Summary

In the following, a summary is given for each chapter of the doctoral thesis with the title *Design of robust 2D barcodes for industrial environments.*

1 Introduction

After some barcode history, the motivation for this work is explained.

When considering 2D barcode systems in industrial environments, it is important to direct one's attention to the appearance of a 2D barcode's modules. When a Data Matrix code (DMC), for example, is printed in black on a white surface, each module is represented by a black or a white square referring to a binary one and a binary zero, respectively. This represents the usual case as described in the appropriate standard.

However, in the case of direct part mark identification (DPMI) applications, the modules are not printed but instead milled, laser etched or dot peened on various kinds of material. Before the actual decoding can be proceeded, an acquisition of the 2D barcode has to be done. Therefore, a picture is taken in an illumination setting that is adjusted to the surface of the material and the cavities that represent the 2D barcode. In the case of dot peening or milling, the black squares then turn into shapes similar to circles. 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. In addition, the white squares, that stand for a binary zero, are now represented by the untouched material, that is not necessarily white anymore as in the printed case.

This means that a picture of a 2D barcode looks quite different in the case of DPMI applications compared to the standard case that is characterized by modules depicted by black or white squares. This mainly affects the following points:

1. The localization of the 2D barcode.
2. The image processing.
3. The error-correction.

The localization of a 2D barcode is much more challenging in the case of DPMI applications, since the edge-detection algorithms given in the standard do not work anymore. This is due to the round shape of the one-modules that do not form detectable edges.

The image processing part, which is responsible for delivering binary information to the following decoder depending on the modules values, suffers from the same issue. It is not possible to decide if a module represents a binary one or a binary zero by means of the provided edge-detection algorithm.

This yields a greater demand on the error-correction capabilities of a 2D barcode, since it is more likely that errors occur due to the increased challenge for the localization and image processing.

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

The target of this thesis is to design a robust 2D barcode, in order to overcome the unfavorable conditions that a barcode system has to face in DPMI applications.

2 Barcodes

This chapter offers a brief overview of 1D barcodes and 2D barcodes. Typical applications are explained with a focus on 2D barcodes utilized in industrial environments. One 2D barcode called Data Matrix code (DMC) is described in a more detailed manner since it is taken as a reference for the 2D barcode developed in this thesis.

3 Channel-models

Here some basics are provided by considering channel-models that are important throughout this work. For example, the concept of 2-state Markov-modulated channels is explained since it is used later on when constructing a channel-model for 2D barcodes. Furthermore, it is shown how to compute soft-decisions and hard-decisions by means of a channels output.

4 Low-density parity-check codes

The 2D barcode designed in this thesis applies a class of channel-codes called low-density parity-check (LDPC) codes. The definition of LDPC codes, the encoding and decoding as well as the available construction and design methods are explained in this Chapter. The focus is thereby on the later application of LDPC codes on 2D barcodes.

5 Design of short irregular LDPC codes

LDPC codes with short block length are addressed since the number of bits that can be stored inside of a 2D barcode is limited by the available space. The class of irregular LDPC codes is promising because these codes have very good error-correction capabilities on a variety of channel-models. There are standard tools available (e.g. based on density-evolution) for the determination of the parameters that define irregular LDPC codes that work very good considering long codes. For short block lengths, these tools are not suitable. In this Chapter, an original contribution is given with the development of an optimization method for the design of short irregular LDPC codes that is based on a direct search algorithm called downhill-simplex (DHS) algorithm. The results based on the new design technique are compared with a method that follows a similar approach. It is proven that the design method developed in this Chapter provides superior decoding performance for the additive white Gaussian noise channel and for the Markov-modulated Gaussian channel compared to methods known from literature.

6 Estimation-decoding

Here the basics of estimation-decoding are given first to then explain the concept of a newly developed variant of estimation-decoding. The purpose of using estimation-decoding in general is to increase the error-correction capabilities of a LDPC code by considering the memory of a multi-state channel during the iterative decoding. The Tanner graph (a graphical representation of a LDPC code), on which LDPC decoding is based, is extended by adding a hidden Markov chain to the Tanner graph. The estimation-decoding algorithm comprises of the LDPC decoding that is based on the Tanner graph and the state-estimation that is processed on the hidden Markov chain.

An evaluation proves the effectiveness of using the new variant of estimation-decoding. The developed algorithm is later used when designing the decoder for LDPC-based 2D barcodes.

7 LDPC-based 2D barcodes

The main contribution of this thesis is explained in this Chapter where the principles of 2D barcodes based on LDPC codes are explained.

After a desired information has been encoded by means of a LDPC code, the code word's symbols have to be placed in the data region of the 2D barcode. This is done by use of an intelligent interleaver that is developed in order to increase the error-correction capabilities of the resulting 2D barcode. The placement of a LDPC codeword's symbols in the data region is optimized based on two distance measurements, i.e. the geometrical distance and the tree-distance. The geometrical distance is the Euclidean distance that two symbols have to each other in the 2D barcode's data region. The tree-distance is measured by means of a tree constructed out of the LDPC code's Tanner graph, and evaluates the relation of two symbols to each other, depending on the LDPC code's properties. A cost-function then evaluates a complete symbol-placement set based on the distance measurements of all possible symbol-pair combinations. An optimization algorithm then minimizes the cost-function and provides the best symbol-placement in terms of error-correction capabilities.

Since the LDPC decoder requires so called soft-decicisions as an input, a channel-model is constructed by which the computation of soft-decisions is possible. The computation of soft-decisions is based on correlation-coefficients that are calculated for each module of the 2D barcode and that represent the output y of a channel. The channel-model is then constructed by analyzing the distribution of the correlation-coefficients considering 2D barcodes embossed on different kinds of material and captured in different illumination settings. The distribution of the correlation-coefficients is heavily influenced by damages that may occur and that are typical in industrial environments. This is considered by utilizing a 2-state channel-model with one state representing the case without damages and the other state taking damages into account. For the analysis of the correlation-coefficients in the case of damages, a simulation of typical damages is developed in order to get a big statistic.

Due to the multiple state characteristic of the constructed channel-model, the design of the following decoder is based on the estimation-decoding principle. Considering 2D barcodes, the one dimensional time line of a common communication system turns into a geometry of 2 dimensions. This is considered by the construction of a 2D hidden Markov model that represents the channel's memory. The new estimation-decoding variant developed before is then extended to operate based on the 2d hidden Markov model. The complete algorithm developed for the decoding of LDPC-based 2D barcodes is called ED2D algorithm which stands for estimation-decoding based on the 2D hidden Markov model.

In a last step short irregular LDPC codes are designed especially for the usage with 2D barcodes in industrial environments. This is done based on the new design method, the developed channel-model and the new variant of estimation-decoding.

8 Evaluation

For the evaluation, a test environment and a test procedure are developed that enable a comparison of different versions of 2D barcodes. Fair conditions are thereby provided by

1. the usage of simulated pictures instead of real pictures taken of 2D barcodes,
2. the usage of simulated damages instead of real damages and
3. by the evaluation of the decoding performance depending on the number of pre-decoding bit errors.

The picture-simulation of captured 2D barcodes ensures the elimination of possible variances that occur due to the embossing and the acquisition and that are caused by the illumination, the material and the milling. By using simulated damages instead of real damages it is possible to affect different 2D barcodes with exactly the same damage. The pre-decoding bit errors are computed based on hard-decisions that are made for each module before the actual decoding is conducted. The number of pre-decoding bit errors offers a great measure on how much a damage affected a 2D barcode. By evaluating the decoding performance depending on the number of pre-decoding bit errors, a fair comparison of different 2D barcode variants is ensured.

Based on the test environment and the test procedure, the following evaluations are processed:

1. The effectiveness of the optimized symbol-placement by means of the intelligent interleaver is checked.

   The results in Figure 1 confirm the effectiveness of the intelligent interleaving. Since an average gain of about 10.7% is obtained with a optimized symbol-placement compared to a bad placement, one can say that the decoding performance of LDPC-based 2D barcodes increases with decreasing cost of the symbol-placement.

2. The effectiveness of the designed decoder for LDPC-based 2D barcodes is checked.

   The results in Figure 2 show that in average a gain of 15.2% is obtained by means of the ED2D algorithm compared to the MSc decoder that does not include any state-estimation.

3. The decoding results of 2D barcodes based on regular LDPC codes and irregular LDPC codes are compared. It is shown that in the context of 2D barcodes, no gain is obtained when using irregular LDPC codes instead of regular LDPC codes.

4. The LDPC-based 2D barcode developed in this thesis is compared to the DMC.

   The advantage of using the new 2D barcode variant developed in this thesis instead of the standard DMC can be well seen in Figure 3 where the obtained gain is shown for the several numbers of pre-decoding bit errors. The gain when using the LDPC-based 2D barcode compared to the Reed-Solomon-based DMC increases up to 71.9% for 50 pre-decoding bit errors and then decreases to 0.3% for 170 pre-decoding bit errors. In average a gain of 30.8% is obtained.

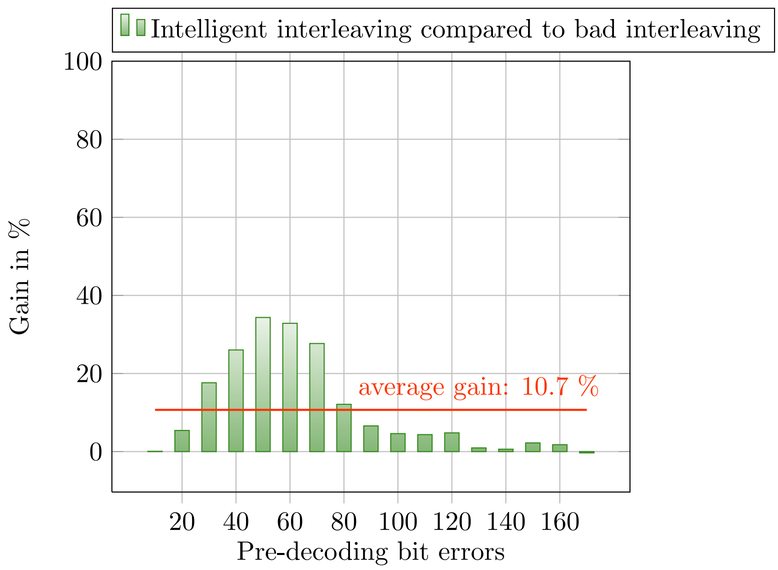

Figure 1: Gain in decoding successes that is obtained by using the optimized symbol-placement.

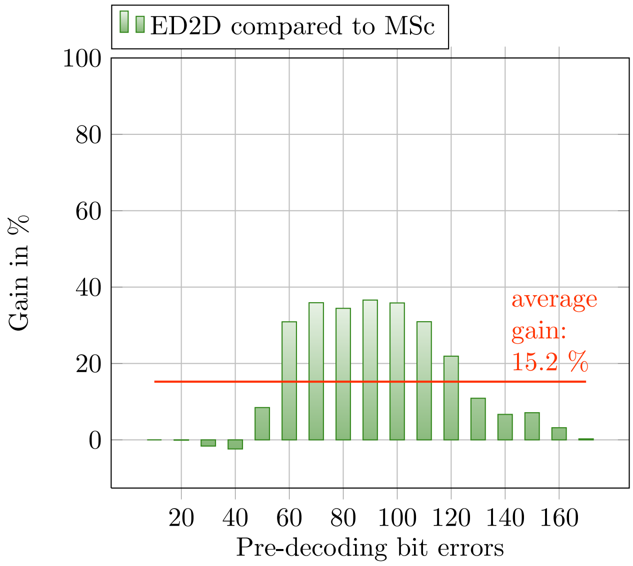

Figure 2: Gain obtained when decoding a LDPC-based 2D barcode with the ED2D decoder instead of the MSc decoder.

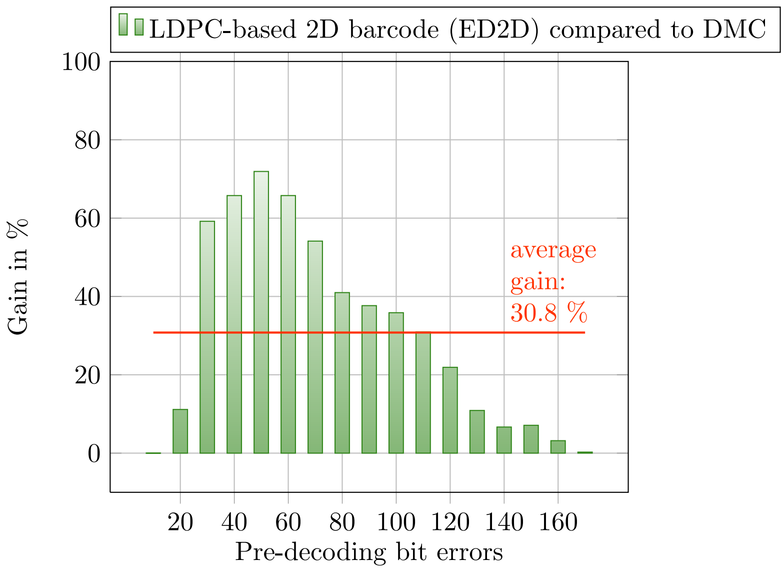

Figure 3: Gain obtained when using the LDPC-based 2D barcode instead of the standard DMC.