Product authentication based on the physical link induced by the photo-inscription of a (sub-micron) bar code

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Abstract. A method dedicated to authentication of products submitted to a data inscription during their manufacturing process is suggested. It includes a management of the origin of the machine providing the reference product signature. The strength of the method is based on some links established by turns at the registration stage between all the elements to protect. Specific variations coming from product data photo-inscription physically induce a fundamental link between material and immaterial product components. This link is exploited via a specific signature extraction.

1. Introduction
The optical techniques dedicated to the authentication of manufactured products can be divided into two categories according as the structure of the probed zone (at the registration stage) is locally regular or not. Last category often corresponds to manufacturing processes including unpredictable variations due to some components (as cellulose fibers, stones, and fillers in the manufacturing of paper [1]) or certain steps (as laser printing for producing printed documents [2]). The aim of this paper is to suggest the use of the inhomogeneities resulting from the photo-inscription of a bar code encoding some crucial informations associated to a photosensitive product in order to verify originality. One of the potential interest of photo-inscription is to inscribe the informations at a sub-micron resolution by working in the UV domain. Photo-inscription will serve to physically establish a link between immaterial and material. Such a link is the ground of the (off-line) authentication method suggested in section 2. A specific feature extraction is introduced for this purpose in subsection 3.1. Its discriminative power is tested on a set of actual samples in section 3.2.

2. Off-line products authentication with management of the origin of the registration machine
Let us view any manufactured product to be traced as a set of three components: material element $m$ embedded in the product, non-reproducible and characteristic from the material constituent or its packaging, data $D$ associated to the product and Intellectual Property owner $O$. At the registration stage, a signature denoted $M$ can be extracted in the production line from element $m$ by automatic reading device $R$.

With respect to the authentication method suggested in [2], the motivation is here to have a method where the integrity and origin of information is ensured by the original entity producing it, checkable
by everyone. A practical situation corresponds to the management of data \( D \) by IP owner \( O \) and the extraction of reference signature \( M \) by device \( R \). At each time, the problem can be solved by making a digital link thanks to a digital signature \( (S_D = S(D, K_O)) \) and \( S_M = S(M, K_R) \), respectively) where the private key is provided by the original entity \( (K_O \) provided by owner \( O \) and \( K_R \) by device \( R \), respectively).

The variations inherent to photo-inscription are exploited in order to offer a protection against illegal copies of photosensitive products. These variations come from those of the material structure or the lighting process so that no run repeats exactly and each one is characteristic, unpredictable. By this way, a physical link exists between immaterial component \( S_D \) and material element \( m \) after photo-inscription of the bar code encoding \( S_D \) on \( m \) (as encoding ensures an automatic reading). Next step concerns the feature extraction of signature \( M \). Feature extraction has to be designed for reflecting the variations of the dots of inscribed bar code \( s_D \). Finally encoded digital signature \( S_M \) is inscribed on the product to allow subsequent off-line verifications.

The verification procedure associated to the above sequential registration procedure (figure 1) consists in the test of each of the links. The links can be tested separately. The digital ones are tested by checking the digital signatures and the physical one by assessing a discriminative decision function. The decision function aims to determine if the extracted signature matches or not the registered one.

3. Feature extraction

3.1. Description

The signature resulting from feature extraction is classically a \( n \)-dimensional descriptor formed by \( n \) characteristics as in statistical pattern recognition. The protection against illegal copies is ensured by the fact that no device can physically reproduce the descriptor. The resolution required in [2] to physically reproduce the edge of a given printed secure mark \( (n = 32 \) radii typically) is 17 times larger than today’s highest-end laser printer. No physical means appears available to physically reproduce the coordinates of the centers of gravity of the ten largest convex shapes \( (n = 20 \) coordinates) obtained by projecting on the detector according to a given view angle, the shadow of polymer fibers contained in a certain 3D piece.
Here, the objective is to design a signature characteristic from the photo-inscription run, short enough to remain compatible with the limited storage capacity of bar codes. As photo-inscription concerns a dot matrix, a single characteristic per element is considered. More precisely, the coordinates of the autoconvolution centers \([4]\) with respect to the centers of gravity of the \(n/2\) elements of bar code \(s_D\) (conventionally \((0,0)\) when there is no dot) form the signature. The notion of autoconvolution center is an extension to non-convex shapes of the Besicovitch notion of symmetry center for convex planar bodies \([5]\). If it is mathematically proved, for convex bodies, that such a center is unique \([6,7]\), it seems to be difficult to locate it a priori with respect to the center of gravity given by any planar shape. All the coordinates are computed at a sub-pixel precision. The autoconvolution centers coordinates are estimated by means of sub-pixel interpolation as in correlation peak location \([8]\).

3.2. Generation of photo-sensitive samples and experimental results

For testing the discriminative power of the suggested signature, a series of five \(36 \times 36\) photo-inscriptions was produced by focusing a \(244\) nm laser beam on a photosensitive object. The object is made up of a mesostructured hybrid silica supported by a slide of glass. The layer, formed according to a sol-gel process, contains uncoloured \(\text{Ag}^+\) ions that can be reduced and aggregated under the incident light to produce coloured areas \([9]\). The object was moved at \(2\) mm.s\(^{-1}\) by using a motorized x-y translation stage synchronously with a mechanical shuttering of the laser beam in order to produce a full dot matrix with a period of \(200\) \(\mu\)m. Alternatively switched on/off during the exposure, the shutter had some uncontrolled oscillations which were the main source of photo-inscription variations. The dots resulting from the migration and reduction of \(\text{Ag}^+\) ions during exposure, appears orange-coloured and the background gray when observing the object in reflection with an optical microscope (figure 2). Consequently, RGB images can be easily binarized on the Blue component giving non-convex shapes having one or more connex components (figure 3).

![Figure 2. Optical microscope image of a photo-inscribed 36x36 dot matrix photo-inscribed in a sol-gel structure (SiO2 sol with Ag\(^+\) ions).](image)

![Figure 3. Labelled connex components after binarization of the image shown in figure 2.](image)

In this experiment, the image resolution is \(0.9\) \(\mu\)m per pixel and each characteristic is measured within \(0.1\) pixel. The number of characteristics is fixed to \(n = 24\) which corresponds to a pair of lines of \(6\) dots (vectors) in a photo-inscribed matrix (figure 4). The disagreement score between two signatures is measured by the sum of the \(\ell_1\) distances between \(i\)th vectors of the signatures \((i = 1, \ldots, 12)\). The histogram of the disagreement measurements from 105 pairwise comparisons among 15 different signatures is shown in figure 6. The minimum disagreement value is \(74.2\) pixels which indicates that the mean distance between two corresponding vectors in compared signatures is \(6.1\) pixels. As this value is comparable to the value of the median magnitude of the measured vectors (7.1 pixels), the discriminative
power of the signature is rather good even if the standard deviation is relatively high (its adimensional value is close to 0.4).

However, the variations due to the shuttering should be rendered more isotropic. In the experiment, the x-coordinate deviation is statistically smaller than the y-coordinate one as an effect due to the x-axis motion of the object. Moreover, the y-coordinate is slightly biased towards negative values. Dynamical beam shaping could be a promising way to generate variations as desired.

**Figure 4.** Numerical one-way signature extracted from the second pair of lines of image dots in image of figure 2. The signature is represented as a rose of the vectors joining the centers of gravity to their corresponding autoconvolution centers.

**Figure 5.** Numerical one-way signature extracted from another pair of lines of image dots. The disagreement score between this signature and the signature represented in figure 4 is 174.8 pixels.

**4. Conclusion**

The suggested method of products authentication is based on some digital links which guarantee information integrity and origin, and on a physical link induced by photo-inscription which prevents
Figure 7. View (binarized TEM image, resolution 1 nm per pixel) of some bars of a 1D bar code photo-inscribed in a sol-gel structure (SiO2 sol with Ag⁺ ions).

from copying. The physical link is the crucial point here. It exists through the unpredictable variations of bar code inscription. A numerical one-way function defined on the space of planar shapes is introduced to provide signatures reflecting such variations. The discriminative power is tested on actual samples and should be confirmed on larger amount of data. The variations exploited above at a resolution of 1 µm per pixel comes mainly from shuttering. At a smaller scale, the material structure can be sufficient to obtain unpredictable variations after bar code photo-inscription. The global illumination of a (dynamical) mask can replace scanning. In figure 7 the binarized image of 60 nm photo-inscribed bars gives connex components defined by the mesoscopic structure of the hybrid silica layer. The suggested signature could be used to locally analyze such shapes in a sliding window.

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