DEVELOPMENT OF IMAGE ANALYSIS PROCEDURES FOR EVALUATION OF PRINTED ELECTRONICS QUALITY

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Key words: printed electronics, image analysis, RFID, ImageJ, printed UHF antenna.

Abstract: The procedures described in this work show the feasibility of the first stage of standardized methods for evaluation of printability of printed electronics.

Printed electronics are electronically functional devices printed onto media like paper, plastic, flexible materials, textiles etc. One of the main goals of printed electronics is simply that electronic components could be printed with mass printing technologies, enabling fast production speed and cheaper products. A new area of applied research is focusing on providing several methods for quality evaluation of printed components to perform fast on-line characterisation.

Within present research we study the potential to develop a system for detection of printing defects and imperfections such as substrate non-uniformity and poor surface ink coverage during in-line (in-situ) production of printed electronics. The possibilities for fast and relevant in-line control of printed electronic devices are introduced and applied on printed antenna samples applied for RFID (Radio Frequency Identification) tags.

For evaluation and the prospects of development of procedures for in-line control, image analysis is used with applying ImageJ software. Each separate layer (surface of printing material and conductive printed ink) was captured by CCD camera, stereo microscope and scanning electron microscope. Further, it was evaluated by ImageJ software. For automatic and relevant evaluation different routines were used, developed, modified or upgraded; 1) macro for printing surface coating non-uniformity, 2) macro for evaluation of percentage of coverage of conductive ink on the printed substrate and 3) procedure including 3D visualization plug-in to evaluate ink layer thickness in all three (x, y, z) dimensions.

The first routine presented here gives the information about the homogeneity or potential defects of printing material surface (with or without pre-coating). The non-uniformity of surface coatings and functional layers is an important property of printed electronics as it is directly related to the electrical properties and therefore to the performance of printed electronic. Other two routines give relevant information about percentage of coverage and thickness of printed functional ink layer. That tells us whether printed electronic element is OK or destruct. This way a reliable procedure was obtained for quick on-line (in situ) testing of printed electronics.

These results present the first stage of our research, which is focused on to set up the steps and possibilities for using presented in-line control methods for evaluation of printed electronic devices. The presented procedures could in future be applied for in-line control at printing speeds.

Razvoj metod slikovne analize za oceno tiskovne prehodnosti tiskane elektronike

Kjučne besede: tiskana elektronika, slikovna analiza, RFID, ImageJ, tiskana UHF antena.

Izvleček: Pokazana je možnost hitre in učinkovite kontrole kvalitete struktur tiskane elektronike, ki se izvede med procesom oz. med posameznimi fazami tiska. Pokazan je primer uporabe na tiskani anteni za pasivni RFID. Uporabljena je slikovna analiza mikroskopskih posnetkov s pomočjo ImageJ programa. Površine tiskovne podlage v vsaki fazi tiska se posnamejo s CCD kamero, optičnim mikroskopom in/ali elektronskim mikroskopom, dobljeno sliko pa se digitalno analizira. Za potrebe te analize so bili prilagojeni, razviti ali uporabljeni različni numerični pristopi: 1) makro za analizo enakomernosti površine, 2) makro za vrednotenje deleža površine, ki je pokrita s funkcionalno prevodno plastjo in 3) makro za 3D vrednotenje debeline in oblike plasti v (x,y,z) smereh. Prikazani rezultati so del raziskav v smeri iskanja učinkovitih in hitrih metod za nadzor tiskovne prehodnosti sistemov tiskane elektronike. Za integracijo predlaganih postopkov v tiskarske sisteme bi bilo potrebno vanje vgraditi zgolj vhodne naprave, kot so, npr. CCD kamere..

1. Introduction

Electronically functional devices printed onto media like paper, plastic, flexible materials, textiles etc. are today represented as printed electronics. The majority of applied materials are organic, therefore also the term "organic electronics" is applied – this distinguishes it from classic electronics which base on inorganic materials.

However, in practice organic materials are not applied only by some printing technique, therefore the terms printed electronics and organic electronics may designate products of different technologies.

One of the main goals of printed electronics is simply that it could be printed with mass printing technologies, enabling fast production speed and cheaper products.

Printable electronics technology has the potential to drastically reduce ecological footprint and energy consumption in manufacturing process. For example, digital fabrication using inkjet technology, by patterning high-purity electronically functional materials without the original patterning masks, can reduce costs and turnaround time /1/.

Print techniques used in production of printed electronic structures are screen-printing, offset, gravure printing as well as flexography, inkjet printing and laser-based printing. The first demonstration was performed on screen printing, which is also used for defining source-drain electrodes (channel length 200 mm, thickness 10 mm) /2/. Offset, the most commercial printing technique, is also very attractive for electronic manufacturing when the right compromise between ink viscosity, surface tension and evaporation rate is established /3/. Gravure printing is less used, but conductive carbon-based ink for interconnections and gate-electronics can be printed with this technique /4/. Flexography is also much less used because the flexible printing plate causes stamp distortions on the prints, resulting in problems with prints accuracy /5/. Plastic transistors created with ink-jet printer present a new low-cost electronics option.

Xerox has reported in 2005 that they have come up with air stable versions of printable electronic elements (conductors and insulators) needed to make long lasting circuits easier /6/.

Another advantage of organic electronic is capability to bend without losing its functionality. The creation of stretchable electronics originates from metal electrodes on rubber substrates, showing good mechanical but poor electronic properties. Nevertheless, active matrix sheet was reported that can be stretched by 70 % without mechanical or electrical damage /7/.

For such applications electrically functional printing inks are needed. Simplified structures of electronic components can be prepared by very small number of them /8/. This is in principle in agreement with industrial printing machines where typically 4 to 12 printing inks or the same number of printing processes are available in series. A number of research studies are focused on modification of different polymer materials to get various electronically-functional properties which are suitable for printing with conventional high-speed printing technologies /9-12/. The potential to adapt graphic art printing techniques to the manufacture of functional devices is today the focus of many research groups. They put the emphasis on the structures for integration of advanced functionality, other than only graphic information on different substrates. It is inspired by the need to reduce the manufacturing cost of existing electronic devices like radiofrequency identification (RFID) tags. Low cost printing can also enable the use of electronic devices in modes, applications and environments, which are currently not accessible by conventional electronics.

A functional ink which is printed in a given shape must form more-or-less continuous layer to assure its proper (acceptable) functionality. Most printing techniques give dot-shaped off-prints rather than uniform coverage of printed shapes. The print quality of normal graphic art applications regards visually accepted quality which, most likely, will not fulfil demands of electronic functionality. In this area more continuous coverage is desired and should be evaluated accordingly. Therefore new and precise methods to evaluate coverage are desired.

Those would also reveal whether some parts of the functional layer were damaged. In this case the coverage of substrate is considerably smaller what may cause inappropriate operation of printed layer or not operation at all. By precise evaluations those faults could be eliminated on time.

Suitable methods that control printability of printed electronic devices are based on structure - property relations. The microscopy methods, like AFM (Atomic Force Microscopy) or SEM (Scanning Electron Microscopy) are used to see the surface. X-ray diffraction data are used to understand the relationship between nucleation, growth, crystallinity and device performance /13/.

By using AFM a wide variety of growth morphologies were observed in organic thin films, revealing the complexity of the building blacks /14/. Other methods used to evaluate the printability are layer thickness determination, optical density and surface resistance.

A new area of applied research is focusing on providing several methods for quality evaluation of printed components to perform fast on-line characterisation.

Image analysis is one of them and is fast and suitable for in-line control of printing process even thought images are captured by digital still cameras. It was already shown that digitally captured images are comparable when compared to newly developed coloured films, though films still show better 3D structure, better details, higher sensitivity and wider dynamic range /15/.

Optical images of printed polymers at magnification rates showing the whole array or just small regions are used to estimate the quality of print. At that stage, the print errors can be determined while still in the production line (in-line control) /16/. Analysis and measurements need to be carried out to pre-process the images and minimize the deformations. In the paper from 2006 the authors have defined five steps for image analysis and processing; 1) the threshold to isolate the area of interest on the image, 2) isolation of pixels in the background, 3) simple calibration of pre-set dimensions in X and Y dimensions, 4) particle filtering analysis to remove particles according to their morphological properties, and 5) the edge-enhancement analysis to enhance the edge, separating it from the background /17/. Following these steps the line patterns in a circuit image can be enhanced so the centre and width of the circuit can be analyzed.

In the field of printed electronic the base surface uniformity of printed material (i.e. a substrate) is also very important. The completely uniform surface without any cracks or any other surface defects has to be achieved, especially when several layers are overprinted to get the final functionality. The polymer foils which are frequently used as printing substrate, usually have adequately uniform surface. In applications in which the paper or board are used as substrates, more surface defects are usually observed. In such cases, the printed conductive ink layer may not enable desired conductivity and destruction of electronic component may not be an exception. This is the reason why hydrophobic pre-coatings are applied on absorptive materials like papers and boards.

It is essential to recognize problems concerning non-uniformity of the surface as early as possible, best during the printing process. This way the quality of printed electronics could be detected practically on-line during successive printing steps.

2. Materials and methods

For the purpose of present research the professional example of printed UHF (Ultra High Frequency) RFID antenna from a commercial design (COPACO) from the LOPE-C exhibition brochure (Organic Electronics, OE-A) /18/ was investigated. It is presented on Figure 1, reproduced by diverse image capture methods. Antenna was printed with conductive silver ink directly onto cardboard, frequently used for printing electronics in packaging, which was at the same time evaluated by the means of surface coating non-uniformity.

Images of selected sample (antenna and printing surface) were captured using stereo microscope Leica EZ4D with integrated digital image capture device, digital camera NIKON D300 with Nikkor AP-S micro 105mm, 1:2,8G-ED lens and SEM - scanning electron microscope JSM6060LV by JEOL. For SEM observation the sample was coated by C+Au/Pd mixture in vacuum evaporator by JEOL, Japan.

The images were saved in either .jpg and .tiff file format and analyzed with ImageJ /19/. It is freeware software for image processing and analysis in Java, inspired by NIH Image for Macintosh. For automatic and relevant evaluation different routines were used, developed, modified or upgraded; 1) macro for printing surface coating non-uniformity, 2) macro for evaluation of percentage of coverage of conductive ink on the printed substrate and 3) procedure including 3D visualization plug-in to evaluate ink layer thickness in all three (x, y, z) dimensions.

3. Results and discussion

3.1 Diverse image capture methods

RFID antenna, reproduced by diverse image capture methods is presented on Figure 1.

Different image capture devices results in different surface texture details of the sample presented. Digital camera images and images obtained by stereomicroscope can be used both for research, as well as for in-line control, though magnification conditions have to be experimentally determined. SEM images were later used for 3D calibration of 2D images taken by other two capturing methods to determine the thickness of printed layer and were.

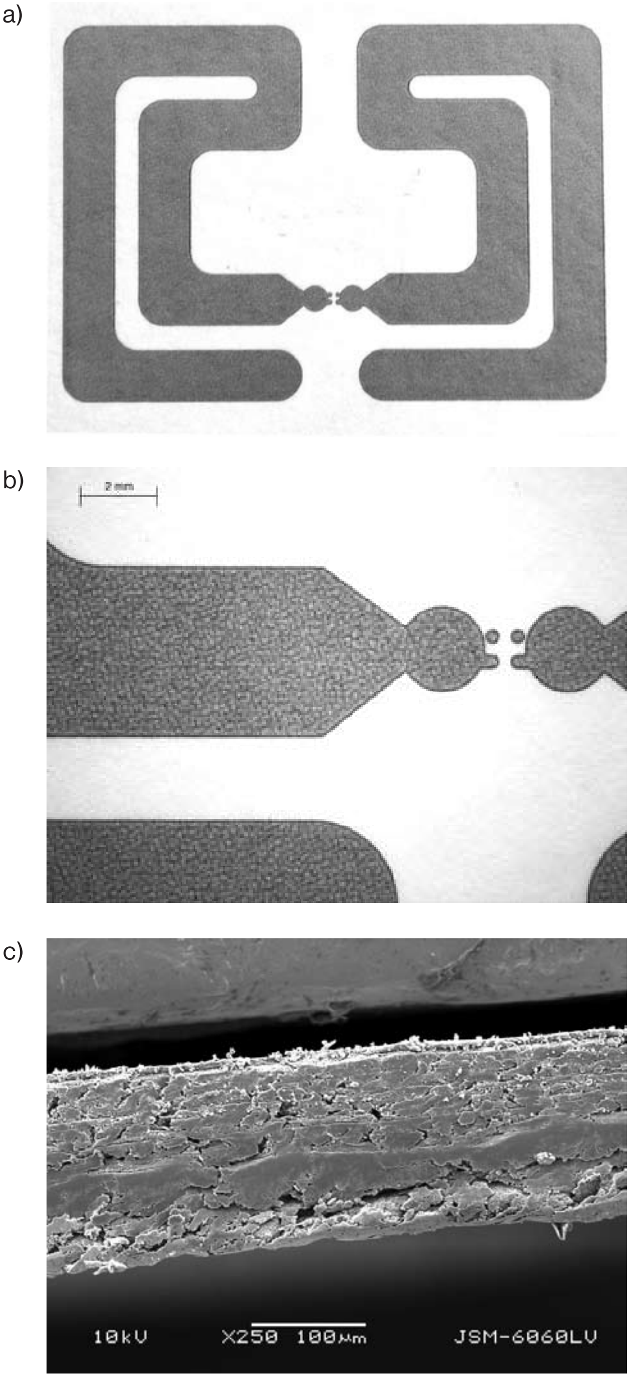


Fig.1: RFID antenna captured with digital camera (a), stereomicroscope (b) and SEM (c) respectively.

3.2 Surface coating non-uniformity

To evaluate the non-uniformity of the printing substrate surface coating as an important property of printed electronics, a special macro was developed. The amount of non-uniformity is calculated on the basis of the image's histogram which represents the number of pixels as a function of their intensity (gray value). The amount of the non uniformity is expressed as the Non-uniformity index (NU):

$$NU = U_x - L_x \qquad (1)$$

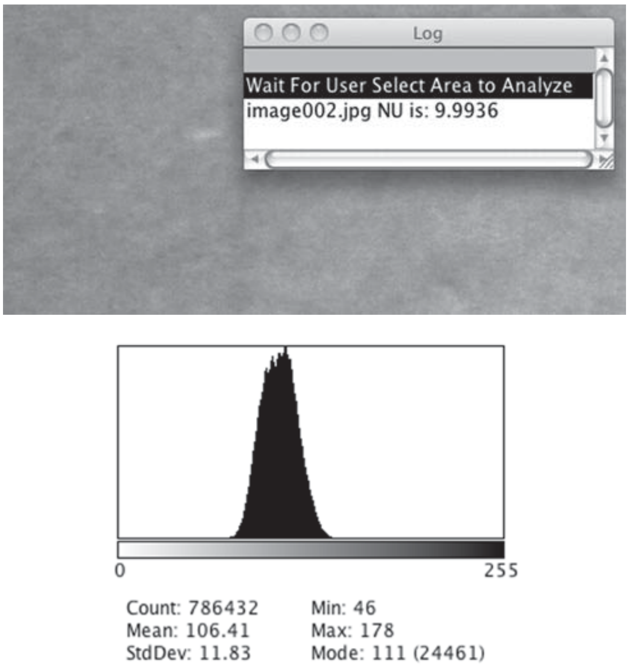
where U_x and L_x are the average gray values of pixels above and below median grey value, respectively. U_x is calculated as the mean of the intensities between median and maximum gray values of the histogram, whereas L_x is calculated as the mean of the intensities between minimum and median gray values of the histogram. The larger is NU, the greater is the surface non-uniformity. It reveals the relevant measure of the usefulness of the surface texture for application of a functional layer with desired properties. NU value measures whether its surface is uniformed enough.

The designed macro includes sequence steps:

```
saveSettings();
setBatchMode(true);
run("8-bit");
run("Set Measurements...", "mean min median limit
redirect=None
decimal=2");
Dialog.create("Select Area Dimensions to Evaluate");
Dialog.addNumber("Width (px):", 200);
Dialog.addNumber("Height (px):", 200);
Dialog.show();
w = Dialog.getNumber();
q = Dialog.getNumber();
makeRectangle(0, 0, q, w);
ID1 = getImageID();
setTool(0);
beep();
print("Wait For User", "Select Area to Analyze");
if (selectionType () !=0)
exit("Please select rectangle!");
selectImage(ID1);
run("Measure");
median = getResult("Median");
getMinAndMax(min, max);
selectImage(ID1);
//run("Threshold...");
setThreshold(min, median);
run("Measure");
mean = getResult("Mean");
Lx = mean;
resetThreshold;
selectImage(ID1);
//run("Threshold...");
setThreshold(median, max);
run("Measure");
mean = getResult("Mean");
Ux = mean;
resetThreshold;
selectImage(ID1);
NU = (Ux-Lx);
showMessage("Histogram Mottle: ", "Non-uniformity number (NU) is:
"+NU);
title = getTitle();
print(title+" NU is: "+NU);
restoreSettings();
```

The evaluation of surface non-uniformity is shown on Figure 2. The example shows the printed antenna's substrate – a commercial base material, frequently used for printing electronics (coating barriers paper). The NU of the sample is 9,99. If the value would be higher (more uneven base) the functionality of ink layer printed over such a base could be unacceptable. The limit NU level must be defined for each applied substrate individually.

In each case the range of acceptable values have to be determined with some separate experiment.



```
Wait For User Select Area to Analyze
image002.jpg NU is: 9.9936
```

```
Count: 786432     Min: 46
Mean: 106.41      Max: 178
StdDev: 11.83     Mode: 111 (24461)
```

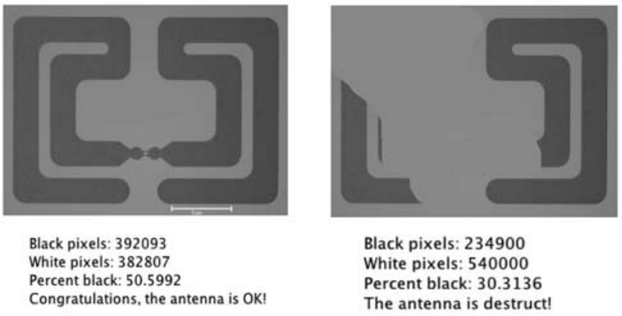
Fig. 2: An example of evaluating of surface coating non-uniformity. The coating barrier paper was captured by stereo microscope Leica EZ4D at 35 x magnification in reflection mode. The histogram of gray values on this picture was obtained by its analysis with ImageJ software.

3.3 Percentage of coverage of functional ink on the printed substrate

To evaluate the print quality of the ink layer, the macro for evaluating the percentage of coverage was upgraded and modified. It measures the coverage of the printing substrate with the printing ink. The adequate percentage of ink coverage is limited by minimal and maximal area covered. These values must be given in advance experimentally.

The procedure was tested on test RFID antenna sample, shown on figure 3.

The example (Figure 3) shows a UHF-antenna designed by COPACO and printed with conductive silver ink directly on cardboard. The applied macro gives relevant information about the print quality in terms of adequate ink coverage



```
Black pixels: 392093
White pixels: 382807
Percent black: 50.5992
Congratulations, the antenna is OK!
```

```
Black pixels: 234900
White pixels: 540000
Percent black: 30.3136
The antenna is destruct!
```

Fig. 3: RFID antenna with application of the macro for evaluation of percentage of coverage of conductive ink on the printed substrate. Left image: good antenna with adequate ink coverage and good ink printability; right image: completely destroyed antenna – ink coverage is not sufficient.

of the passive antenna. If the area of ink layer is not adequate, the macro gives the information that the antenna is destruct. In the presented example the sufficient ink area was determined according to area of CCD captured image on the good-working antenna. For a good on-line evaluation process the limit for covering has to be defined in advance.

The macro steps were as follows:

```
run("8-bit");
run("Make Binary");
if (bitDepth!=8)
exit("This macro requires an 8-bit image");
black = 255;
white = 0;
getHistogram(0, hist, 256);
total = 0;
for (i=0; i<256; i++)
total += hist[i];
print("");
print("Black pixels: " + hist[black]);
print("White pixels: " + hist[white]);
print("Percent black: " +100*hist[black]/total);
P=100*hist[black]/total;
if (P<=30)
print("The antenna is destruct!");
else
print("Congratulations, the antenna is OK!");
```

3.4 Ink layer thickness evaluation in three dimensions

The thickness of conductive ink layer of passive RFID antenna is very important. Among others, it determines the conductivity level and thus, the quality factor of the antenna. With the use of 3D visualization plug-in and custom developed routine, the quick and relevant method for analysis of ink thickness in z-direction from 2D sample image captured by CCD camera can be performed. First, the ink thickness was evaluated by cross cutting of the sample and capturing it by SEM (Figure 4). The thickness of the ink layer was determined by image analyzing tool included in SEM software. The printed passive RFID antenna was then captured by CCD camera. The image was transformed into 8-bit image and Set-scale tool was used to calibrate x and y dimensions in millimetres. After that, the 8 bit image was calibrated in z-direction, by determining and calibrating the ink thickness to grey value. For the final evaluation of ink layer thickness in three dimensions, the image was transformed into 32-bit image type and the plug-in 3D interactive surface plot /20/ was used (Figure 5).

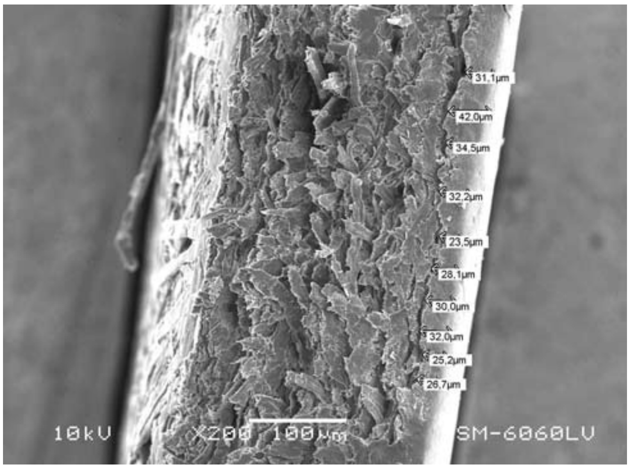


Fig. 4: SEM micrograph of UHF-antenna sample from Fig. 3. Cross cut shows the conductive ink layer on the right side and its determination of the thickness.

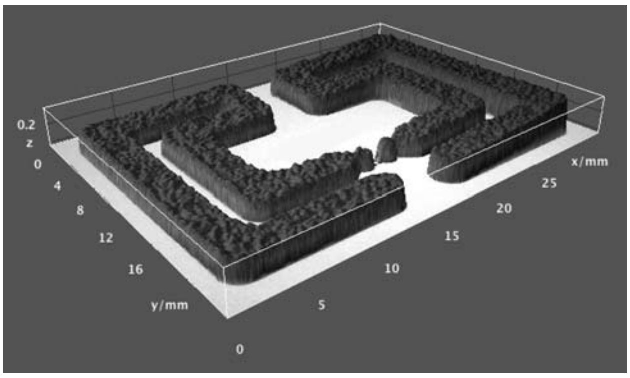


Fig. 5: The example of using macro/plug-in for evaluating the ink layer thickness in three dimensions. In image the UHF-antenna sample from Figure 3 is presented.

Figure 5 shows that captured 2D image, by applying 3D interactive plug-in, can be used to visualize and obtain precise information about ink layer of passive printed antenna in all three directions, acting as a fast analyzing tool for the evaluation of final printed antennas.

4. Conclusions

The procedures described in this work show the feasibility of the first stage of standardized methods for evaluation of printability of printed electronics. We study the potential to develop a system for detection of printing defects and imperfections such as substrate non-uniformity and poor surface coverage with ink during in-line production of printed electronics.

For automatic and relevant evaluation of printability of printed electronics different routines were used, developed, modified or upgraded utilizing image analyzing software Image J; 1) macro for surface coating non-uniformity, 2) macro for evaluation of percentage of coverage of conductive ink on the printed substrate and 3) procedure including 3D visualization plug-in to evaluate ink layer thickness in all three (x, y, z) dimensions.

The first routine presented here gives the information about the homogeneity or potential defects of printing material surface (with or without pre-coating). Other two routines give relevant information about percentage of coverage and thickness of printed functional ink layer, which is an indicator whether printed electronic element is OK or destruct. This way a reliable procedure was obtained for quick on-line (in situ) testing of printed electronics.

The presented procedures could in future be applied for in-line control at printing speeds. For performing described analysis, in existing printing equipment only the input devices like CCD cameras in the line of printing units should be incorporated.

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