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Research Article

Color Barcodes from Debut to Present: A Broad Survey on the State of the Art

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ABSTRACT

Efficiently transferring information, which is of major importance for almost all engineering systems, requires a data representative appropriate to maintain the density and consistency of the information dispatched. As such a machine-readable representation of data, barcodes are one of the most recognized and powerful instruments of the purpose in every domain. Likewise, from the perspective of engineering, colors are excellent sources of information exchange, since the transmission of color connotes the conveyance of its entire scalar attributes in the same spatial channel component. Exerting colors on barcodes as an effective way of bursting the data conveyance capacity has been an active area of research for over 50 years. Significant progress has been achieved through efforts in this regard. It is also envisagable that the evident evolution in related technologies exoterically empowers the enhancement of color barcode capabilities as capacity and reliability, thereby further encouraging prospected research in this direction. Herein, a comprehensive survey of the studies on this main area of interest is presented. To help better acquainted with the field, also a taxonomy of the peculiar interference sources and distortion effects is provided, besides, the 3D barcoding process itself and the research areas are described. Most of the relevant works from debut to the present are broadly examined. Rather than presenting a timeline, studies that pertain to similar issues are addressed together. Amongst those related, premising or pivotal ones are preferably cited as far as feasible. Moreover, all perused works are analyzed by the research areas and the results are presented. Also, the issues relatively more prominent as affecting the performance of the whole process are specified. In the conclusion, some of the research subjects that appear open, scarce, or require further elaboration were remarked on as well. It is anticipated this study to contribute to the efforts toward leveraging color in barcodes.

Keywords: Barcodes, Color Barcodes, 3D Barcodes, Information Transfer, Communications, Automatic Identification

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1. Introduction

Since communication is one intangible yet integral component of every system, the efficient exchange of information is of primary importance for almost all types of applications. The two major concerns of any communication system are the maximum utilization of the channel capacity and the reliable reproduction of the message at the receiving end (Shannon, 1948). It can be paraphrased that the intrinsic goal is to increase the density and consistency of the information dispatched. To duly optimize these conflicting goals, the representative symbols to be transferred should be robust enough with a high data-conveying capability.

As such a machine-readable representation of data, barcodes have become ubiquitous since their debut. Fig.1. intitles the prevalent automatic identification technologies, with the collateral uses of barcoding indicated by +.

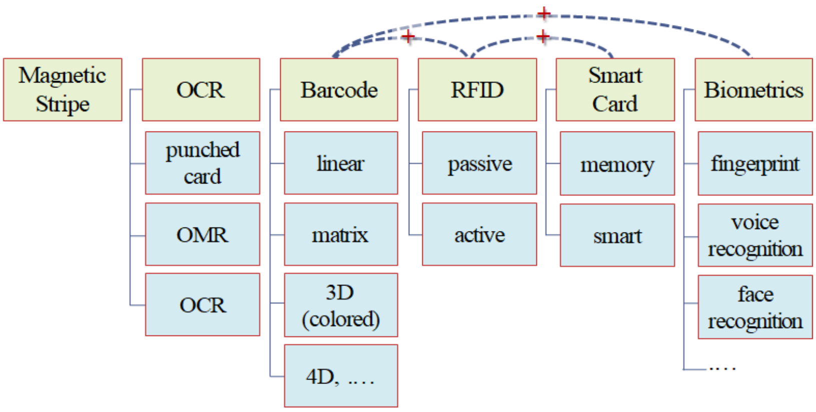

Figure 1. Barcodes in auto-ID technologies.

Among the available auto-ID tools, barcodes endow with a low-cost effective choice. A generic comparison with the radio-frequency identification (RFID) technology (which can be considered tantamount in passive use) indicates that, although functionally superior, the RFID system outlays can undesirably climb, especially as the number of tags needed increases. The study of Burke and Ewing (2014) analogously concluded that barcoding is far more cost-effective for 10 years, especially since the costs RFID tagging incurs are almost twice the barcoding.

Apparently, barcode technology provides a cost-effective and relatively easier-to-implement solution for the needs of efficiently storing and transferring data in most applications, as long as it meets the requirements. Hence today, by involving almost every domain of life, barcoding is probably one of the most recognizable methods to enhance the efficiency of data conveyance.[1]

The aforementioned two major concerns of communication emerge as the data density and decoding reliability issues in barcoding. Through the evolution from 1D (i.e. linear) to 2D (i.e. matrix), barcodes reached high data capacities, remaining legible at fairly small sizes as well. For instance, a QR Code - v.40 symbology can encode 7089, and a Han Xin Code 7827 digits of numeric data in high densities (URL-1, URL-2), e.g.

[1]Designing hybrid systems by combining RFID with barcodes (as exemplified by Costa et al. (2015) and the like) can help reduce outlay and provide applications a sort of cross-validation fortification at almost no cost. A specific method of combining both technologies on one label by giving the meander antenna a barcode shape was demonstrated by (Abdelnour, et al. 2018). Also, Fan, et al. (2019) propose equipment for barcode and RFID mutual information transformation that could improve traceability.

the data density QR Codes reach is 5016 bits-per-square-inch (Querini, et al. 2011). The technical details and patents pertaining to the QR Code can be reached at (URL-3). Besides, in-depth tests in a recent study on the resistance to character substitution errors show that symbologies equipped with Reed-Solomon error correction schema can achieve a 1/797 million error rate in decoded data accuracy (Berisso, 2018).

It can be furthermore envisaged that these two contradicting cruces of a barcode are largely related to the quality of the printing and reading operations. Besides the other factors, the main determinants of both issues are the resolution (in terms of dots-per-inch) and color depth (in terms of bits-per-pixel) capacities of the printer and image-capturing (i.e. scanner/camera) technologies. Fig. 2 and Fig. 3 would give an idea about the evolution of the relevant features in the pertaining technologies over the last decades.[2] As the steady progress of these technologies is evident, it would be quite fair to expect that advancements in the highlighted features exoterically empower the likelihood to develop more reliable barcodes with larger conveyance capacities in the future.

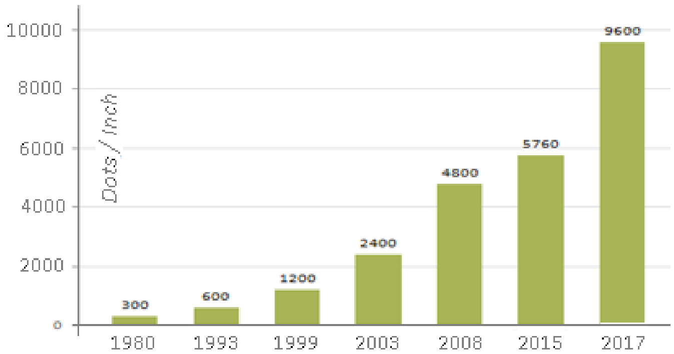

Figure 2. Evolution of printer resolutions over the recent years.

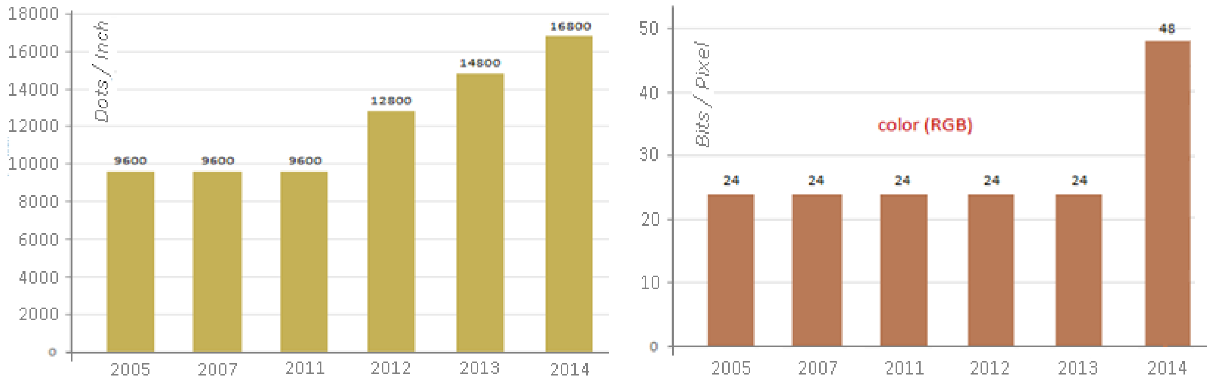

Figure 3. a) Evolution of scanner read resolutions. b) Evolution of scanner color-depths.

Likewise, transferring a color as a data representative would also connote conveying its entire scalar attributes in the same spatial channel component. A comprehensive information-theoretical evaluation of the information capacity and cost-effectiveness of color symbols and palettes involve can be found in (Sirmen and Üstündağ, 2017). (The term *palette* herein states the combination of specific colors to

[2]Obtained by reviewing open source information of some widely used manufacturers (such as cnet.com, openprinting.org, scantastik.com, etc., and official documents and web pages of Canon, Epson, HP, Kodak, etc.). Epson claims 5760×1440 dpi, and Canon claims 9600×2400 dpi max resolution in-color for some of their series' data sheets.

be integrated into the symbology.) Thus, from the perspective of engineering, colors should be seen as excellent sources of information exchange. With the motivation of further increasing the data densities, introducing colors to barcodes has been a very attractive area of research for many decades.

Adding colors though is not an arbitrary procedure. Boosting the information density in this way causes crowding of the source space and consequently hinders the color distinguishability presumably since the authentication process is to be accomplished in the presence of various deteriorating effects. Hence in 3D barcodes, the inherent cost of higher data density is the need for increased decoding complexity and precision of the printing and reading devices to be used. (The adjective *3-Dimensional* in this context should describe a barcode utilizing more than two colors.) As an example, the data density has reached up to 16000 bits/square inch with Microsoft's HCCB-8, and there are also other trials as Querini, et al. (2011), (URL-4) that claimed even higher densities.

The whole process takes place under various interference effects that occur at every step as a peculiar challenge, hence demanding diverse dealings. The encountered interference sources and the deteriorations they cause, as well as the main steps of an information transfer process via 3D barcodes in connection, are briefly described under the ensuing titles so that the research areas could be easier to recognize.

1.1. Taxonomy of Interference Sources and Deteriorations

1.1.1. Interference Sources

There exist a variety of unpredictable interference effects involving in. they can be observed mainly in two groups:

Operational Interference Sources

Most of the interference sources and their effects would dynamically vary depending on the instruments (i.e. devices, media, etc.) used and the operational environment unless it is implemented under a fully controlled experimental condition. The following sources and the like should be counted in this category:

- printer and media properties
- ink quality
- fading
- reflection
- smudges or damages
- ambient light
- reader properties
- blurring
- performance of the preprocessing operations

Structural Interference Sources

Regardless of the operational conditions, environment, devices, or such, the presence and effects of some sources rather relate to the methodic design preferences. Typically, these are:

- palette quality
- encoding quality
- the formal design quality of symbology (i.e. shape/geometry)
- color space and image format conversion inaccuracies
- performance of the employed decoding method

Under the influence of these structural and operational factors, it is almost inevitable to encounter at least one, or a simultaneous combination of essentially the three types of distortions. They can be also briefly described as follows:

1.1.2. Distortion Types

Geometric distortions

The appearance of the barcode could get distorted in its spatial form basically due to irregularities in the printing surface, variations in the reader's angle of view or lens magnification, or such effects. It could occur in horizontal/vertical, linear/non-linear scaling, skew, perspective, projection, shear, or more complicated ways.

Chromatic distortions

Apart from the geometric distortions, some of the effects can modify the color properties to a significant degree, which may get noticeable sometimes even to the naked eye.

Other types of distortions

Furthermore, other types of deterioration effects are induced by some factors like motion or focus blur, reflection-based glare blindness, or even stain, smudge, hole, crack, scratch, or such. Their nature is mostly random.

Thus the 3D barcoding steps briefed below have to deal with all of these issues. In-depth analysis of the overall 3D barcoding process and the color acquisition model are available in the study of Sirmen (2022) with further exploration.

1.2. Information Transfer Process via 3D Barcodes

Fig. 4 provides the basic template of information conveyance by 3D barcodes. This workflow somehow conforms to the generic structure of a typical communication system. The production process of the barcode corresponding to the transmitting stage is symbolized on the left, while the receiving and reproducing of the conveyed message is portrayed on the right. Reading the barcode from the screen and scanning the label are analogous practices.

Every step should somehow maintain the ultimate goal of improving decoding reliability. While the *encoding* step relates to applying the error detection/correction (*EDC*) coding schema to be incorporated; *palette construction* refers to the selection of the colors to use according to the operational color space, code design, and forming the symbol shapes if involved. The encoded message is mapped into the *representative* colors and then printed.

On the receiving hand, *preprocessing* is associated with the barcode/edge/symbol detection/localization, and interference mitigation-related operations such as orientation, scaling (i.e. geometric distortions), de-blurring, etc. from the refined input sequence, the colors *authenticated* (i.e. clustered) and mapped back. Then the *decoding* process reconstructs the message distorted under interference.

In means of an effective transfer of information, every step has its specific importance and should be well elaborated. Research in the field has been developed within this framework.

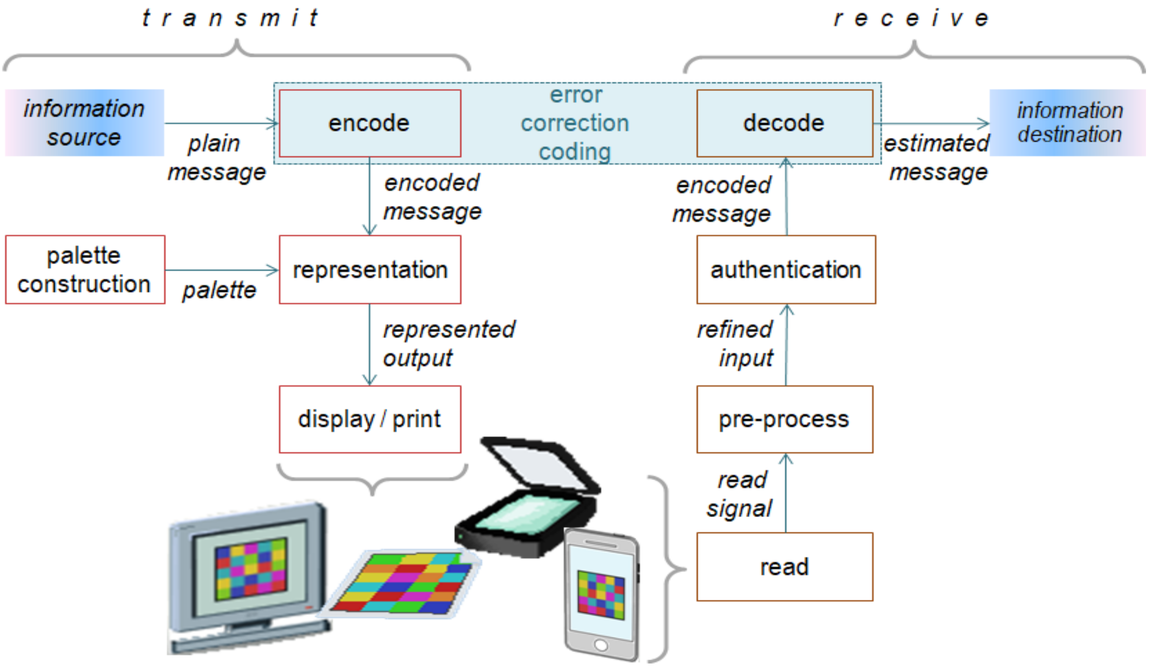

Figure 4. Main steps of an information transfer process via 3D barcodes.

1.3. Research Areas in the Field

This technology interacts with research in a variety of fields, just like the others. The Euler diagram in Fig. 5 presents the generic work titles of research associated with 3D barcodes. (Intersections indicate corresponding transitions.)

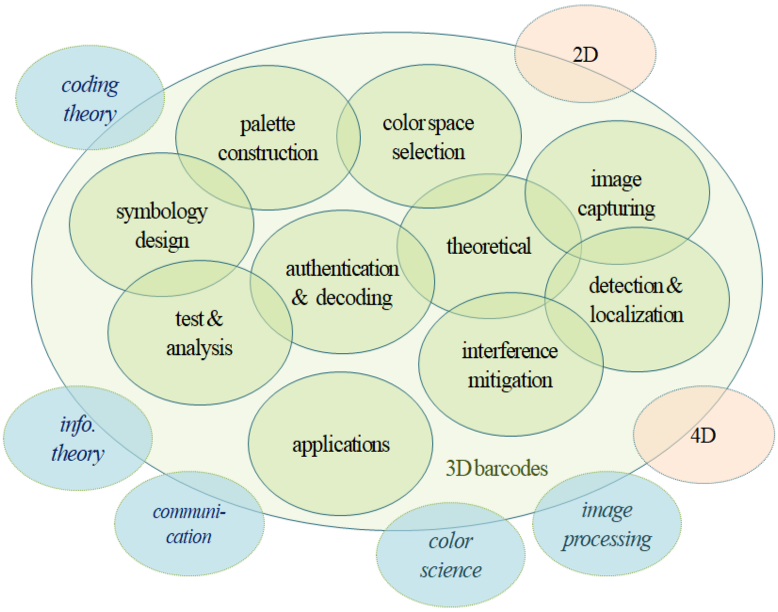

Figure 5. Euler diagram of research areas associated with 3D barcodes.

Along with the other environs, advances in coding theory, information theory, color science, communications, and image processing probably have the most influence in the field.

Color space selection: Research on color space selection is about investigating the optimum operational color space most suitable for field applications.

Palette construction: As explained above, deals with the issue title implies.

Symbology design: Spans the coding as well as the formal design of the barcode.

Image capturing: This title is essentially meant to point out the research on issues of the image capture formats (e.g. JPEG readability, etc.).

Detection and localization: Studies in this area are on techniques such as the design and use of finder patterns, borders, dealing with multiple barcodes, and the like.

Interference mitigation: There are works also on the rest of preprocessing that cover interference mitigation, such as deblurring, reflection, geometric distortion, occlusion, cross-module interference remediation, or modulation schemes.

Authentication and decoding: Research in this is rather on issues like discriminating colors or color patches, clustering, and classification, illuminant estimation, as well as the use of coding algorithms such as LDPC, Expectation-Maximization, Reed-Solomon, etc. in the field.

Tests/analyses: Some studies provide the results of the tests, comparisons, and analyses of similar compatible designs or method proposals relating to security threats, color detection and decoding performances, first-read rates, or such.

Applications: There also exist application proposals including document authentication, visual (or visible) light communication (*VLC*), biometric data recognition, speech data storage, augmented reality, payment systems, hybrid systems with RFID, environment-sensitive barcodes, steganography, security, anti-counterfeiting, even bee monitoring, etc. utilizing barcodes.

Theoretical: Further theoretical studies address rather underlying matters such as symbol entropies, evaluation metrics, algorithm complexities, or channel models.

Besides, the results of some research on *2D* as well as *4D* barcodes are prevailing also for 3D.

1.4. Method and Outcomes

Due to the acknowledged application possibilities in diverse areas, there is a great deal of ongoing research being carried out, focusing on each aspect of the process. The prospect of this study is to serve future endeavors. The major expected outcomes are to provide a review of the works associated with 3D barcodes together with their interrelationships, to recognize relatively prominent issues by influencing the performance of the whole process, and to highlight the subjects that appear open, or need further research as well.

The broad survey of the selected typical works of the field presented in the following section portrays the prior efforts and the state of the art. However, rather than generic issues relevant to various application areas such as image processing (e.g. edge detection, pattern recognition, etc.), studies that are more peculiar to 3D barcodes were adverted here to a greater extent. Hardware implementations of asserted symbologies or solutions have also been incorporated amidst several patent applications, though pure hardware studies have not been subsumed.

Reviewed studies on similar problems were addressed together, instead of presenting a timeline. Amongst those related, premising or pivotal ones were preferably referred to as far as feasible.

Later, the works perused were analyzed by the signified research areas, and the results were presented in the related section. Hence in the conclusions, some of the subjects that seem open or require further research are also remarked on.

Scrutinizing the reported experiences indicate that, the issues of constructing the optimal palette (which underlies the whole process), and authentication/decoding (which is the ultimate goal) deserve additional emphasis. As the evolving technology promises to achieve an even more cost-effective way of information transfer, this study is anticipated to contribute to the efforts towards leveraging color in barcodes.

2. Current Status of the Knowledge

Color barcodes have caught wider use and attraction to a certain extent after Microsoft announced the 'High Capacity Color Barcode' (HCCB) along with their mobile solution 'Microsoft Tag' in 2009 (Jancke, 2004, 2010; URL-4). However, studies for utilizing the attributes of color in barcodes go as far as a couple of decades. KarTrak ACI, developed in the late 1960s in the USA, can be counted as the first commercial example. Although it was a 2D linear discrete system, it involved affixing colored stripes in various combinations on railroad rolling stocks (URL-5). Also, we can find patented 3 or more colored barcodes by Christie, et al. (1972a), and a colored barcode reader by Christie, et al. (1972b), both dated 1972. The work of Wahli, et al. (1972) involved designing a method and apparatus for converting primary and complementary (i.e. RGBCMY+W) color codes into binary-coded information.

Colored dots in the form of checkerboard matrices designed by Shamir (1994) should be considered also as a 3D barcode implementation. Yet another similar attempt was by (Kinoshita, et al. 1995). Also, Kaufman, et al. (2000) proposed a stacked color transition code, using the additive and subtractive (i.e. RGB and CMY) color sets in adjacent rows by alteration.

Glyphs are singular visual marks used to encode data by assigning their attributes such as size, shape, or orientation. They can be spatially arranged independently. The history of their use goes back to the 1950s. The study of Hecht (2001) at the Xerox Palo Alto Research Center added the color dimension to data glyphs. By inspecting 64 different experimental studies, Fuchs, et al. (2017) provided compact knowledge of the 'DataGlyph' technology. Also, the studies of Ward, (2002, 2008) can be seen for the taxonomy of multivariate data glyphs.

Encoding relies on the hue of the used colors in most of the designs. Trials of encoding data based on the other attributes are quite exceptional. Such a design was proposed by Hagstrom, et al. (2002) using the changes in hue and intensity to convey data, by exploiting the reflectance properties under infrared light. A smoothly changing color from end to end formed the background, and strips were printed on the surface, some reflecting infrared light. Under selected light sources, an infrared detector is used to discriminate the reflected patterns, which are not identifiable by the naked eye.

A system proposed by Taylor (2006) of HP Company, represented data in two layers and exploited the luminance information as well. There, data was encoded in the 1st and 2nd layers respectively making use of the luminance and the hue differences. Therefore the 2nd layer vanishes as photocopied in black-white. The data in the lossy layer was to be interpreted using both the saturation information and the luminance information forwarded by the 1st layer.

Such another one was by (Collomosse and Kindberg, T. 2008). A finite sequence of video frames in a continuous cycle was encoded within an arbitrary image displayed on the video screen, as a changing pattern of brightness fluctuations. The fluctuations were observed and decoded by a camera-equipped mobile device, and the baseline image was reconstructed over time.

One of the colored quick response code (QR) compatible designs based on Euclidean distances in decoding, weighted so that it would be more sensible to the luminance component than to the chromatic component was worked on by (Querini, et al. 2011). Their reference palette was displayed beneath the printed code and the colors composing it were sorted by the brightness values. They chose the use of colors with different brightness values for performance issues and claimed that their 8-colored version achieved data densities very close to the values reported for Microsoft's HCCB.

The symbology design and coding were commonly worked based on the color (i.e. chromatic) differences, other than a few rare examples such as those mentioned above. Among numerous studies and patent applications, only a few of them exclusively suggest methods for selecting and calibrating palette colors. However, even if not designed for a particular one, some of the offered systems produced colors only for a certain camera reader that was expected to be used, and one environmental condition in which the reader was expected to operate (Sali and Keselbrener, 2005;

Sali and Lax, 2005, 2007). Besides, it was assumed that the colors chosen through the proposed procedure were to be generally distinct.[3]

A sequential scalar quantization (SSQ) method for designing an optimized universal color palette was developed also by Kolpatzik and Bouman (1995), for use with halftoning methods such as error diffusion. SSQ may be implemented using a series of look-up tables to minimize the visual error in an opponent color system. Their weighted mean squared error measure was based on the color difference in CIEL*a*b* space and modeled for human contrast sensitivity. Although the main goal was to improve the quality of the displayed image, the employed approach is instructive.

Moreover, it was pointed out by Kato, Tan, and Chai (2009) that the selection of colors encoding data is the most challenging task, throughout the entire barcode development process, and the importance of selecting the colors that are furthest apart from each other was especially emphasized. 9 equally dispensed colors on a suggested 2D plane, plus an additional one were namely advised. Yet, by definition, the advised colors do not satisfy the best possible maximum distance distribution in the known color spaces. Besides, the suggested scheme would confront extra complications when different numbers of colors are to be considered.

Sirmen (2016), though, proposed a generalized method of color palette construction, independent of the number of colors and the preferred reference space. The 'duality' concept was introduced in this study as well, besides providing plausible techniques for comparing palettes. Developed pallets yielded comparatively better scores, so were to promise better performances.

While almost all symbology designs assumed square-shaped symbols (i.e. tiles), some preferred circle or dot shapes instead. Yet, very few researchers have focused on the geometry of the symbol to increase the areal density of the printed information. Jancke (2004, 2005, 2010) claimed that the triangles could be packed more closely together, as preferred in the HCCB.

Consistently identifying colors at the destination is the ultimate issue for 3D barcoding. To serve mainly this purpose, it is a common practice to incorporate a reference palette having the color set used for encoding the data within the barcode. Even so, enhancing the performance of any preprocessing operation would serve to pave the way to improve color identification authenticity. Some works particularly concentrated on operations like detection and localization. Detection and localization are mostly realized by making use of the corner or border/edge features and detecting the reference marks or patterns when available. These kinds of guides are generally printed along with or within the barcode.

As an example, the black boundary around the HCCB and the white band surrounding it were designed to act as finder patterns to locate the barcode in an image (Parikh and Jancke, 2008). Also in the design proposed by Cattrone (2007), the number of data blocks in the horizontal and vertical direction was specified in an isolated configuration block, besides the number of gradation values for tile colors (in RGB,

[3]Although it sounds similar, there is another study area of building palettes, which deals mainly with harmonizing the chosen colors. Even irrelevant, it may still be interesting to look over the efforts in this area (as such recent ones as Sabo and Lagoda (2017), Tan, Echevarria and Gingold (2018), and Lara-Alvarez and Reyes (2019) to discover some relative relations of different colors.

CMY, or other color sets). Sometimes finder patterns and data could be overlapped. In the work of Pinson (2004), cells included at least one overlapping data and finder pattern value. Finder and data patterns get discernible as the image is filtered for the 1st and 2nd colors.

It was told by Yin, Yuk, and Lee (2008) that, the MaxiCode of Wang and Ye (1995) requires a long recognition time since all six finder patterns (i.e. the central bull's eye) should be searched to decide the direction. Also told that in the QR Code, all three finder patterns should be searched and position detection is difficult when any one of them is damaged. So they claimed that their proprietary 8-colored design offers a larger capacity with faster processing time. Furthermore, the key properties of finder patterns were specifically discussed and categorized by Kato, Tan, and Chai (2008) to help design a reliable finder pattern for a 3D barcode. In conclusion, the findings were shared to improve robustness and functionality.

The Mobile Multi-Colour Composite (MMCC) code, also employs reference palettes and boundaries, and the header information could be acquired from the black and white barcode embedded in the finder pattern. The code structures, color selection, coding techniques, etc. of MMCC were outlined by (Kato, Tan, and Chai, 2010).

A multi-color marker and detection approach was designed by Bagherinia and Manduchi (2013), in the framework of the particular goal of helping blind people find their way. Also, a strategy for selecting surfaces that provide low specular reflection was suggested.

This work inspired Zhang and Lu (2015), and studied 3D barcode detection in natural scenes, suffering camera focus changes, weak light conditions, motion blur, and scaling. Here a symbology of square symbols in at most 4 or 8 colors, with a black boundary on a white quiet zone was considered. A feature detector was designed for finding X or T-shaped crosses formed by juxtaposition cells. Regions containing more than a specific number of crosses were declared as barcode regions. Comparisons with the baseline Hough transform detection method were also performed. This method could be modified to be suitable for symbologies using different symbol forms (such as triangles in HCCB).

There are various other attempts at satisfactory performances for barcode detection and localization. In general, the Jaccard coefficient of similarity (please cf. Tan, Steinbach, and Kumar (2006), p. 74 and the cont.) can be used for a posterior evaluation of the detection accuracy, which measures the regional overlap of the real and the detected barcodes (R and D respectively), that can be stated as $J(R, D) = (R \cap D) / (R \cup D)$.

Deblurring constitutes another foremost area of work. Blurring caused by the mis-focus, motion, or such, of the reading devices, makes the colors and edges indistinct which then causes a nuisance in discrimination. Although some of them are not solely for 3D barcodes, several useful approaches for the estimation of the blur motion direction and size have been developed. By Xu and McCloskey (2011), the direction was estimated using a local autocorrelation histogram which measured the similarity of a signal to itself in a local spatial neighborhood. Also by Lou, et al. (2014), a method of deblurring was proposed when some features of the clean barcode were partially known. Noting that the out-of-focus blur depends on the geometry of the object, an image formation model based on geometrical optics was considered.

An iterative decoding algorithm in the presence of blur was presented by Bagherinia and Manduchi (2014a), yet using a small number of colors. Here the blur was assumed to be uniform. They tested the algorithm by reading the barcode, which was made of m × k quarter-square triangles (in 3 colors), from various distances (using one camera), and compared the performance by employing a minimum distance decoding method.

As another example, an approach of blind deblurring and denoising for QR codes was studied by (Gennip, et al. 2015). Like the others, a priori knowledge of the finder-patterns information was exploited to estimate the unknown point-spread function. Then it was complemented by the total-variation-based regularizations for deconvolution and denoising. It also provided a comparison with a few methods offered previously.

Noise reduction and interference removal are also similarly important areas of research. Reducing the image noise by adjusting the contrast and brightness of the rectified image was tried in the work of Langlotz and Bimber (2007), for developing time-multiplexed 3D barcodes. It was claimed that the applied method leveraged the recognition rate.

Distortion parameter estimation through an unsupervised Bayesian color classification with expectation-maximization was worked in CMY/K space by (Mayer et al., 2009). Gaussian density distribution of the received colors was assumed. A set of printers and scanners were used in the experiments and some hard noise was applied.

Some studies conducted in the HP Laboratories on improving the color authentication accuracy and thus the payload density (PD), introduced the concept of spectral pre-compensation (SPC). It was asserted over their tests that this technique ensures that the colors are maximally dispersed after scanning (Simske et al., 2008).

The deterioration impacts of 4 factors (Print-Scan cycles, image restoration to PS degradation, the authentication algorithm, and the use of the spectral pre-compensation mentioned above) on PD were explored by (Simske, Sturgill, and Aronoff, 2009). Experiments were held on a custom-designed 6-colored barcode. For PS cycles, 3 generation copies were tested. It was seen that copying consistently reduced PD roughly by 55%; while SPC nearly doubled it. Testing 2 authentication algorithms, both essentially based on the minimum-distance approach, showed that selecting the better authentication algorithm increased PD approximately by 50%. The restoration they applied, however, did not provide a substantial increase.

Among their findings, restoration and SPC applications were case-specific, and the tests for algorithm selection were rather limited. Yet the impact of Print-Scan cycles could be generalized for comparable copying cases.

It was also contended by Simske, Aronoff, and Sturgill, M. (2010) that, among other factors, the effective design of the authentication algorithm is the surest way to increase the payload density. For the experiments the colors which are counterparts of the 8 corners of a cube with R, G, and B axes were chosen; black for orientation calibration, white for the background, and the remaining 6 for data encoding. The farthest possible dispersion of 8 points within a cube is apparently the corners of it. However, for numbers other than 8, such a direct picking of the limit values as in this one would not be obvious; thus more sophisticated strategies that consider thresholding for discrepancies would be inevitable. The SPC technique requires testing on color palettes of different numbers.

Sirmen (2022) proposed a novel two-layered color authentication and decoding schema in a recent study, called Iterative Decoding with Predictive Convergence (IDPC). With this method, firstly, the color data of the 3D barcode read were fuzzy-clustered, and weakly classified data points were identified. Subsequently, the unresolved errors iteratively converged to their local minima in interaction with the outer Reed-Solomon layer. Since only the weak points needed to be worked the method had a low computational burden, still able to resolve over 84% of the errors that occurred in the inner layer. Consequently, the observed average correct authentication performance was over 99% in the tests conducted in different noise environments. As a derivative of iterative decoding, the method was claimed applicable also in different fields of technology.

Complementary spectral characteristics of primary and secondary colorants can be utilized toward separability. The R and B channels of conventional scanners can separate C and Y mixtures (or vice versa) at an adequate level. This feature was exploited by Bulan, Monga, and Sharma (2009) by printing two colors at the same spatial spot, also consolidated with a specific dot orientation modulation. It was claimed that the presented system significantly outperformed the current 2D applications by delivering a better conveyance rate.

Another custom-designed 10-color barcode using a reference palette was proposed by Kato (2010) and evaluated using a camera-equipped phone. It was claimed that most samples were decoded correctly and achieved 100% first-read-rate, within a reading distance range of ~10-20cm, except the smallest (2 × 2 cm2) one.

Yet another study by Bagherinia and Manduchi (2011) focused on color authentication without a reference palette. Borrowing the idea of statistical modeling of joint color changes, the offered method tried to map a subspace of a few barcode elements using the nearest-neighbor techniques, rather than individual ones. This method requires prior subspace training which relies on examining the color changes in the taken sample (i.e. the captured picture).

Two subspace generation procedures were offered in their work, yet the first one was not practical and the second resulted in an increase of the error rate by 10 times. Over the experiments using synthetic images, with 1 printer and 1 camera, it was claimed that this method could be useful for decoding barcodes not displaying a reference palette. Although it offers a different approach, the proper generation of the subspaces seems crucial.

Realizing this need, the same authors extended the strategy in Bagherinia and Manduchi (2012), by including a reference palette of 1-5 colors. Through similar experiments, (although the actual error rates were not supplied) the correlation between the probability of incorrect decoding, the number of reference colors included and the selected subspace dimension did not look consistent. However, the leverage of adding reference colors to the decoding accuracy seems evident.

A rarely studied issue, the error in the captured images added by the baseline-JPEG lossy-compression was dealt with by (Tan and Chai, 2012). By appraising the Discrete Cosine Transform coefficient distributions, they tried to improve the JPEG compression, to produce images with higher PSNR values. The comparisons of the recorded average PSNRs in the resultant images (produced by the simulations on 4, 8, and 10 colors, and experiments on a 10-color barcode) were shared.

Provided a performance analysis on methods of different edge-based color constancy by Gijsenij, Gevers, and De Weijer (2012), and presented their classification based on photometric (such as shadow-geometry, material, highlights) characteristics. It was derived that for the evaluation of the illuminant, specular/shadow type edges are further estimable compared to material types. It was claimed that the stated weighted Grey-Edge method performs better in edge-based color constancy up to 11%, compared to the others. This algorithm was used as a preprocessing part of some color identification studies such as by (Yang et al., 2016).

Another approach was proposed by Bulan and Sharma (2012) for estimating especially the printer, capture device, and illumination interference parameters using an expectation-maximization style iterative algorithm. These parameter estimates were then utilized to mitigate the effect of interference. After experiments (yet on only 1 printer and 1 scanner) they claimed that the proposed method provides greater applicability and generality, compared to their earlier work Bulan and Sharma (2011), which also offered encoding data into colored elliptical dot arrays.

In addition to the expectation-maximization algorithm mentioned above, also an alternative approach to cross-channel interference cancellation was proposed by Blasinski, Bulan, and Sharma (2013), now for colored QR and Aztec codes. For the new approach, the Pilot Blocks (i.e. finder patterns) of the original designs were printed in six combinations of the CMY colorants. Using them, optical channel densities were computed and interference parameters were estimated through thresholding. Yet experiments returned that the attained best results of EM and PB approaches vary for different colorant channels.

Being parallel to their previous work of Querini and Italiano (2013), the same authors experimentally studied to identify the most suitable color classifiers also in (Querini and Italiano, 2014). Different algorithms (minimum-distance, logistic tree, k-means clustering, probabilistic naive Bayes, support vector machines, and additionally community-detection in the later study) were tested. It was seen that the clustering algorithms and probabilistic classifiers yielded the best error rates, although their experimentation was restricted only to their proprietary barcode and scanner conditions. Due to the computational overhead, clustering seems to be the better choice.

The previously introduced subspace-based decoding approach was extended by (Bagherinia and Manduchi, 2014). Instead of assuming a Lambertian reflectance like in the older one, the new algorithm accounts for specular reflections using a dichromatic model. An ideal Lambertian surface reflects the entire incident light equally in all directions and appears uniformly bright regardless of the observer's angle of view as expressed by (Koppal, 2014). Yet again, training for the subspaces was required. Experiments were held, using labels in up to 24 colors, printed by 1 printer, and read by 1 camera only at a constant distance, under different illuminations. It was said that the new algorithm showed substantial improvement compared to their older work.

Although not 3D, a remarkable belief-propagation-based method was used by Kamizuru et al. (2015) for the recognition of distortion and occluded areas, and for identifying barcode lines. Despite its complexity, it overcame highly irregular, non-uniform, and non-periodical distortions better; especially occurring in barcodes printed on paper, cloth, etc.

It was told by Dinesh and Sharma (2016) that modeling the display-capture process enabled development methods for mitigating the impact of cross-channel color interference in a better way. It was also claimed that for their method which was given by Blasinski, Bulan, and Sharma (2013), this type of interference is quite small and can be further reduced via interference estimation and cancellation by using either the synchronization regions or expectation maximization.

Some studies such as Yang et al. (2016, 2018) proposed a layered framework for colored high-capacity QR codes; which adopted a learning-based approach for color recovery and used a geometric transformation algorithm to circumvent the geometric distortion. There addressed also the cross-module color interference in high-density 3D barcodes. It was claimed that the proposed method outperforms the approach offered by Blasinski, Bulan, and Sharma (2013), both in decoding success and bit-error rates.

While some studies attempt to devise novel designs, there are also some researchers trying to reveal and address some specific needs, such as (Feng and Zheng, 2010). Common 2D barcode criteria are mainly designed for alpha-numeric character sets; hence -so it was told- it leads to a low compression ratio for Chinese characters. A 3D design especially for encoding Chinese characters was proposed, based on the usage frequencies.

It has been observed that quite many other attempts of introducing color to the QR Code structure are also available. The basic idea in Multi-Layered QR (MLQR) codes was superimposing different QR codes independently encoded in different color layers (e.g. RGB). Layer colors perceived in the current lighting conditions were to be used first to balance the overall color values through analogous classifier techniques. The application of 64 colors on the QR Code design -with 4 or 8 reference colors- was proposed by (Shimizu et al., 2011). 64 colors were selected by arraying them with equal intervals in the RGB space and then applying a non-linear transformation. Classifiers were trained in several lighting conditions. Among the classifiers tested, it was told that the support-vector-machine algorithm returned the best performance with a 1.17% error rate.

A multi-layer QR code, named Paper Memory (PM) Code, was proposed by Onoda and Miwa (2011) to improve the data capacity through its hierarchical structure design. Also by Memeti et al. (2013), time-dimensional data transfer through sequentially displayed 3D barcodes (of their QR-based design) on the mobile phone screen was tested. In another study, using mutual information theory, an analysis of the channel capacity of traditional QR codes (and its proposed 5-colored version as well) was provided by (Melgar and Santander, 2016). Also, a 9-colored version of it was developed by Melgar et al. (2016), and it was claimed that the tests (with 1 printer and 1 camera) returned reasonable error rates in 7-13 cm reading ranges.

In a more recent work by Pang, Wu, and Long (2017), yet another QR Code-based multilayer 8-colored barcode was designed. Three independent data arrays were encoded in RGB channels using the proposed Byte-Array-Reorder method, adding a header as well as a checksum to data blocks. Also proposed was a blur-aware border methodology, assuming blur is often encountered over the boundaries of changing colored blocks. It was asserted that experiments on Android smartphones yielded reasonable decoding success rates within some reading and viewing angle ranges.

Was also tried by Nandhini (2017) to embed colored QR Codes on logos. Through the above-mentioned logic, the information was encoded in CMY layers first, and the QR Code was produced by superimposing layers. Then blocks of the final QR Code were embedded into blocks of the desired image using Discrete Wavelet Transform and RGB-HSV conversion. Another system that inserts QR information bits into the luminance value of the user-selected image was presented by (Chandran and Sekhar, 2017). Developed visually appealing QR codes with an L-shaped locator pattern and improved decoding stability using the BCH algorithm. However, the decoding performance achieved in the experiments was not clearly stated.

A color selection schema for MLQR codes was proposed by Noppakaew, Khomkuth, and Sriwilas (2018), with a reference palette additionally included in the standard QR Code design. Yet the proposed method (worked on geometric sequencing) seems not to satisfy the farthest-apart color distributions, and thus could not be generalized for the maximum separation of any desired number of colors. They concluded that their use of more than 15 colors could not assure distinguishability.

Yet another QR-compatible code was developed by Melgar and Farias (2019) for 8 different sizes with 5 or 8 colors. They claimed that it was robust to channel and compression degradations, and could provide the highest data density in the tests at distances within 7 to 12cm. In another QR Code design, the display modulation scheme standardized in IEEE 802.15.7-2018 was used by (Nguyen et al., 2020). With this design, data density was enhanced by using edge detection instead of corner pattern detection and RGB colors.

In a similar attempt by Chatterjee et al. (2018), the QR code sections were redesigned. Moreover, they encrypted the data to improve security. Also, Fu et al. (2020) proposed a distributed color QR code embedding secret images or messages into QR codes maintaining its readability by a standard decoder. They applied Shamir's secret sharing algorithm of Shamir (1979) used in cryptography for key management to ensure the security of the secret information. The embedment of sub-secrets in the red, green, and blue channels was controlled through threshold setting and analyzed the influence of threshold values on the reading performance.

The use of a lookup table was introduced for multiplexing data into colors so that a single colored QR code was generated by Galiyawala and Pandya (2014), epitomizing several message chunks. Yet in a recent study by El-Sheref, El-Licy, and Asad (2020), instead of the lookup table of Galiyawala and Pandya (2014), another multiplexing technique that maps equidistance color shades for encoding was offered. It was claimed that their technique considerably improves the processing time. In the design presented by Wu and Wu (2020), a method of altering the module sizes of the QR code was applied to serve the covert insertion of facial data. Although not utilize colors, also it can be referred to as a 3D application, considering the use of symbol shapes of different sizes. The use of a 3D barcode was presented also by Querini and Italiano (2012) to store biometric data, in particular for facial recognition, secured through digital signature algorithms. They combined local feature descriptors such as SURF, together with shape landmarks.

Huang, Cao, and Li (2022) proposed a novel composite 3D QR code (MC2D) combining color coding and multiplexing technology. The public identification data was presented as plain code and the secret data (such as authentication or blockchain information) was concealed as hidden code. The distinction between plain and hidden codes was realized by optical filtering. They claimed that the tests showed better reading performances than other comparable states of the art and users can obtain plain and hidden information without special equipment.

Taking the QR code as one possible solution for a direct link between the TV picture and smart devices, Trpovski (2017) offered several geometric and color modifications, and partial transparency, to increase the aesthetical acceptancy of the QR code while decodability is fully maintained. Proposed and analyzed modifications were on a) module shapes, b) image square shapes, c) black and white contrast, d) transparency, and e) combinations of them. Although was not specifically for it, it applies also to 3-D.

Besides the QR codes, on the other hand, coloring some other self-proven 2D structures were also studied to a limited extent. For instance, the DataMatrix structure was exploited by Bogataj et al. (2010) for applying colors. 4 colors were applied, yet only the readability was inspected (i.e. 2D encoded). (Also Dragicevic et al. (2017) inspected the readability of dot-peen-marking of DataMatrix on products.)

Although the majority of the designs prefer rectangular forms, there are 'circular' barcode symbologies, such as ShotCode created by Cambridge University, UK (URL-6), or SpotCode (Scott et al, 2005). An earlier one with a 'bull's-eye' shape was the TRIP Code, which is mainly for applications such as tracking the real-time location of moving targets (López-de-Ipiña, Mendonça, and Hopper, 2002). Although they generally suffer lower areal information density, it is also suggested that circular designs have a greater strength against geometric distortions in 2/3D barcodes (Yi, Zhai, and Zhu, 2019).

It was tried to adopt color-coding by Yi, Zhai, and Zhu (2019) also into circular 2D barcodes. They proposed a new decoding method, besides two new measures (maximum distortion ratio and maximum support opening angle) of geometric distortion. Also in this study, discussions on modeling the barrel (radially moving of points away from the center of the image as a result of the reduction in the lens magnification by the axis) and the sphere (caused by the irregularities of the printed surface) type distortions can be found.

It should be noted that the techniques used to remedy the geometric interference effects in 2D barcodes are fairly applicable to color barcodes as well. Employing finder patterns, borders, alignment lines, segmentation, or the like successfully serves this purpose. There are several method proposals in this regard, such as (Bulan, Sharma, and Monga, 2010; Nakamura, Kawasaki, H., and Ono, 2015, 2016; Tribak and Zaz, 2017). As such, Tan et al. (2012) designed a finder with an L-shaped guide bar and checker borders, that also include reference color cells to save the data capacity. They also used borders between adjacent cells and their tests indicated that a white border is better than a black one.

An experimental study of some known color classifier algorithms was provided by Firmani, Italiano, and Querini (2014) to identify the most promising approaches to decoding color barcodes, especially in mobile scenarios. They also proposed a new decoding algorithm based on force-directed graph methods. Experiments showed that more complex methods were more efficient in terms of accuracy, but involved higher computational costs, so not practical on low-end platforms.

A novel data coding scheme worth mentioning was proposed by (Zeng and Chang, 2015). Using the color intersection coding (CIC), four sub-pixels were generated, as their average color to represent a target pixel and encode 1-bit data. During decoding, the hidden data was estimated through the average colors of non-overlapping blocks of the image. The color intersection of four adjacent blocks was realized by referring to additive color mixing. Although data was encoded in generic images, the CIC scheme can be also applied to barcodes, as it was in the experiments.

There are also different approaches to the use of colors in barcodes. A quite inventive was presented by (Li and Chen, 2014). Instead of constant, their barcode (D&S) is to be printed with environmentally sensible material so that it can monitor information about the environmental state (e.g. temperature) via a change of colors.

Another use of 3D barcodes was proposed by Pei, Li, and Wu (2008) suitable for storing continuous data such as movies, music, voice, etc. It (Continuous Color Barcode) offered 'motional' scanning, instead of stationary. They developed prototype decoder hardware and encoded voice binary data as an example. The claimed decoding success rate in tests was 92% for 4-colored and 75% for 8-colored versions.

Analogous to this, progressive barcodes as incremental information objects were studied by Vans, Simske, and Loucks (2012, 2013), and their possible applications by (Simske and Vans, 2014). The principal was to print successive barcodes on the same location over time. In this way transferring the progressive information through time was aimed.

Visual (or visible) light communication (VLC) is one kindred application to mention, in which light sources are modulated with a digital signal in a way that the data is printed into on-screen barcodes (mostly 2D or 3D), and captured and decoded by camera-equipped devices including mobile phones. Such types of applications provide an easy-to-use contactless communications interface without dependence on additional wireless or internet infrastructure.

A VLC method was proposed by Hao, Zhou, and Xing (2012) for real-time data transfer between smartphones via 5-colored barcodes. To mitigate the impact of the blur, adaptive configuration and blur-aware color ordering were implemented. Adaptively changing the size and layout of code blocks, data was encoded and displayed on the screen at a certain frequency, then read and decoded by the receiver phone. In the experiments held under various environmental conditions, it was claimed that 64% to 98% of total frames were successfully decoded.

One matter to deal with peculiar to VLC applications is frame synchronization between the display and camera. This means, that reducing the display rate of the screen to avoid losing frames was discussed by (Hu, Gu, and Pu, 2013). To better exploit the transmission capacity, they proposed the use of an in-frame color tracking and linear erasure coding method that would recover lost frames. They asserted higher decoding performances on 2D barcodes. Again to recover lost frames, a three-layered error correction was stated by (Wang et al., 2014). Focusing essentially on improving transmission reliability, they reported an error rate of 10%.

However, in a later study by Wang et al. (2015), it was pointed out that the cost of such excessive coding could be a reduction in average communication throughput. They further noted that also the method by Hao, Zhou and Xing (2012) underutilized the transmitter's capability, and could not accurately localize some code blocks; thus proposed such solutions as flexible frame synchronization and a progressive detection/localization scheme. It was claimed over the experiments that higher communication throughputs, as well as faster and more accurate decoding rates, were reached at longer distances.

Zhou et al. (2018) introduced a feedback mechanism via imperceptible acoustic signals for the synchronization challenge. Mainly associated with the work by Wang et al. (2015), it was claimed that their new design provides the first feasible feedback mechanism, with the full guarantee of reliability and capacity under different communication qualities. The design was also compared with the work introduced by Hao, Zhou, and Xing (2012), and other compatibles.

The VLC method proposed by Jung et al. (2020) also transmits the information encoded in color barcodes in a format invisible to humans. They also included pilot symbols in transmission packets to help sending-receiving color synchronization.

The recent study by Zhao and Li (2020) rather focused on security issues, more specifically to prevent the 'eavesdropping' threat in VLC. Based on the determination that color deviation is related to the angle and distance between the transmitter and the receiver, they experimentally depicted the stable reading boundary for a legal receiver. They tested the decodability beyond this certain range. To enhance security they also applied encryption through hashed keys. Possible jamming attacks through visible light weren't considered, assuming that they could be easily detected. It was claimed that in experiments their unidirectional scheme granted higher security prevention against illegal intruders, and also achieved a communication efficiency comparable to the others.

As a different application, another recent study by Rani and Deep (2017) offered the use of 3D barcodes in steganography. In the proposed scheme, the secret image was encoded via the XOR encryption, and embedded using the Least Significant Bit method. Then the message was printed as a colored QR barcode.

A further interesting application proposal to note is the acoustic barcodes by (Harrison, Xiao, and Hudson, 2012). Somehow structured patterns of physical notches there produced a complex sound when swiped with a fingernail, etc., and captured with the help of a contact microphone attached to the surface. Then that sound was resolved into a binary ID, which could be used for information retrieval or to trigger some interactive functions. Another one worth examining is the Bokode developed by MIT Media Lab (Mohan et al., 2009). It consists of a circular data tag of about 3 mm, a photomask-covered LED, a lens, and a tiled series of DataMatrix codes readable from different angles up to 4 meters. It claimed to hold much more information over the same area than a regular barcode. Powered Bokodes are relatively expensive.

Also, a method was developed by Yang et al. (2019) for carving a QR code on a surface, with minimum visual and decoding loss. Although called it 3DQR Code, it was mainly for artistic purposes, far from what is meant here by 3D.

ColorCode was introduced as a color-based configurable image code that can present a visual automatic identification interface for mobile environments (Cheong et al., 2006a). Over it, the patented Mixed Code tried a novel approach to comprise more than one type of barcode or symbol through colors (Cheong et al., 2006b). Later Chae et al. (2016), also applied ColorCode to their marker-based augmented reality system, with improvements using a new tracking technique for various angles and distances.

There are as well a couple of works that can be considered 4D barcode design attempts. For instance, besides colors, the orientation of dots was also to be used for data encoding in the aforementioned design by (Bulan, Monga, and Sharma, 2009). Another one by Braginsky (1999) offered using background frame regions of specific shapes and marks printed on them in colors different than the background. Han et al. (2006) patented a machine-readable code using different symbol patterns, printed in four different colors (YGRK) or shades, to encode data. Another 4D symbology design trial was of Look (2008) which exploited plural characteristic features such as colors, grey scales, cell shapes, patterns within a cell, or groupings in combination. Also, the use of colored elliptical dot array orientations was proposed in the above-mentioned by (Bulan and Sharma, 2011). Yet another one by Tian (2015) tried to employ a plurality of combinations of various colors and shapes for encoding.

In some of the VLC works like advertisement presentations or movie sequences, even data is split and embedded as smaller chunks and then extracted from the barcode series taken sequence, based on the cross-correlation of the inter-frames. Thus the '4D' acronym was suggested also for such implementations as the 4th dimension associated with time-multiplexing. Such an unsynchronized optical 4D-VLC technique was presented by (Langlotz and Bimber2007). Also, the study by Memeti et al. (2013) was a similar trial to see.

When the display rate is close to the camera capture rate, VLC systems suffer from both CMOS rolling shutter and inter-frame mixing problems. Wang, Han, and Wang (2020) proposed a system called FareQR that adds an outline border to the barcode stream to help the receiver detect mixed frames, using a Viterbi algorithm to resolve each block in the mixed areas were realigned the unmixed QRcode into the correct position. Tests showed that the block transfer error rate i.e. the percentage of error blocks in one QRcode was reduced.

The primary causes of errors in camera-display communication applications with color barcodes are path loss and synchronization, especially in unidirectional communication scenarios. To address these challenges, Bufalino et al. (2020) introduced an adaptive framework, named Medium-Aware Mobile Barcode Adaptation (MAMBA). MAMBA leveraged bi-directional communication by dynamic adaptation of both frame rate and length based on environmental conditions and processing capabilities. It consisted of a 5 colored custom barcode including corner trackers to extract the metadata and scaled with the number of blocks in the barcode, rather than with the number of pixels in the captured image. They claimed that such an approach overcomes message loss.

Another 4D VLC system offered by Chen et al. (2018) formulated the color recognition problem as a machine learning task, using reference colors and a semi-supervised color clustering algorithm.

As mentioned, some works use inter-frame pixel change to modulate data. Such video-based extraction suffers a high processing cost. However, invisible barcodes were embedded into color images by Cui et al. (2019), and the data were extracted based on the cross-component correlation of the on-screen content, in CIE XYZ space. It was claimed that the experiments under the various screen and camera settings showed up to 2.5 kbit capacity with less than a 5% error rate.

The selected typical studies mentioned here broadly portray the state of the art. The extended analysis presented below is to provide a better conception.

3. Analysis and Results

For imminent or consecutive studies in analogous titles, only key works were covered in the analysis; i.e. the proffered statistics subsume a total of 281 selected works (including the ones mentioned in the previous chapter) as reports, technical/white papers, dissertations, magazine or web articles, journal articles, and patents. Although hardware implementations of proposed symbologies or solutions were also incorporated in various patent applications, hardware studies are not comprised in the analysis. Also, the common issues reported and best practices were identified from the reviews.

The change in the number of works (between 1991 and 2022) is as can be seen in Fig. 6., with some of the milestones shown in the timeline. (Please note that only the selected works considered pivotal were included.)

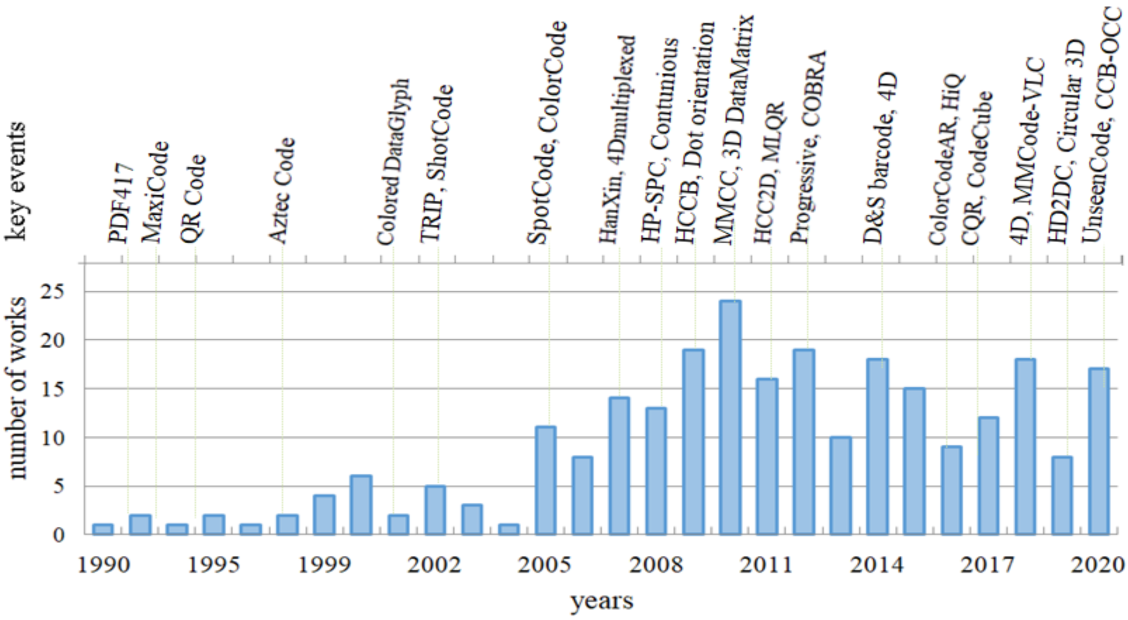

Figure 6. Change in the number of assessed specific works by years.

It can be interpreted as, although the attempts to introduce colors to barcodes were initiated quite earlier (in the late 1960s), noteworthy practices could be achieved as the related printing and image-capturing technologies evolved to a certain level, thus the research gained momentum in the 2000s. The field got the peak attention around the years MS-HCCB was introduced. Afterward, as the emerged complications were experienced in practice, the studies maintain a steady trend level.

Many of the works may pertain to more than the titles inscribed above. The clustered view and the percentages of the analyzed studies by the research areas are observed as seen in Fig. 7.

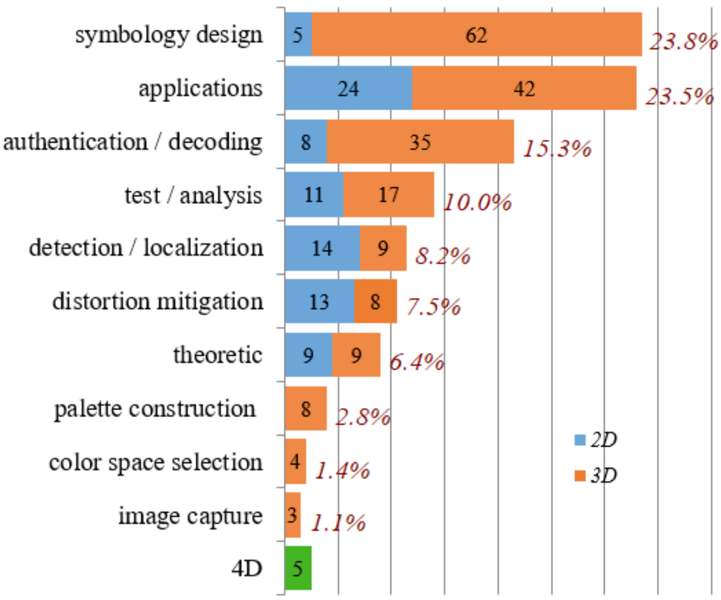

Figure 7. Clustered number of studies and percentages by research areas.

Here seen, studies focusing on the design of novel 3D symbologies hold the biggest share. Together with the ones on application possibilities, research in these two titles constitutes almost half of the current works. Besides, in more than half of the proposed symbology designs the QR Code was taken as the basis. In particular, the finder pattern structure was mostly used as-is. Additionally, VLC implementations constitute about 26% of the work on application possibilities. While studies on issues such as symbol entropy, distortion metrics, algorithm complexities, channel models, and the like represent 50% of the theoretical research; the rest was related to topics such as the effect of the selected error detection/correction coding schema, the contribution of data compression to channel capacity, or such.

As the figure suggests, some of the research on 2D barcodes can provide appraisals valid for 3D as well. Additionally, there exist also a few works towards 4D implementations in the forms of color and shape use, time multiplexing, or progressive barcodes.

Conducted tests demonstrated that printed color barcodes are more resolvable in scanner-type sheltered environments rather than capturing at a distance using cameras. (The reader resolution imposes the readable symbol size limit. If for example, the size of a symbol printed with a resolution-competent printer is 0,2mm, then a scanner resolution smaller than 0,2mm is needed.) Accordingly, applications that are out of the influence of some interference sources due to their features yield better results. Two application areas below come to the fore as best practices.

Document processing: It refers to transferring documents via 3D barcodes with higher throughputs, and even serving security/authentication needs as well. Document authentication involves verification of authenticity through 3D security barcodes printed with the document.

A symbol of an 8 colors symbology can be represented by 3 bits, thus 3 symbols can digitally encode 2 characters of 2^8 bits. Even considering the variable overhead imposed by the symbology in use, it indicates at least 1.5 times higher information density. When a character is printed on the screen using a human-readable standard font in 6*8 pixels, and the minimum barcode module (i.e. symbol) size is 4*4 pixels, the 2 times increase in the throughput justifies the computational burden to occur. Gain is similar for printed material too. Besides the spatial gain, printed 3D barcodes are better machine-readable than OCR-type character recognition.

Another point to make is that the accompanying barcode can be examined whether it matches a predetermined identifier or a hash code produced from the printed content. This as well gives us the ability to link the document (be it a ticket or the like) only to authorized personnel, by embedding a ciphered password in both the barcode and reading software.

Reading documents with a scanner will considerably prevent ambient interference. Document processing through 3D barcodes can be quite suitable, especially for applications that require security control, as requiring no additional hardware, nor access to an external authentication source on a network.

VLC: It represents transferring data from screen to camera (such as smartphones) via 3D barcode sequences. Because of its transfer structure, it is not subject to print distortion. Also, the influence of some interference like ambient light or shades can be assumed relatively low.

It requires no additional hardware or any network infrastructure. Besides, the short visible range provides good control over security. VLC can also be used as time multiplexing to transfer sequenced information, as suggested in progressive barcode practices.

On the other hand, it brings in some additional concerns to deal with, such as frame synchronization, progressive code detection, or tuning the display-capture rates.

Briefly, 3D barcode-based VLC applications can provide a more secure, easy-to-use short-range wireless communication link without the need for a network infrastructure.

Based on the analysis made, some of the issues that appear scarce or require further research are also remarked on in the conclusion section below.

Conclusions

In the designs reviewed, it was reported that the maximum achieved information density was around 16000 bpi, and reading accuracy of more than 80% was tested. However, an adverse observation is that the details of the tests conducted within the artifacts were often not supplied with certainty. It is therefore hard to assume that the validity of the reported performance values is satisfactory to reliably articulate the limits technology has reached. Hence, comparative assessments of compliant studies would not be plausible unless the practical boundaries are established, which are closely related to the development of the related technologies.

It would not be reasonable to suppose 3D barcodes are to replace existing 2D implementations such as QR codes. As being based on only light and dark colors, 2D Barcodes have far better discriminability. It can be propounded from the observations that color barcodes can be authenticated more reliably in relatively protective reading environments. Consequently, applications such as VLC and document processing that exclude some of the interference resemble more effective.

Except for the ones designed for specific uses (like circular barcodes), the principal purpose is to increase the information density. Yet the increment is up to the limit not imperiling to maintain the decoding performance acceptable by the appertaining application. As long as the application requirements are satisfied, 3D barcodes excel the 2D practices in terms of information density, and RFID in terms of costs.

The analysis reveals that there is a significant amount of work that attempts to design a variety of 3D barcodes, probably with the motivation to increase the information density by adding colors. Moreover, several of them are founded on the base QR Code structure. Since each proposal was ultimately evaluated based on the attained decoding accuracy compared to the others, the literature especially focusing on improving the color authentication performances is very rich as well. In parallel, a deal of studies has turned to testing, evaluation, and comparison of designs and methods. In the context of applications, VLC, as well as document processing seem to retain the most interest, yet application opportunities could be further enriched.

On the contrary, it was observed that research dealing with certain issues marked below seems scarce.

- A distinct need to identify the optimal color space specifically for color barcodes stands out. Authentication methods relying on parametric techniques are more likely to get affected by the selection of the operational color space, compared to the non-parametric i.e. histogram-based, or the like relative representations. The choice of color space though may not always be a matter of preference, because of the factors like available image format, or the possible requirements imposed by the preprocessing operations. Deciding the most robust color space against various ambient conditions remains a call to research.

- The readability of image capturing and storing formats is yet another issue that requires elaborating further. Similarly, possible readability enhancements over the current JPEG format stand likely to bring along valuable advancements.
- The importance of color selection was emphasized in several studies. Nonetheless, it can be noticed that there exist very few studies on this issue in particular. The rare ones abovementioned are also, mostly suboptimal, or specific rather than generic to provide a consistent methodology for robust pallet construction. Moreover, comprehensive system proposals for evaluating and comparing palettes are exceptional.
- The selection of the colors, as well as the decoding approach, should be closely related to the estimated characteristics of the factual distortion. Exclusive studies to inspect the expected distortion would be fruitful in this sense.
- A limited number of researchers have focused on symbol forms. Most designs used square-shaped tiles, while some preferred circle or dot symbols instead. Further research appears needed also on the geometry of the symbols to increase the areal intensity and distortion robustness of the printed information.
- It was evidenced that including the reference palette pays the cost of sacrificing some of the information density back, by the decoding consistency it contributes. However, investigating the optimum number and selection of reference colors could be encouraged.

In addition to the current praiseworthy efforts in the field, research especially on the issues highlighted above deserves to be promoted in particular. Besides all, as expressed also above, a description of the proper testing conditions (in terms of the relevant constituents such as the reading environment and distance, minimum symbol size, and the like) consistent with the practical limits is needed to plausibly evaluate comparable studies.

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