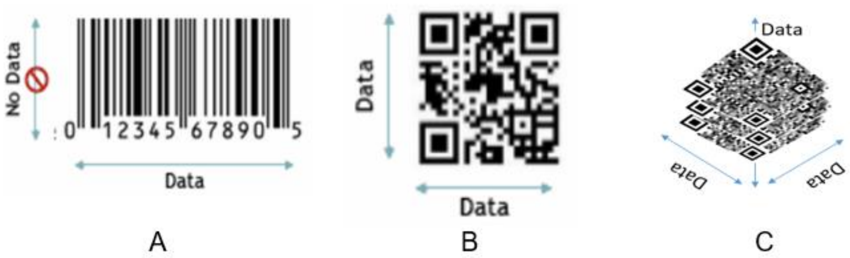

Figure 1.1: Barcode Examples

1.2 Research Problem

The issue with current colour QR codes is the size limitation (Yang, 2018; Blasinski, 2013; and Bhardwaj, 2016). Adding more colours to increase the size will create more challenges for the decoding process, since current colour QR code decoders have a low success rate (45%), and long processing time (3 seconds) (Yang, 2018; and Bhardwaj, 2016). Moreover, adding more colours will create challenges for the colour QR code encoder to provide a dynamic number of colours to fit the encoded data size, for example, 2 colours for a small data file, and 16 colours for a large data file.

Current colour QR code decoders use machine learning techniques such as quadratic discriminant analysis (QDA), and support vector machines (SVMs), which suffer from decoding processes that are quite time-consuming (Yang, 2018) those algorithms explain in details in section 2.11.3, and require major training for the classifiers.

The challenges facing current colour QR code encoders and decoders in increasing the size limitation can be summarized as follows:

- Issues with colour QR code encoders:
    - Current QR code encoders are static, which means they can encode QR codes with a static number of colours, e.g., 2 colours, 5 colours or 8 colours; and this limitation is because the decoders need to know what colours are used in the encoders.
    - The number of colours in the colour QR code is limited. Current encoders can only encode colour QR codes with a maximum of 3 layers (8 colours), and this limited number of layers is due to the

number of primary colours in the colour model (Mahssa 2019; Blasinski, 2013; and Bhardwaj, 2016).

- Issues with colour QR code decoders:

    - Current colour QR code decoders can decode QR codes with a certain number of colours based on the QR codes of the encoders.
    - Low decoding success rate due to cross-channel interference, colour illumination, and other types of noise, (Mahssa 2019; Yang, 2018; and Bhardwaj, 2016).
    - Slow decoding speed, since a colour recovery algorithm is required and multiple layers of the QR code have to be decoded. Current colour QR code decoders can decode colour QR codes with 3 layers within 3 seconds. (Yang, 2018)

1.3 Research Objectives

To attain the main objective of increasing the size limitation for current colour QR codes, the following objectives had to be achieved:

To design a Colour QR code encoder algorithm with the following criteria:

- dynamic colour QR code encoder with a colour reference to enable the decoder to detect the colours used in the encoder.
- colour QR code with four layers using a 16-colour format to overcome the limitation of the colour model.

To design a Colour QR code decoder with the following criteria:

- dynamic colour QR code decoder algorithm that can decode the proposed colour QR codes.
- has colour enhancement algorithm to improve the decoding success rate.

high-speed colour QR code decoder that can decode the proposed 16-colour QR code to obtain the original data

1.4 Research Scope

This study was focused on solving the current issues affecting colour QR codes, and its main aims were to extend the size of the colour QR code, and solve the issues affecting current encoders and decoders. The research focused on colour QR codes on computer screens and printed on paper. Two fuzzy algorithms were proposed, one for the encoder, and the other for the decoder. The evaluation was performed on a dataset from existing research (Yang, 2018), which used printed QR codes, and the proposed solution was tested in terms of the enhanced QR codes on a computer screen using the datasets.

1.5 Thesis Organization

Chapter Two presents the literature review of existing works. First, the limitations of current QR codes are explained. Second, the benefits of having QR codes with a larger capacity are discussed. Third, existing works on colour QR code encoders are explored. Fourth, existing works on QR code decoders are established. Finally, the architecture of the fuzzy logic system for colour identification is discussed.

Chapter Three shows the research steps taken to achieve the research objectives as it shows the following steps: research problem, literature review, evaluation of data, designing the algorithm for the 8-Colour QR code decoder, evaluating the results of the 8-colour decoder, designing a dynamic colour QR code encoder, design of dynamic colour QR code decoder, generating the dataset, and finally evaluation.

Chapter Four shows the proposed algorithm for the encoder, where an overview of the proposed encoder is shown, followed by the fuzzy process, assigning of colours, addition of a colour reference, and the pseudo code.

Chapter Five shows the proposed algorithm for the decoder. First, an overview of the decoder is given, followed by the colour recovery speed, colour enhancement, and pseudo code.

Chapter Six shows the results for the encoder and decoder. First, the output for the proposed encoder is shown, followed by a comparison with existing encoders. Then, the decoder output is shown, followed by a comparison with existing decoders.

Finally, Chapter Seven presents the conclusion and suggestions for future works.

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