ON INFORMED CODING AND HOST REJECTION FOR COMMUNICATION OVER INKJET PRINT-AND-SCAN CHANNELS

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ABSTRACT
This paper describes novel approaches to achieve robust communication over inkjet print-and-scan (IPS) color channels. The IPS color channel poses even greater challenges than the laser printer-and-scan channel due to the resulting mixing and spreading of the ink dots. We propose a novel informed coding and two host color rejection approaches, one based on a novel color rejection and another on a whitening filter, to deal with the aforementioned inkjet printer distortions. A substitutive spatial domain embedding is proposed to enable robustness optimization using the proposed informed coding. Analyses and examples are provided to evaluate the performance enhancement on robustness and transparency achievable by the proposed approaches.

KEY WORDS
Watermarking Methods and Protection, Hardcopy Color Watermarking, Information and Document Security.

1 Introduction

Robustly decoding side information transmitted over color printed media is very challenging [1, 2, 3, 4] due to various non-linear distortions from the color print-scan channel, particularly those originated by ink spreading and mixing existing in inkjet printers and other disturbances from the coated media properties, optical, mechanical and scanning sensor responses [5]. Several techniques have been proposed for hardcopy watermarking over print-scan channels. The technique in [6] conveys information by modulating the angle of oriented periodical sequences embedded into image spatial blocks, while dedicating one block to embed synchronisation information. However, it exploits only the luminance and considers neither informed coding nor the color channel properties. It achieves a resulting payload of 40 bits per page. The method in [2] modulates information into the luminance image phase spectrum with differential quantization index modulation. It exploits the printer halftoning to estimate the rotation, and achieves a payload of hundreds of bits for monochromatic images. The method in [3] relies on adaptive block embedding into the DFT (Discrete Fourier Transform) magnitude domain. Each block is classified into smooth or texture type and a different embedding method is applied to each block type. The Hough transform is used to detect the printed image boundaries for watermark synchronization. The approach is robust to the print-scan channel and to rotation, providing a total payload of 1024 bits with a bit error rate (BER) around 15% for monochromatic images. In [7] a circular template watermark is embedded into the Fourier transform magnitude to facilitate inversion of rotation and scaling after the print-scan process. Another template watermark is embedded in spatial domain to invert translations. The message watermark is embedded in the wavelet domain. This technique achieves a payload of about 135 bits using an error correction algorithm, resulting in a BER of 1.5%, it is also designed for monochromatic images.

The approaches just described do not deal specifically with the color channel distortions, as they embed information only in the luminance channel. In order to exploit all color channels for modulation, it is necessary to investigate new efficient strategies to address distortion from the color print channel. The work in [8] proposes to use the Discrete Fourier Transform to embed information into the red component, while the approach in [9] performs frequency domain informed embedding using halftoning modulation. Halftoning modulation may provide high capacity but requires control of the printer driver to bypass the printer processing and halftoning, which is reportedly difficult. Color hardcopy approaches based on embedding in frequency domain [8] or in halftoning [9] are more efficient for laser print-and-scan channels.

For inkjet print-and-scan channels, however, additional techniques to the aforementioned approaches are required in order to deal with the stronger channel distortions due to the IPS ink mixing and spreading. Some work in this direction is proposed in [10] and the informed coding approach is inspired on the work of Professor Max H. Costa [11] named "Writing on Dirty Paper". The informed coding approach has been exploited by [12] for single channel (monochromatic) image modulation achieving very high payload for noise, filtered and compressed channels, however it is not designed to convey information on color host images over the IPS color channel.

This paper provides detailed discussions and analyses on the robustness and detection improvements due to the novel proposed informed coding and color rejection techniques designed to deal with color IPS channels.

2 Proposed Improvements

2.1 Information Embedding

Consider an m-bit information to be conveyed by a digital color image I which is deployed as inkjet printed media. We propose to embed this information through a set of K color dot patterns (a randomly generated sparse matrix of color dots) from a set of N available patterns, $P_i, i = 1, \ldots, N, (N \geq K)$. The set of K patterns is uniquely represented by an unordered set $S = \{k_1, k_2, \ldots, k_K\}$, where $k_i \neq k_j$ for $i \neq j$. The resulting watermarked document I_w is

$$I_w = I \oplus \sum_{i \in S} P_i \tag{1}$$

where the operation $\oplus$ represents a substitution embedding, instead of the traditional additive embedding. The pixels of the image I are replaced by the pixels of the pattern whenever color pattern dots exist, as illustrated in Fig. 1(a) at left side.

This approach provides a transparent embedding only for small size square dots and using inkjet printers. This is because the inkjet printing process helps to mix and hide the embedding dots as illustrated in Fig. 1(a) at right side and in Fig. 3, provided that the dot size is smaller than 6x6 pixels in resolutions of 600 dpi/ppi for printing and scanning. Section 3 provides performance evaluations using dot size of 4x4 pixels at 600 dpi/ppi resolutions for printing and scanning.

2.2 On the Choice of Patterns for Informed Coding

We have experimentally verified that the ink spreading of the dots differs depending on the color of the embedding pattern dots, k, and on the colors of the pixels surrounding the embedded dots in the host image, as indicated in Fig. 1(b). This is due to specific ink chemical properties of the inkjet printer cartridges. As one result, the detection performance based on correlation is considerably better for certain color combinations of the embedding patterns and the host backgrounds. Hence we propose to use the correlation as the robustness metric for selecting the best pattern of one unique color from L alternative patterns depending on the pixels colors of the image host background.

For example, the robustness estimates illustrated in Fig. 2 for only 4 background colors using an HP4280 printer, indicate that higher robustness is achieved by embedding magenta pattern dots over a cyan image background rather than over a yellow background. To estimate this robustness, $R(k, b)$, of embedding a pattern of color k in a background of color b, a training is performed with the specific printing system. We need to estimate all combinations of colors of the patterns k and backgrounds b. We may use a fewer background representative colors, by clustering sets of background colors using Euclidean distance, aiming to reduce the computational complexity but also reducing the performance of the informed coding approach. Thus, for a given color k, a pattern P_{i^*k} from a set of L equivalent patterns is chosen at embedding by maximizing

$$P_{i^*k} = \max_{i=1,L} \Phi\{P_{ik}, I_w\} \tag{2}$$

where $\Phi\{P_{ik}, I_w\}$ represents the average robustness for all D pattern dots, after IPS channel, between the D color dots of pattern P_{ik} and the U pixels surrounding these dots in the host image. Thus,

$$\Phi\{P_{ik}, I_w\} = \frac{1}{UD} \sum_{d=1}^{D} \sum_{[r,s] \in \mathcal{N}_d} R(k, Color(I_w[r, s])) \tag{3}$$

where $[r, s] \in \mathcal{N}_d$ represents the set of U pixels at the neighbourhood of the embedded dot d and $Color(I_w[r, s])$ is the color of the watermarked image at location $[r, s]$.

As we propose to use L alternative patterns, for each of the N patterns, which convey the same message, both encoder and decoder must share a secret key ϕ in order to generate the same set of LN patterns. The price paid for this additional flexibility and performance optimization is the increase of the total number of required detections (time complexity) to decode the message from N to LN detections. The information payload (m bits) achievable by the proposed modulation is determined by the number K of color patterns per region, the total number N of patterns and the number N_R of embedding regions (time division modulation). Therefore, using K patterns per region from a database of N patterns and considering N_R embedding regions, we can achieve a payload of at least m bits:

$$N_R \log_2 \binom{N}{K} \geq m \tag{4}$$

where $\binom{N}{K} = N!/[K!(N-K)!]$

2.3 Color Rejection to Reduce Host Interference

Since each pattern in a region is set with a unique color k, the detection metric in (6) is computed for this pattern disregarding pixels with any other color. The rejection of pixels of other colors in the received image is based on a statistical distance as follows. Lets represent a pixel of color k as a vector with CMYK color components: $\boldsymbol{B} = [B_c\, B_m\, B_y\, B_k]^T$. Assume this pixel color is a random variable distributed as $\boldsymbol{B} \sim N(\boldsymbol{\mu_k}, \boldsymbol{C_k})$. After transmitting Z pixels of such color k over a given IPS channel, we estimate the mean vector and covariance matrix as $\boldsymbol{\mu_k} = \frac{1}{Z}\sum_i \boldsymbol{B}_i$ and $\boldsymbol{C_k} = \frac{1}{Z}\sum_i \boldsymbol{B}_i \boldsymbol{B}_i^T - \boldsymbol{\mu_k}\boldsymbol{\mu_k}^T$. Thus, when testing a pattern of color k, an unknown color pixel $\boldsymbol{X}$ of the received image is accepted only if its Mahalanobis distance to the color k, defined by

$$d_{M_k}(\boldsymbol{X}) = \sqrt{(\boldsymbol{X} - \boldsymbol{\mu_k})^T \boldsymbol{C_k}^{-1} (\boldsymbol{X} - \boldsymbol{\mu_k})}, \tag{5}$$

is smaller than to the other colors: $d_{M_k}(\boldsymbol{X}) < d_{M_i}(\boldsymbol{X}), i \neq k$. Notice that this criterion of rejection is optimal for Normal distributed pixels as assumed here and verified in the experiments. For instance, suppose we decide to embed 4 patterns, each with one unique color from CMYK. Then, to detect the yellow pattern, we reject the other (CMK) colors generating the modified image I_{wR} before correlation.

2.4 Pattern Detection and Message Decoding

The K color patterns embedded in a region of the color image are assumed to be printed into paper and digitized using an image scanner before detection. The detection of a pattern P_{ik} is based on the correlation (performed in the frequency domain, for speed, after rejecting the other colors $\neq k$, as described above) between the observed watermarked image after the print-scan channel and the known patterns, which are locally generated with the help of a secret key ϕ.

After transforming both images to the HVS (Hue, Value and Saturation) color model, a $LoG[m,n]$ whitening filter (Laplacian of Gaussian) of dimension 3×3 is employed to decorrelate the host signal. This operation can be summarized as an average correlation over the channels of the received color image I_{wR} and known pattern P_i represented in HVS color model as

$$C_i = \frac{1}{3} \sum_{k=H,V,S} \mathcal{F}^{-1}\{\mathcal{F}(I_{wR_k}[m,n] * LoG[m,n]) \cdot \mathcal{F}(P_{i_k}[-m,-n] * LoG[-m,-n])\} \quad (6)$$

where $\mathcal{F}(\cdot)$ and $\mathcal{F}^{-1}(\cdot)$ denote, respectively, the fast 2D direct and inverse discrete Fourier transforms. The operator $*$ represents the 2D linear convolution which performs the whitening filtering. After LN detections, the K indexes of patterns P_i corresponding to the highest correlations C_i are selected to compose the set S of indexes required to decode the message m. As an example, consider the CMYK colors ($K = 4$) and redundancy factor $L = 3$. LN correlations are performed for each of the 4 colors and the indexes of the K patterns with highest correlation peak value for each color are stored. The selected set of K indexes are associated by a look-up table to the message and the decoder will follow the same encoder assignment of message and indexes.

2.5 Expected Performance of the Proposed Detection Metric

Recalling the Central Limit theorem, where a large sum of independent small disturbances tends to follow a Normal distribution, by modeling the detection metric (correlation Ci in (6)) as $\sim N(\mu, \sigma^2)$, we find the probability of missing a pattern $P_P(\tau)$ by

$$P_P(\tau) = P_{FN}(\tau) + P_{FP}(\tau) = \frac{P_1}{\sqrt{\pi}} \int_{\frac{\mu_1 - \tau}{\sqrt{2\sigma_1^2}}}^{\infty} exp(-t^2)dt + \frac{P_0}{\sqrt{\pi}} \int_{\frac{\tau - \mu_0}{\sqrt{2\sigma_0^2}}}^{\infty} exp(-t^2)dt \quad (7)$$

where $P_{0,1}, \mu_{0,1}, \sigma_{0,1}^2$ parameters are estimated from data and are respectively the prior probabilities, means and variances of the detection statistics of regions with no pattern (unmarked hypothesis H_0) and regions with pattern (marked hypothesis H_1). The optimal detection threshold τ is determined and employed to decide the hypotheses based on the observed metric $C_i \underset{H_1}{\overset{H_0}{\lessgtr}} \tau$ by solving

$$(\sigma_0^2 - \sigma_1^2)\tau^2 + 2(\mu_0\sigma_1^2 - \mu_1\sigma_0^2)\tau + \sigma_0^2\mu_1^2 - \sigma_1^2\mu_0^2 + 2\sigma_0^2\sigma_1^2 \ln(\frac{\sigma_1 P_0}{\sigma_0 P_1}) = 0 \quad (8)$$

which minimizes the probability of missing a pattern, $P_P(\tau)$. Henceforth, as LN patterns are tested in order to find the K embedded patterns in each one of the N_R regions, the estimated probability of missing the entire message, Pe, is

$$Pe(\tau) = N_R((1-(1-P_{FN}(\tau))^K)+(1-(1-P_{FP}(\tau))^{LN})) \quad (9)$$

3 Experiments

The detection performance improvements are illustrated at Fig. 4. We observe an increase of 70% in μ_1 due to the informed coding after the IPS channel for a chosen pattern P_{i^*k} in a given background. Clearly, the detection performance is superior when proper embedding patterns are defined at embedding (informed coding). Moreover, by employing the color rejection, the correlation statistics μ_1 is increased by 15% while de deviation σ_1 is decreased by 50%, providing an huge gain on detection.

For a payload of 1035 bits, we need at least 23 bits per region, $NR = 45$ regions, a color host image larger than 2100×2100 pixels, $K = 4$ patterns per region and according to Eq. (4), it would be necessary to detect $N = 140$ patterns with $L = 3$ alternatives each (informed coding). By estimating the distribution parameters from IPS experiments, the resulting probability $P_{FN}(\tau)$ is about 4×10^{-10} and $P_{FP}(\tau)$ is about 3.9×10^{-10} for a given image. For this payload the estimated probability of missing the entire message is $Pe(\tau) = 45((1-(1-4\times10^{-10})^4) + (1-(1-3.9\times10^{-10})^{140\times3})) = 7.4\times10^{-6}$. This estimation shows that the techniques provide a very robust embedding for the IPS channel, which can be further improved by using an error correction code.

The performance is validated by computing the correlation metrics statistics (μ, σ) from a set of 50 watermarked and scanned images (sizes of about $1.5in^2$ at 600ppi/dpi resolutions), following by the estimation of the error probabilities. Some images are illustrated at Figure 3(a). After employing the proposed color rejection and informed coding techniques, the lowest performance case for $[Pe(\tau), P_{FN}(\tau), P_{FP}(\tau)]$ is improved from $[2.4\times10^{-5}, 2.1\times10^{-7}, 5.5\times10^{-8}]$, respectively, to $[4.3\times10^{-6}, 4.4\times10^{-8}, 9.7\times10^{-9}]$. The results indicted a consistent improvement, for different messages and printers (HP5580 and HP4280), of at least 5 times in probability of detection even for the worst of the 50 cases.

Prior to printing the image, the resulting Peak Signal-to-Watermark Ratio, $PSWR = 20log_{10}\left(\frac{255\times W\times H}{\sqrt{|I-I_w|^2}}\right)$, is very high, $PSWR = 45$ dB, in average, where W and H are respectively the width and height of the images. The structural Similarity (SSIM) index is also high prior printing, $SSIM = 0.96$ in average.

Perceptual evaluation from 15 users indicates a transparent embedding to naked eyes from a normal distance (10 inches) to the printed page using about 400 dots of 4x4 pixels size per pattern of 300 $\times$ 300 pixels at 600 ppi/dpi resolutions. IPS channel hides those dots quite well due to ink spreading and mixing, as illustrated in Fig. 1 and Fig. 3. This setup provides a payload of 100 bits/in^2 at 600 ppi/dpi for IPS color channels with a small probability of missing the message ($\sim 10^{-5}$) and good transparency, a performance very competitive to watermarking techniques discussed in Section 1.

In all the experiments, a careful placement of the printed document in the scanbed resulted in a well aligned image. Notice that the correlation method is robust to any degree of translation; however, the performance may be affected if rotation occurs. In this case we apply the following automatic method based on a coarse alignment followed by a search rotation method to achieve a finer alignment: The corners and boundaries of the image are detected and a rotation is performed on the image to achieve a coarse alignment. Next a fine search is performed aimed to improve the alignment. This is achieved by computing the correlation of some blocks and use this information to select the angle that provided the highest correlation. This approach does not require any additional visual cues or special blocks specially design to recover synchronism. The approach has the drawback of requiring extra computational time to find the best rotation angle from a range of few degrees after the coarse alignment. Fig. 5 illustrates the correlation performance dependent on the rotation angle.

Transparency, payload, decoding speed and robustness are adjustable by using a different set of parameters N, K, N_R, L, dot width and number of dots per pattern for a given number m of embedding bits. Higher payload is achievable by increasing N with some impact on computational complexity and robustness. According to (3) the embedding has complexity proportional to the product $N_R KLUD$. In the experiments, the embedding required about a mean of 3.5 minutes for images of size 800 $\times$ 800 pixels while the decoding using (6) required a mean of 40 seconds using a non-optimized program.

4 Conclusions

This work provide improvements on communication over IPS color channels by proposing informed coding, optimal detection and host rejection techniques. These techniques mitigate the host interference as confirmed by the results and the analyses provided. The detection performance is evaluated with the proposed optimal detection threshold and the results illustrate the significant improvement on probability of detecting a transmitted message over the IPS channel. These approaches improve communication reliability over IPS channels allowing customization for various robustness, transparencies and decoding speed tradeoffs by choosing proper embedding pattern parameters.

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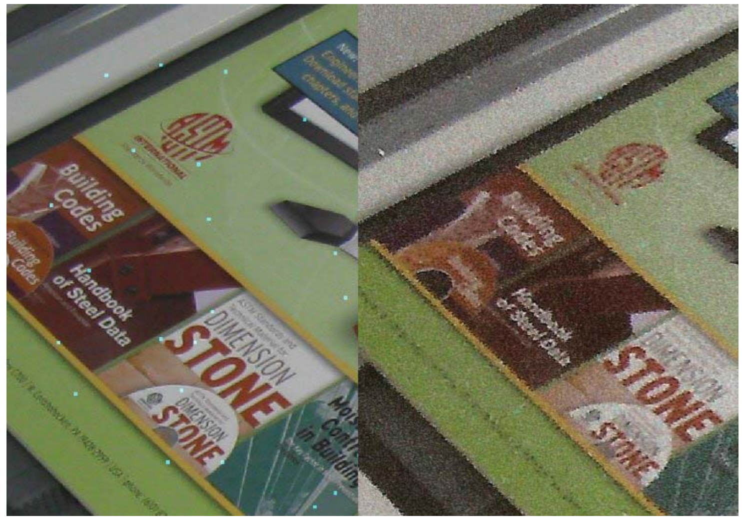
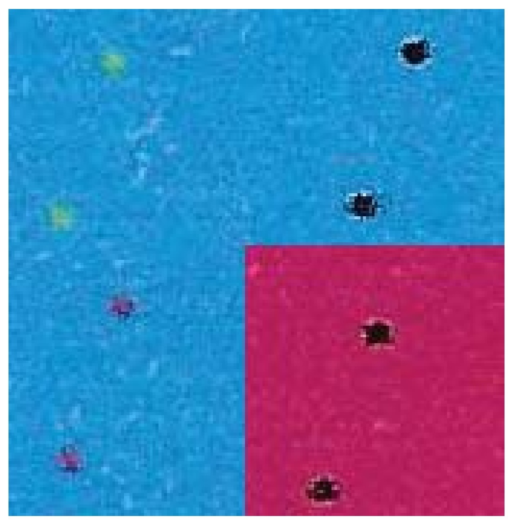


(a) The digital watermarked image and the image after IPS channel.



(b) Dot spreading on different backgrounds.

Figure 1. (a) The digital watermarked image detail (with 1150×850 pixels, corresponding in a real size of 1.9 in $\times$1.4 in) with a cyan pattern. The original image, printed and scanned at 600 dpi/ppi, has 3200×2400 pixels. The digital domain is used only for embedding as the distribution media is the printed version where the embedding transparency is high. On the right is shown the printed and scanned watermarked image with a cyan pattern. (b) Detail (zoom) of the color dot pattern ink spreading and mixing for different color backgrounds.

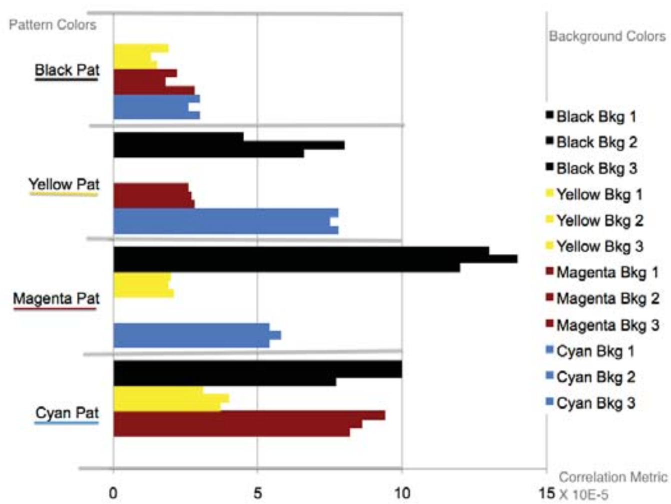
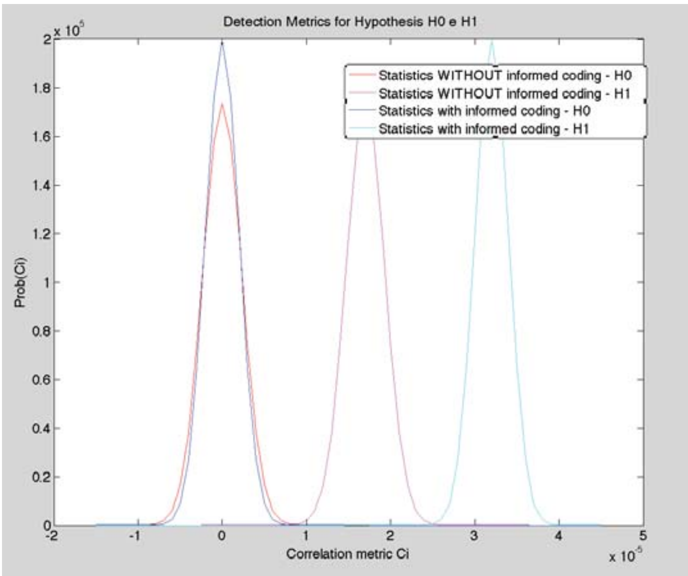


Figure 2. Expected robustness for 3 realizations of a color embedding pattern (Pat) for each (CMYK) color background (Bkg).

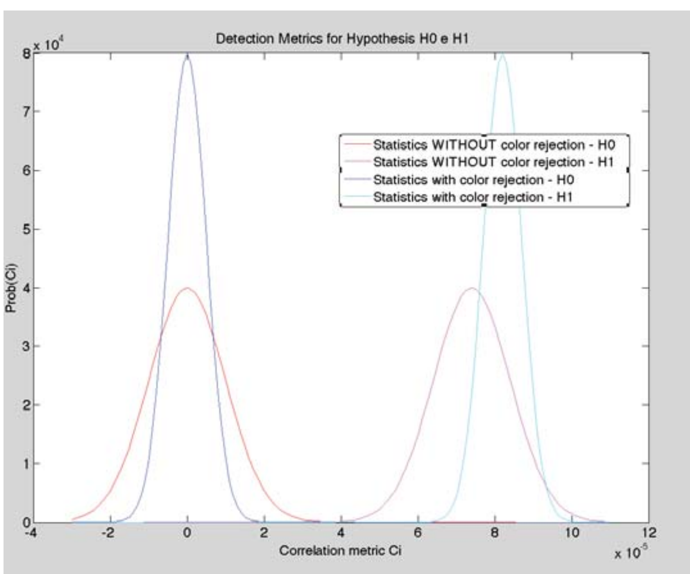
(a) Host images without watermark after IPS color channel.

(b) Watermarked images after IPS color channel.

Figure 3. (a) Original (no watermark) images of size $1.5in^2$ printed at 600 dpi and scanned at 600 ppi in HP5580. (b) Printed and watermarked images indicated high transparency when viewed from a distance of 10 inches. There are less than 1% of pixels marked as cyan dots of size of 4x4 pixels, which are barely seen by naked eye. Only with digital zoom is possible to notice the patterns.



(a) Performance of informed coding approach.



(b) Performance of color rejection approach.

Figure 4. (a) The correlation performance **with and without** informed coding: the mean μ_1 for the hypothesis H_1 is improved by 70%. (b) The correlation performance **with and without** color rejection: the μ_1 is improved by 15% and $\sigma_{0,1}$ are decreased by 50%.

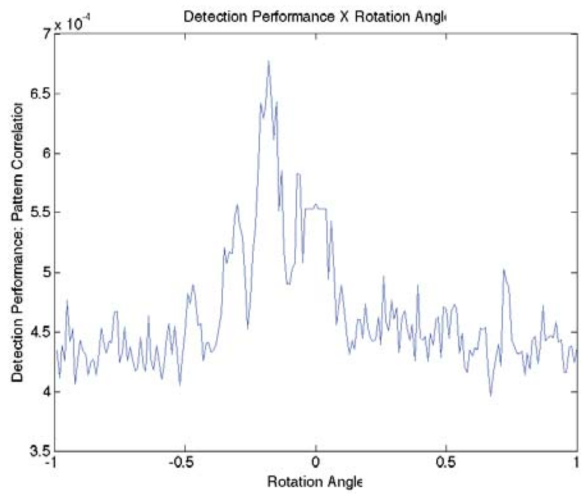


Figure 5. The correlation performance for a range of rotation angles. This approach enables to determine the best rotation angle automatically making the approach robust to angle rotation at the scanning process. The detection method based on correlation is already naturally robust to translation.