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Comparing the error-correction capabilities of different 2D barcodes in industrial environments

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***Abstract*—This paper describes a test-environment that has been developed in order to compare different variants of 2D barcodes in industrial environments. The main focus is thereby on ensuring that only the error-correction capabilities of the evaluated 2D barcodes are compared and thus a fair comparison is enabled. This is obtained by eliminating all circumstances that cause unequal conditions. As an example a comparison of a Data Matrix code (DMC) with a new variant of 2D barcodes based on low-density parity-check (LDPC) codes is carried out by means of the developed test-environment.**

I. Introduction

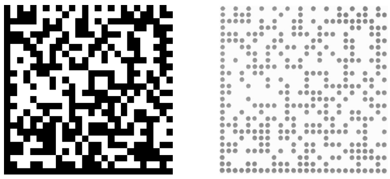
2D barcodes are more and more common in our daily life. Especially the industry takes advantage of the possibility to track parts throughout their entire life cycle based on 2D barcodes. Considering the application of 2D barcodes in industrial applications, the parts are often directly marked with the codes which is then called *direct part mark identification* (DPMI). In our application the target was to design a new class of 2D barcodes that is more robust compared to the 2D barcodes used so far in DPMI applications. As soon as the first version of a new 2D barcode had been developed, the question arose how to evaluate a 2D barcode in industrial applications. For that reason we developed a test environment that enables one to compare different versions of 2D barcodes considering DPMI applications.

II. 2D barcodes in industrial environments

Two of the most important types of 2D barcodes are the Quick Response (QR) code [1] and the Data Matrix code (DMC) [2], where the latter is the most commonly used in DPMI applications. The DMC consists of a finder pattern and a data region. Based on the L-shaped solid border and the broken border, the finder pattern helps in locating the 2D barcode and to determine its size. For more details about how to locate a DMC in industrial environments the reader is referred to [3]. The data region is surrounded by the finder pattern and keeps the actual information.

In lots of applications, the 2D barcodes are printed in black on a white even surface so that a binary one and a binary zero are represented by a black square and a white square, respectively. Based on a picture taken of the 2D barcode, the decoding is then conducted by means of an edge-detection algorithm as described in [2].

When it comes to DPMI applications, the appearance of the 2D barcode's modules is quite different. This is due to the fact, that the codes are embossed on various kinds of material by means of different marking methods like laser etching, dot peening and milling. In the case of dot peening and milling, the binary ones and binary zeros are represented by round cavities and the untouched material, respectively. Considering the acquisition, the illumination setting is adjusted to the surface of the material and the cavities that represent the 2D barcode. The sizes and the gray-values of the round modules thereby depend on various parameters like the camera and its setting, the illumination setting, the texture of the cavities and so on. Figure 1 shows a picture of a printed DMC and a picture captured of a DMC milled into plastic.



(a) DMC printed on paper (b) DMC milled in plastic

Fig. 1. The same DMC printed on paper and milled in plastic.

Due to the different appearance of 2D barcodes in DPMI applications, the edge-detection algorithm of [2] is not suitable to decide whether a module of a 2D barcode-picture represents a binary one or a binary zero. In addition our new class of 2D barcodes is based on low-density parity-check (LDPC) codes [4]

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$$y_{rc} = \frac{\sum_{k=0}^{K-1} \sum_{l=0}^{L-1} (a_{kl}^{rc} - \bar{a}^{rc})(b_{kl} - \bar{b})}{\sqrt{\sum_{k=0}^{K-1} \sum_{l=0}^{L-1} (a_{kl}^{rc} - \bar{a}^{rc})^2 \sum_{k=0}^{K-1} \sum_{l=0}^{L-1} (b_{kl} - \bar{b})^2}} \tag{1}$$

that require soft-decisions (SDs) as an input, i.e. the probabilities for the modules to represent a binary zero or one. For the computation of these SDs a correlation coefficient y_{rc} is computed for each module in row r and column c of the 2D barcode according to Equation (1). k and l are thereby the indices for the K vertical and L horizontal pixels in each module, respectively. Considering one module in row r and column c, a_{kl}^{rc} denotes one pixel in row k and column l of the module. $\bar{a}^{rc}$ is the mean of all pixels a_{kl}^{rc} of a module in row r and column c. b_{kl} is a pixel in the *reference module* which is generated based on an averaging of all modules that belong to the 2D barcode's finder pattern and represent a binary one. $\bar{b}$ is the mean of the reference module. More details about how to compute the soft-decisions based on the correlation coefficients is given in [5].

A correlation coefficient y_{rc} then represents the received value at the end of a channel referring to the sent value x_{rc} stored in the shape of a module in row r and column c of the 2D barcode's data region .

Another important point that has to be considered when evaluating 2D barcodes in industrial environments is the possibility of damages that may occur. Typical interferences like blobs, scratches, dirt, rust etc. change the appearance of the 2D barcode's modules, and further impair the conditions for a successful decoding.

III. Enabling a fair comparison

The main focus of this work was to develop a test-environment that provides fair conditions considering a comparison of different types of 2D barcodes in industrial environments. The developed test-environment is explained in the following based on a comparison of a DMC and a new 2D barcode that we developed based on a regular LDPC code.

A. Code rate

One significant advantage that 2D barcodes have compared to their 1D predecessors is the capability of correcting a certain amount of errors. This is possible due to a channel-code by which redundancy is added in a certain manner to the information that is stored inside of the 2D barcode. k is the number of bits in the digital information to which m bits of redundant information are added which results in a codeword of length n. The code rate of the applied channel-code is then

$$r = \frac{k}{n} \tag{2}$$

One prerequisite when comparing the error-correction capabilities of different 2D barcode variants is to use the same code rate for the utilized channel-codes. In our comparison for example the code rate of the Reed-Solomon (RS) code was given in the standard [2]. According to the DMC-size of 26×26 modules that we utilized, the code rate was $r = 0.61$. For the LDPC-based 2D barcode we then used the same size of 26×26 modules and for the applied LDPC code the same code rate of $r = 0.61$.

B. Simulations

1) Picture simulation: Instead of comparing the decoding performance of different 2D barcodes based on *real* pictures taken of the 2D barcodes, we developed a simulation that enables one to generate 2D barcode-pictures. The picture generation is based on the components of a DMC, the finder pattern and the data region. Since this structure is also used in the case of our new 2D barcode version, the generation of a 2D barcode picture is the same considering a DMC and our LDPC-based 2D barcode.

A simulated picture is obtained by taking a real picture of a 2D barcode apart into disjointed single modules. This is done in a row by row manner where the one-modules and the zero-modules of the data region are separated and stored in two pools, respectively. The finder pattern of the 2D barcode's picture is kept as is. A simulated picture is then created based on a binary matrix that describes the 2D barcode. The stored finder pattern forms the frame for the simulated picture. Then in a row by row manner again, a one-module or a zero-module is taken out of the appropriate pool, depending on the entry in the matrix. So the simulated pictures of different 2D barcodes show as similar an outer appearance as possible since the finder pattern is exactly the same and the modules stem from the same pools. Hence possible variances that occur due to the embossing and the acquisition and that are caused by the illumination, the material and the milling are eliminated.

2) Damage simulation: In a next step damages that are typical in industrial environments are added to the 2D barcodes. This is also done based on a simulation which enables one to affect different 2D barcode-pictures by identical damages. Furthermore it is possible to get a sufficiently high statistic which would not be the case when manually damaging the codes. We developed a simulation of two typical interference types in DPMI applications, namely water drops and oil drops. These simulated damage patterns can then be added free-scalable to a desired location on the simulated 2D barcode pictures.

Table I shows simulated pictures of a RS-based DMC and a LDPC-based 2D barcode milled into different materials. In addition simulated water drops

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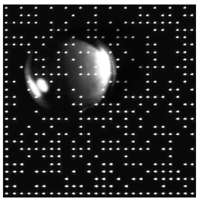
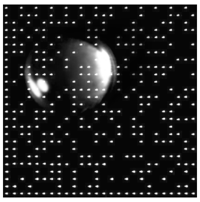
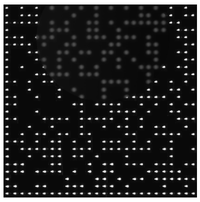
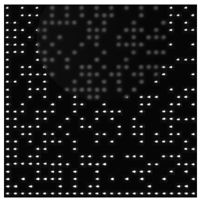
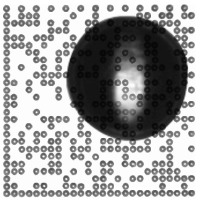
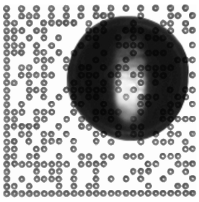
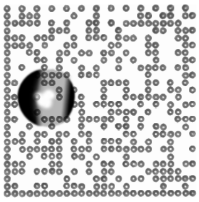
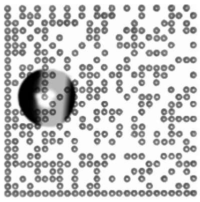
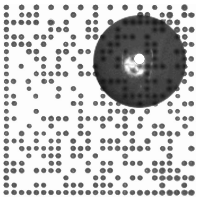
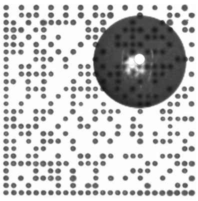
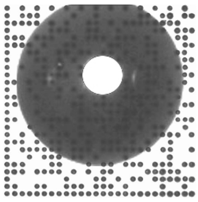
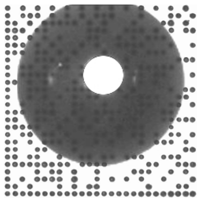
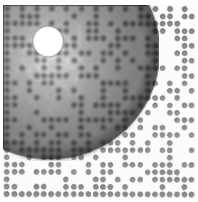
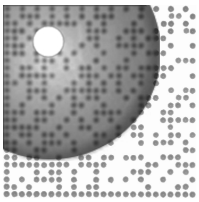
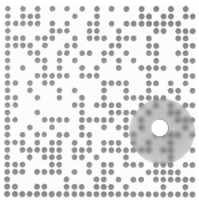
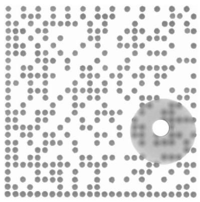
Material	Water drops		Oil drops	
	LDPC	RS	LDPC	RS
Brass				
Alu				
Plastic gray				
Plastic yellow				

TABLE I
EXAMPLES FOR SIMULATED PICTURES WITH ADDED DAMAGE SIMULATIONS.

and oil drops are added to the pictures that are exactly the same for the two different 2D barcode variants.

C. Pre-decoding bit errors

After the damage-simulations have been added to the simulated 2D barcode-pictures, the correlation coefficients are computed based on Equation 1. Then the soft-decisions are calculated and passed to the appropriate decoders. Based on the soft-decisions, a decision is made for a module to be a zero or a one in the case of the DMC since contrary to the LDPC decoder, the utilized RS decoder operates based on so called hard-decisions. Even though the LDPC decoder operates based on soft-decisions, we compute hard-decisions in the case of the new 2D barcode as well. The reason for that is the ability of measuring how much a damage-simulation affected a 2D barcode-picture based on the pre-decoding bit errors. These bit errors can be computed by comparing the hard-decisions, made before the actual decoding is conducted, with the code word that has been stored inside of the 2D barcode. The decoding results are then compared based on the pre-decoding bit errors which offers two main advantages:

1) All circumstances that cause unequal conditions when comparing different types of 2D barcodes are eliminated.
2) The frequency distribution of the pre-decoding bit errors is considered.

This makes only sense if a sufficiently high statistic is made. For our evaluation we generated four pictures for each analyzed 2D barcode referring to the materials brass, aluminum, gray plastic and yellow plastic. Then we added 20000 different oil drop simulations and 20000 water drop simulations to each of these pictures. It was thereby ensured that the damage-simulations have been exactly the same considering the different barcode variants.

Due to the characteristic of the semi-automated test-environment, the probability that the 2D barcodes were affected by only a few pre-decoding bit errors is very high compared to cases with more bit errors. Thus a 2D barcode variant that would have a decoding advantage only for more pre-decoding bit errors would be disadvantaged by not considering the frequency distribution of the pre-decoding bit errors.

Furthermore the same damage pattern added to different types of 2D barcodes that store the same information, often yields a different number of pre-decoding bit errors. This is due to the different arrange-

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ment of one-modules and zero-modules. This fact can result in a different pre-decoding bit error frequency distribution of the evaluated 2D barcodes.

Both problems described above can be seen in Figure 2, where the number of decodings are plotted over the pre-decoding bit errors considering a comparison of the DMC with the new LDPC-based 2D barcode. It can be seen that way more decodings have been influenced by only a few pre-decoding bit errors compared to the case where lots of pre-decoding bit errors complicated the decoding. It can also be seen that the decoder of the LDPC-based 2D barcode had to face much more cases with more than 170 pre-decoding bit errors than the RS-decoder of the DMC.

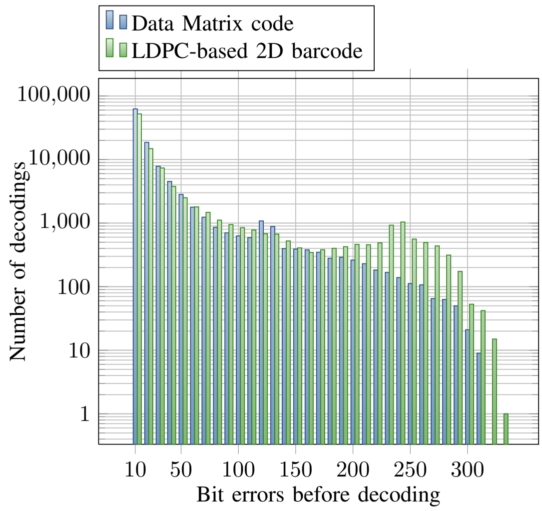

Fig. 2. Total numbers of decodings plotted over pre-decoding bit errors for a 2D barcode based on a regular LDPC code and the DMC, respectively.

If one wants to provide fair conditions for a comparison of different 2D barcode variants, it is necessary to consider the frequency distribution of the pre-decoding bit errors when evaluating the error-correction capabilities of the barcodes.

IV. Results

The following results are based on the developed test-environment that is explained above. The decoding results of the standard up to now in DPMI applications, the RS-based DMC, is thereby compared with the new developed LDPC-based 2D barcode.

A. Simple comparison

In this first step a simple comparison is shown in Table II where the decoding successes are listed depending on the material and the applied drop-simulation. It is very important to mention that in this type of comparison the frequency distribution of the pre-decoding bit errors is not considered.

Following from the results in Table II, the overall performance of the LDPC-based 2D barcode beats the DMC by 10%.

			RS-based DMC		LDPC-based 2D barcode	
Material	Damage	Decodings	OK	%	OK	%
Brass	Water	9460	8819	93	9298	98
Alu	Water	18568	12579	68	17734	96
	Oil	15614	10876	70	12081	77
	Total	34182	23455	69	29815	87
Plastic gray	Water	17721	15192	86	16717	94
	Oil	15869	10351	65	12419	78
	Total	33590	25543	76	29136	87
Plastic yellow	Water	16008	15318	96	15169	95
	Oil	14421	9779	68	10061	70
	Total	30429	25097	82	25230	83
Total	Water	61757	51908	84	58918	95
	Oil	45904	31006	68	34561	75
	Total	107661	82914	77	93479	87

TABLE II
DECODING SUCCESSES FOR A LDPC-BASED 2D BARCODE AND A DMC, RESPECTIVELY.

B. Comparison based on pre-decoding bit errors

The next comparison is based on the same simulations that the results in Table II are based on. In contrast to the latter, the results in Figure 3 consider the frequency distribution of the pre-decoding bit errors by plotting the decoding successes over the pre-decoding bit errors.

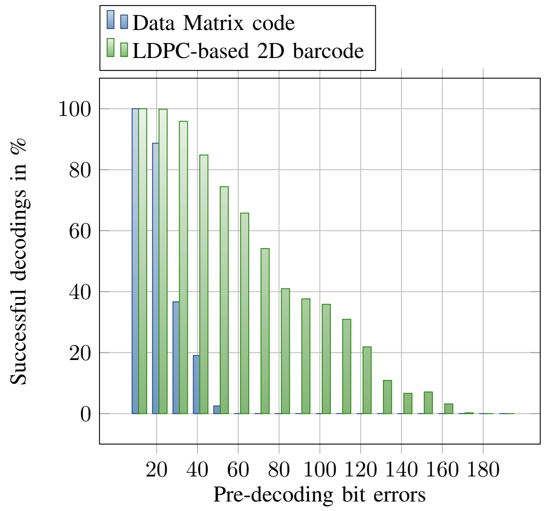

Fig. 3. Decoding successes plotted over pre-decoding bit errors for a LDPC-based 2D barcode and a DMC, respectively.

The view that Figure 3 provides on the comparison results reveals the advantage that the LDPC-based 2D barcode offers compared to the standard DMC in the cases where more then just a few pre-decoding bit errors occur. For up to 10 pre-decoding bit errors, the decoding performance of the two barcode-versions are equal. But if the damage-simulations result in more pre-decoding bit errors, the new 2D barcode clearly beats the DMC.

Figure 4 shows the gain in % that is obtained by using the LDPC-based 2D barcode instead of the DMC. It can be seen that in average a gain of 30.8%

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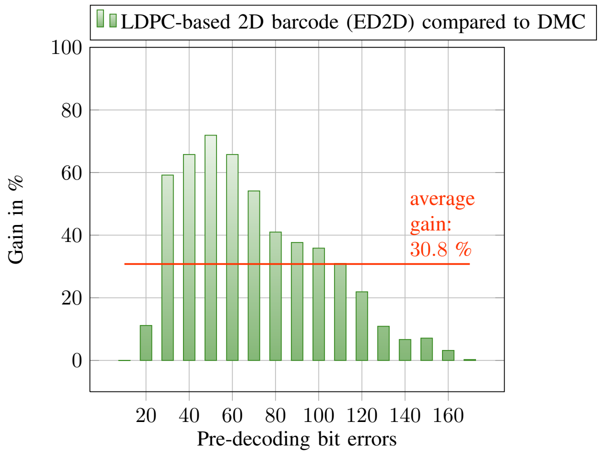

Fig. 4. Gain obtained when using the LDPC-based 2D barcode instead of the standard DMC.

is obtained.

When comparing the results in Figure 4 (30.8% of gain) with the results in Table II (10% of gain) one can see that there is a huge difference considering the average gain. This is due to the misinterpretation of the decoding results in Table II due to the non-observance of the pre-decoding bit error's frequency distribution.

V. Conclusion

This paper offers a method of evaluating 2D barcodes in industrial environments. A test-environment has been developed that provides a fair comparison of different variants of 2D barcodes. This is mainly obtained by the following features:

1) the code rate of the applied channel-codes is chosen to be the same.
2) the decoding is done based on simulated 2D-barcode pictures.
3) damage-patterns that are typical in industrial environments are simulated and added to the generated pictures.
4) the decoding results are compared based on the pre-decoding bit errors.

These points ensure that all circumstances that cause unequal conditions when comparing different types of 2D barcodes are eliminated. Thus only the error-correction capabilities of the evaluated 2D barcodes are compared without the influence of any side effects. Furthermore the developed test-environment delivers the basis for a sufficiently high statistic.

Acknowledgment

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