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Sub-surface Laser Encoding of Physical Objects for Enhanced Privacy and Digital Security

Vygantas Mizeikis[1] and Kamen Kanev[2]

[1]Research Institute of Electronics, Shizuoka University, Japan
[2]Faculty of Informatics, Shizuoka University, Japan

E-mail: dvmzks@ipc.shizuoka.ac.jp

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We present an improved method for encoding digital information in plastic objects using embedded bulk marking by tightly focused pulses of an infrared nanosecond laser. The marking consists of a machine-readable pattern of laser damage spots in the sub-surface region of the object. Compared to surface marking by printing or laser ablation, this method presents the advantage of improved durability of the code. This easy to implement method is suitable for marking the types of objects or their parts as well as of local positions on their surface. In particular location-aware information encoding using this method would provide novel opportunities to enhance the document security, since it prevents unwanted alteration of the initial data.

1. Introduction

Encoding of machine-readable information into various objects and documents allows one to create additional hidden layers of information and to enhance security (e.g., by providing counterfeiting protection). Physical marking and encoding is typically done via surface-based modification processes, such as printing or laser ablation where the information is human-readable. Typical examples of such encodings are text and grayscale photos generated by laser ablation of plastic films. Despite the popularity of laser-based marking techniques, their use is typically limited to surface modification processes. However, the use of laser carries another important, but still rarely used advantage, namely, the possibility to induce damage in sub-surface layer and bulk of transparent objects. Tightly focused pulses of an infrared laser can easily penetrate into most objects and induce permanent damage in the highly localized area at the focal point [1]. The damage is fully embedded in the bulk of the object, and is therefore well protected against environmental factors. Moreover, the damage sites, which can be regarded as information bits, cannot be easily erased or modified, which means an enhanced security. Here, we exploit these well-known advantages for encoding of digital information in the sub-surface layer of transparent and semitransparent plastic objects. The encoding was done using a dedicated opto-mechanical setup with a sub-nanosecond near-infrared laser as the light source. The recorded information bits are practically invisible for a naked eye, but can be read out by a computer-based vision system under moderate magnification. Since the recording is done in the sub-surface region (tens of µm depth), it is reliably protected from the environment, and cannot be easily altered.

2. Experimental System

Our experimental system for localization encoding (Fig.1) employs as a light source a diode pumped Nd:LSB solid-state nanosecond micro laser (STA-01, Standa Ltd.) with a wavelength of 1.06 µm, a pulse duration of 0.6 ns, a maximum repetition rate of 1 kHz, and a maximum pulse energy of 100 µJ. The laser beam is collimated to a diameter of 5 mm, attenuated by a variable neutral density filter, and focused into the bulk of the sample about 0.1mm below the surface by a microscope objective lens (Olympus) with numerical aperture (NA) of 0.1-0.65.

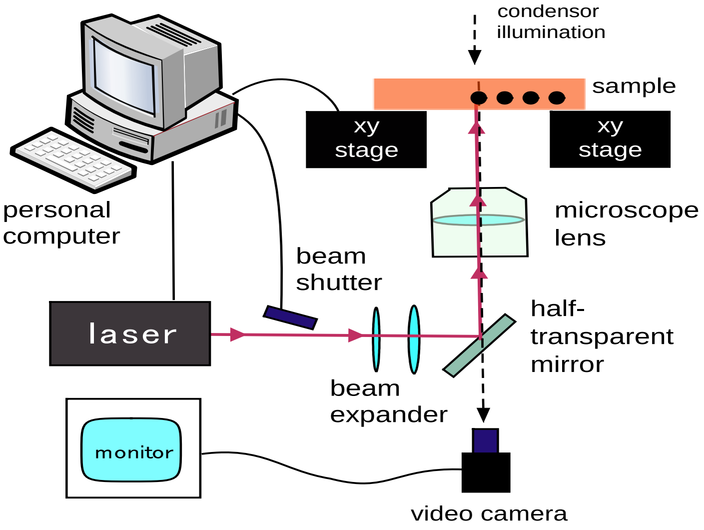

Fig. 1. Experimental system for localization encoding using laser-induced damage.

To facilitate laser marking, the sample is mounted on a mechanical X-Y translation stage having positioning accuracy better than 1μm, and stroke of (75x100) mm^2 (BIOS-Light, Sigma-Koki). The stage has two embedded stepping motors connected to a stage controller (SHOT-702, Sigma-Koki). The SHOT-702 unit is connected to a PC via a serial RS232C link and can be controlled by sending command sequences through the PC serial port. Given the sequential nature and the relatively low transmission speed of the RS232C communication channel measures have to be taken to optimize the queuing of commands and ensure proper synchronization.

3. Code Generation and Software Control

The initial code generation is carried out by the Cluster Pattern Interface (CLUSPI) Toolkit [2,3]. A sample CLUSPI-encoded 20x20 surface patch generated by the Toolkit is shown in Fig.2(a).

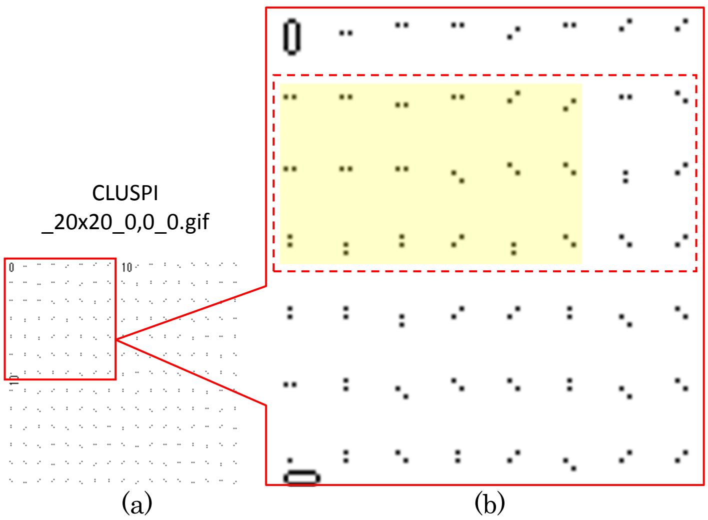

Fig. 2. A 20x20 CLUSPI-encoded surface patch (a) and an enlargement of its top left corner (b).

For more detailed observation the top left corner of the pattern is enlarged in Fig.2(b) where the clearly visible black dots correspond to individual pixels in the original image. Patterns generated by the CLUSPI Toolkit are essentially raster images that are suitable for content integration and printing but not for direct laser marking. Indeed, in order to produce a laser encoded pattern a specific sequence of stage movements and laser shots have to be executed synchronously. Deriving such a sequence from a raster image is not a straightforward task so an appropriate support environment and software tools are required.

As a first step, we have considered employing in the code conversion and laser marking process the existing stage control package available from the stage supplier. Unfortunately a viable software control system could not be built in this way due to the restrictions imposed on the use of the commercial software and its limited interface. We have consequently attempted to tune and employ a Delphi-based control software package developed in-house. While sample encoding with this approach was possible it provided only limited control over the laser marking process. In our experimental work, however, interactive fine tuning of the stage movements and laser firing on the fly are essential. To address this issue we have developed specialized Raster Laser Marking (RLM) software written in Tcl/Tk. The choice of the Tck/Tk language was mainly dictated by its interpretative nature (vs. the compiler-based Object Pascal system Delphi) and the direct command interface that it supports.

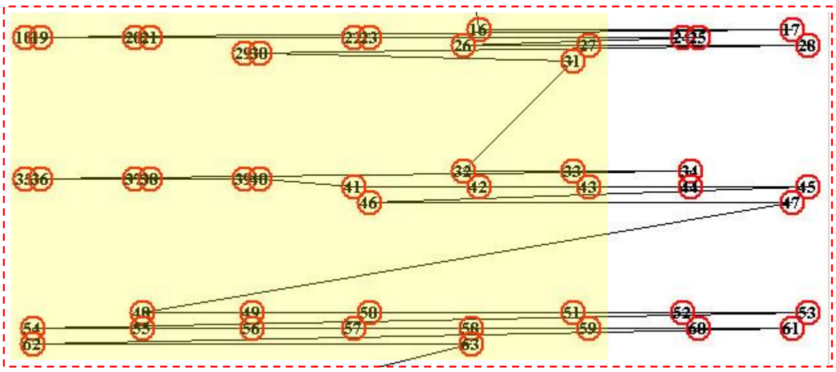

Fig. 3. Laser control sequence obtained by direct scan-line conversion of the raster CLUSPI code enclosed in the dashed rectangle in Fig.2(b) with interleaved cluster components.

The RLM tool accepts as an input a raster image in the output format of the CLUSPI Toolkit and extracts from it the code marks along with their positions. The obtained list can be directly interpreted and converted to a sequence of stage movements and laser shots [4] but in the general case this results in an inefficient encoding path as shown in Fig.3.

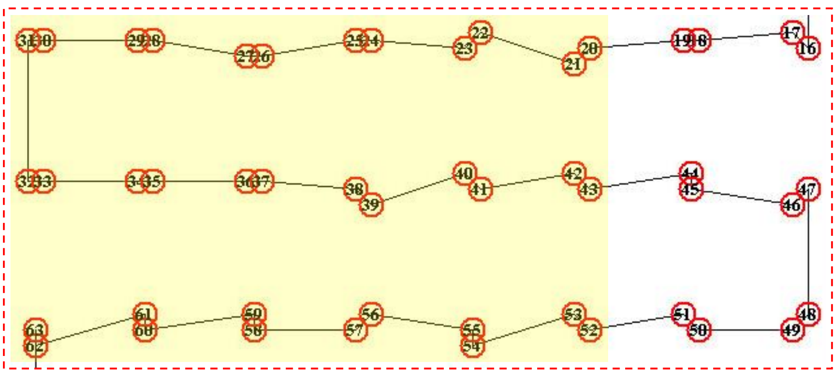

Fig. 4. A laser control sequence for the raster CLUSPI code enclosed in the dashed rectangle in Fig.2(b) with consecutive cluster encoding and no interleaved cluster components.

On the other hand the CLUSPI pattern is not based on individual marks but rather on clusters of related marks so it might be desirable tor components of a given cluster to be marked in a sequence and not interleaved with components from other clusters. The RLM tool is capable of generating cluster-aware laser control paths as the one shown in Fig.4 (which is more efficient than the raster scan based path in Fig.3) as well as other paths.
Comparisons of the laser encoding times for four different types of paths generated by the RLM toolkit are shown in Table I. We employed in the experiment the CLUSPI patch shown in Fig.2(b) consisting of 56 clusters (112 encoding marks altogether). All four encoding paths were generated by the RLM tool (Fig.3 shows rows 2, 3 and 4 of path (3) in the table and Fig.4 of path (2) respectively).

Table I. Laser encoding times for different types of paths.

Path Type	Marking Time
(1) Cluster-aware, left-to-right only	37 s
(2) Cluster-aware, left-to-right and reverse	28 s
(3) Raster-scan, left-to-right only	55 s
(4) Raster-scan, left-to-right and reverse	46 s

The four encoding sequences were executed consecutively under the same conditions and on the same sample (Fig.5). Three laser shots were fired at every marking spot by each sequence (totaling to 12 shots per spot).

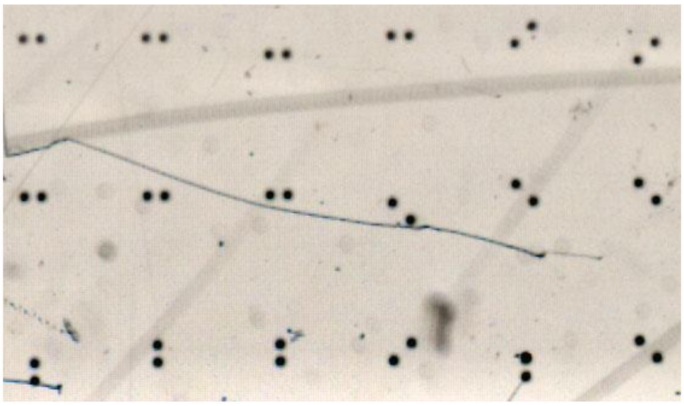

Fig. 5. Partial view of a laser-encoded sample after applying the sequences from Table I. The CLUSPI encoded area visible on this sample is highlighted in Fig.2(b) and in Figs 3 and 4.

4. Surface Encoding with Security Enhancements

So far we have explained how specialized surface codes can be created with the CLUSPI code generation tool, converted into a form suitable for laser control, and finally transferred to the sub-surface layer of a plastic medium. The CLUSPI positional code enables direct position and orientation tracking of the code carrier for augmented interactions and other advance activities as discussed in [5].
Embedded CLUSPI codes can provide significant functional enhancements of identity documents by ensuring instant area-based access to embedded security information. Those might be micro-prints at specific places of the document surface with their positions and orientation linked to the coordinate-encoding digital layer. Security enhancements become possible if digitally encoded

document identification as well as other data is integrated with the CLUSPI code. In fact, the CLUSPI code generation tool supports embedding of identification data alongside the positional surface encoding patterns which is implemented as a separate data layer interleaved and synchronized with the position encoding layer. The novelty of this approach is that the physical integrity of the document could be verified by matching the physical dimensions of the document with the coordinate information in the CLUSPI digital layer and then employing it to decode and verify the secure document ID. This should counter common attacks attempting direct document alterations or trying to piece together components from different documents.
Further security enhancements are possible by employing novel fully integrated surface codes developed by us for simultaneous inseparable position and data encoding. Indeed, as discussed earlier, in the CLUSPI encoding scheme the positional data and the identification data constitute two separate layers that are interleaved but not fully integrated. It is conceivable, therefore, that if the positional code is known, third parties might be able to recalculate the position dependent ID data and thus alter or replace secure document information. In the novel fully integrated surface codes on the other hand the positional and the identification information are inseparable as they are simultaneously encoded. In Fig.6 we show a sample of such an integrated code with capacity of 3 bits/cluster (two coordinate bits and one identification bit.)

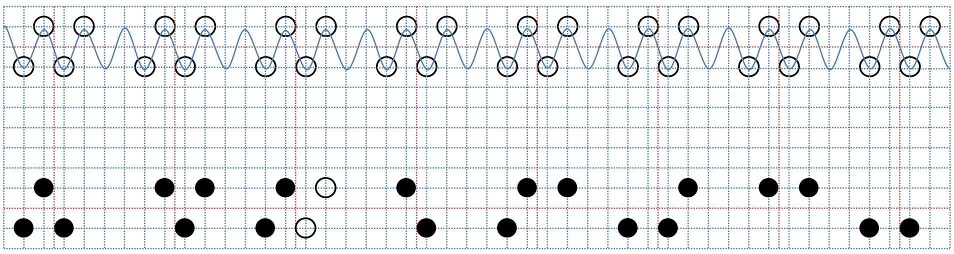

Fig. 6. Sample cluster code pattern specifically designed for efficient laser marking. The laser beam follows a sine path (top row) and shots a fired at selected peaks of the sine wave (top hollow circles). Valid clusters are shown in the bottom row.

This novel code is specifically designed for efficient laser marking by simultaneously firing 2 or 3 laser shots on the fly. The laser path on the encoded surface constitutes a sine-wave as shown in the top of Fig.6. At the peaks of the sine wave y-velocities go down to zero which allows for higher quality laser marking. The employed digital encoding method relies on cluster of laser marks as shown in the bottom of Fig.6. Altogether 8 different types of clusters are adopted which allows for simultaneous and inseparable encoding of 3 bits of information. The code is also orientation invariant due to the different cluster spacing in x and y directions and the embedded cluster asymmetry (note the third from the left cluster in the bottom of Fig.6.)

5. Experimental Encoding of Machine-Readable Codes in Laminating Film

There are various security applications where information recording is conducted in a separate medium which is later applied to a physical object. Typical examples are protective foils and security seals applied to ID cards and passports, etc. To explore such scenarios we conducted series of experiments by i) carrying out laser encoding in the bulk of thin plastic films and ii) laminating documents with such pre-encoded plastic films.
Optical recording of an array of damage spots with varied appearance in the sub-surface layer of lamination plastic films using our system is illustrated below. The sample was 100 µm thick laminating film, attached to a glass plate for better mechanical stability. The marking laser pulses had energy of ~30 µJ and were focused into the film by a microscope lens with a numerical aperture of NA=0.65. The recorded patterns of dots in the film were first observed *in situ*.

Subsequently, the laser-marked film was used to laminate paper cards by passing them through a commercial laminator. During this process the film is subjected to heating, pressure, stretching, cooling and other factors, that may potentially damage or even completely erase the recording. We show in Fig 7 optical images of the same marked area before and after the lamination for comparison and evaluation of the code damage. These images clearly demonstrate, however, that the pattern of laser-induced damage spots and individual features of the spots, as well as their mutual distances are practically not affected by the lamination. The darker background in the right image in Fig. 7 is due to the grainy surface of the laminated paper card.

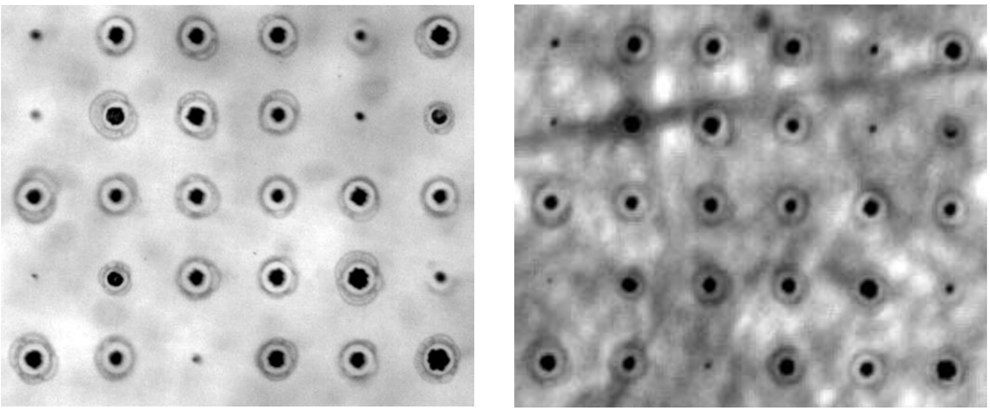

Fig. 7. Optical microscopy images of the dot pattern before the lamination (left) and after it (right).

6. Conclusion

We have presented an improved method for robust location aware information encoding in sub-surface regions of plastic objects using nanosecond laser-induced optical damage. Simple, compact, and relatively inexpensive prototype system was built and employed for experiments. The obtained results suggest that optical marking of transparent objects with volumetric information carrying localization encoding and other security information can be carried out in practice using widely available equipment and consumables. Conducted experiments with plastic sheets and laminating films have demonstrated applicability of this laser encoding approach to a wide class of materials and objects, including those employed in the production of secure documents and IDs.

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