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Experiments on Printed Intelligence and Its Applications

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Printed intelligence technology refers to products and systems that are produced using traditional printing methods and that are able to communicate or react with the user, environment or other products and systems. The technology provides the foundations of innovative products such as printed OLEDs (organic light emitting device), electroluminescent displays, organic photovoltaics, thin film batteries and disposable sensors.

This study presents research on different printing techniques in relation to their advantages and disadvantages in production of intelligent applications. Analysis of the studied literature was conducted and the findings were used as guidelines in creating an interactive campus map in an office room setting. Experiments on producing the map circuitry were done using inkjet technology and nanosilver ink. The campus locations were designed to be represented by electroluminescence light emitting elements. The light components were produced with screen printing and hand-held deposition methods. The methods and results of the performed experiments are discussed and evaluated in this thesis.

As a result, it was concluded that conventional printing techniques can be used for manufacturing of functional printouts such as interactive maps and that more research and development is needed in order to reduce the production costs of intelligent applications.

Keywords	printed intelligence, organic and printed electronics, hybrid media technology, conventional printing

Contents

Abbreviations

OLED – an organic light emitting device.

UAS – University of Applied Sciences

BOM – bill of materials – a list of components that make up a product. The bill of materials is used to determine the costs of producing a product.

SW analyses – strengths and weaknesses analyses.

DoD system – drop-on-demand system. Drop-on-demand inkjet printing systems eject the droplets on demand.

R2R – a roll-to-roll system.

OPV – Organic PhotoVoltaic

PCBs – printed circuit boards.

LED – a light emitting diode.

FET – a field effect transistor.

RFID – Radio Frequency Identification

2D codes – two dimensional codes.

MEMS – Microelectromechanical systems.

GIMP – GNU Image Manipulation Program

SMD – a surface mounted device.

IPA – Isopropyl alcohol.

DPI – dots per inch.

EL – Electro Luminescent

PDF – Portable Document Format

UVA – ultraviolet radiation from 320 to 400 nm in wavelength.

UV – an ultraviolet radiation.

AC – an alternating current.

1 Introduction

Traditional and digital printing are a well-known and established industry. Although researchers have used printing techniques to produce wiring already since the 1950s, adding functionality to printouts is now starting to emerge in the market (Suganuma, 2014). Products produced by conventional printing methods that are able to communicate or react with the user and environment or other products and systems are referred to as printed intelligence in this paper. Developing applications in the fields of electronics, optics, biotechnology, nanotechnology, chemistry and process automation can allow the expansion of traditional printing by producing different solutions using functional inks and substrates.

There is an increasing global interest in the field of printed intelligence as indicated in a recent OE-A (2015) publication. A variety of major consumer brands as well as universities, including Helsinki Metropolia University of Applied Sciences (UAS), and research centres have taken part in the research and development of organic and printed electronics (OE-A, 2015). As a result of launching the Hybrid Media Networking project during 2014, Metropolia UAS is now part of a network of companies and universities with the purpose of cooperation towards innovation in hybrid media technology (a combination of print and digital media). Some of the requirements for this project were a study on printed intelligence and experimental work in a laboratory room where the level of environmental pollutants such as dust are not controlled. Consequently, they became the objectives of this final year project. Creating an interactive map product became the goal of the experimental work as it required the implementation of only one functional layer.

This thesis presents research on the applicability of conventional printing technologies on adding functionality to printouts and uses the findings to guide the development in creating the interactive map of Metropolia UAS campuses. In addition, the thesis aims to provide an overview of the application areas where printed intelligence is applied.

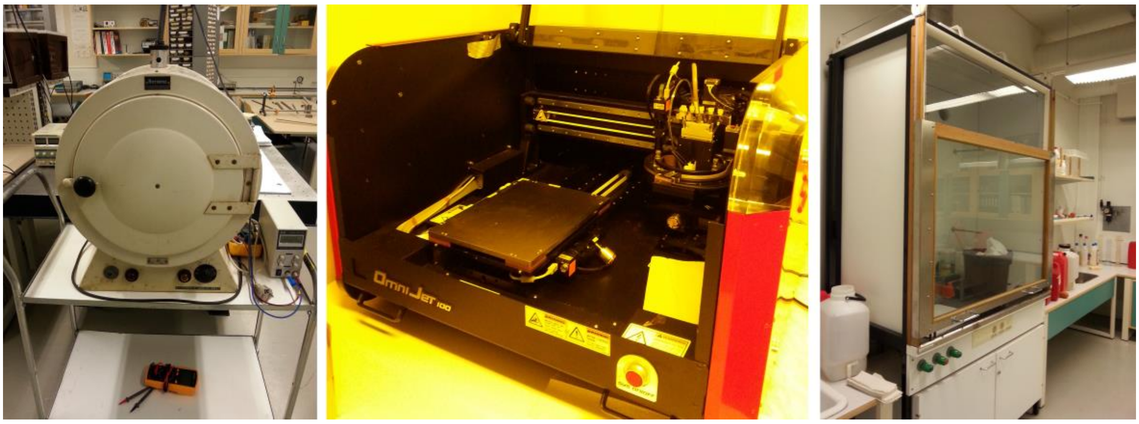
The research questions in this study are:

- Is it feasible to produce functional printouts using conventional printing methods in an office environment setting?
- What is the estimated BOM (bill of materials) of a printed intelligent product such as an interactive map?

2 Project Plan and Work Environment

This project was divided into two phases – research and experimental work. During phase one, the research was done by sifting through data from scholarly articles and publications as well as from books available through Metropolia UAS's library services. The study presents a short description of the printing methods and lists the applications produced using these techniques. Furthermore, SW (strengths and weaknesses) analyses based on the literature are made for traditional and digital printing regarding their use in production of intelligent applications. Phase two was conducted in two laboratory rooms (uncontrolled environment), one of which was equipped with UV (ultraviolet radiation) safe yellow lighting and reserved only for this project. The other facility used during this project was a physics laboratory. Equipment utilised during the experimental work is listed below:

- Sintering oven (see Figure 1, a);
- UniJet's OmniJet 100 Mini Inkjet printing system (see Figure 1, b);
- Chemical fume hood (see Figure 1, c);
- UVA (ultraviolet radiation from 320 to 400 nm in wavelength) curing lamp with UV intensity – 120 mW/cm2;
- Two desktop computers;
- Screen printing set;
- Paper thickness gauge (micrometre);
- Samsung Mini 030 – cartridge;
- Minisart filters;
- Terumo syringe with needle – 5ml;
- Disposable nitrile cleanroom gloves – BioClean Biotac;
- Protective goggles;
- Clean room clothes



a) Sintering oven. b) OmniJet 100 Inkjet system. c) Chemical fume hood.

Figure 1. Laboratory equipment.

At the end of phase one, the conducted analyses were used as guidelines in the development of the interactive campus map. A calculation of the BOM (bill of materials) for the finalized map was created as a final step of the second phase.

3 Printing Methods and SW (Strengths and Weaknesses) Analyses

Printing techniques are being applied in the manufacturing process of different applications varying from interactive posters and journals to luminous packages and printed biosensors (VTT, 2006). According to OE-A's Roadmap publication (2015), the market potential for printed, flexible and organic electronics is increasing due to the numerous beneficial factors accompanying its production line. In addition, utilising printing methods in electronics enables designing thin, flexible, lightweight and robust products that are able to share information with the user (OE-A, 2015). According to the definition of VTT, these products can be considered as printed intelligence. It is essential to get familiar with the methods used in their manufacturing process. For that reason, SW analyses have been carried out to provide guidance in determining which of the printing processes is best for producing a certain component or a whole product. Comparing the benefits and drawbacks of each technique gives an opportunity to make faster decisions to achieve a more efficient production chain.

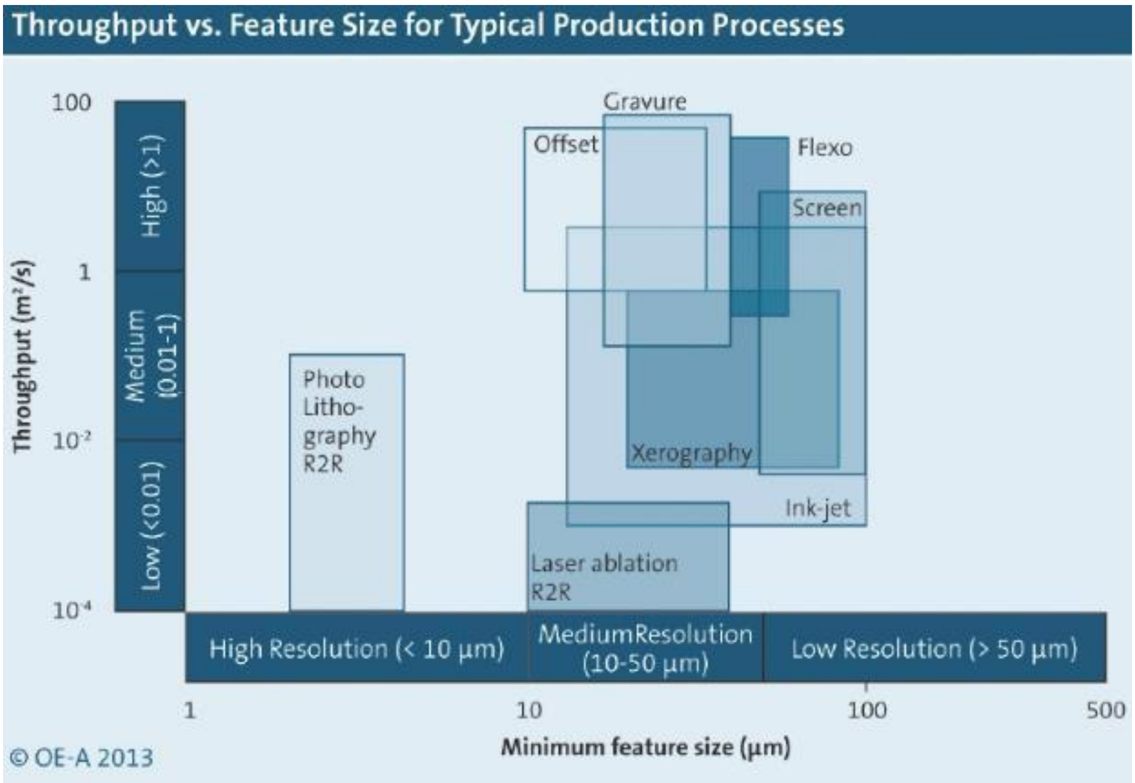


Figure 2. Resolution and throughput comparison. Reprinted from OE-A (2013).

In their paper, Chang, Ge and Sanchez-Sinencio (2012) study and compare additive (fully printed) and subtractive (non-fully printed) processing. Their findings suggest that the additive process has higher ubiquity potential due to its costs and simplicity. Both processes are compared in this study by analysing a number of factors such as usage chemicals (inks, solvents and toner), environmental impact, cost efficiency, resolution, speed, registration, and performance of the printed product. According to OE-A's (2013) research, analysis on resolution and throughput, shown in Figure 2, supports the findings described in an earlier paper of Chang, Ge and Sanchez-Sinencio (2012).

3.1 Additive Processes

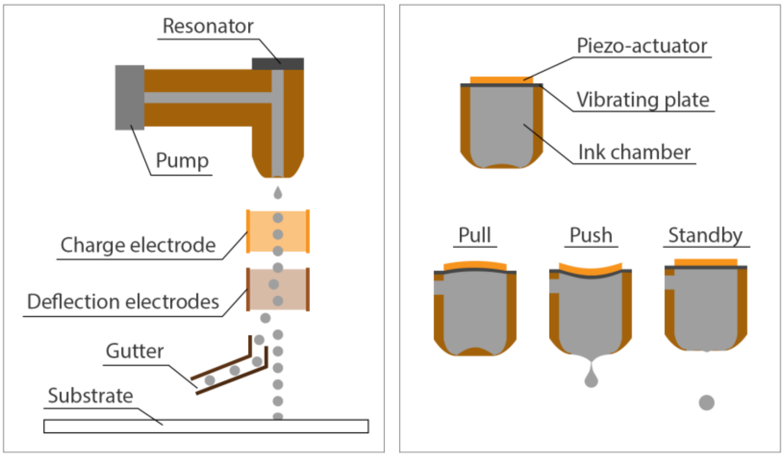
Additive processes in printing are inkjet, flexography, screen, gravure and offset technologies (Chang, Ge and Sanchez-Sinencio, 2012). In this study, the focus of the research is on these methods as they allow fast manufacturing due to the integration of roll-to-roll systems.

3.1.1 Inkjet Printing

Inkjet printing provides advantages in terms of low cost and low temperature process. This particular printing technique has additive patterning, material waste reduction and scalability to large area manufacturing, which are contributing to the increased interest in its usage in functional printing. (Mandelli, 2012)

The process of creating the image in an inkjet printer begins with the production of ink droplets that are electronically controlled (Gamota et al., 2004, p.320). Depending on the method of forming the droplets and how they are directed towards the substrate, the inkjet technology is categorized into two different types – Continuous Inkjet Printing and Drop-on-Demand Inkjet Printing. (Sridhar, Blaudeck and Baumann, 2011)

Continuous Inkjet systems print a dot, when from a stream of droplets moving through a set of electrodes, a droplet is deflected and directed by an electric field towards the substrate as figure 3a illustrates. On the other hand, drop-on-demand (DoD) systems form the droplets on demand, which allows better control over the drop. In a DoD system such as a piezo-electric inkjet printer, a dot is produced when the piezo-electric crystal is exited (expanded or contracted due to applied voltage) and it forces a drop to be ejected from the end of the ink chamber through a nozzle as shown in figure 3b. (Gamota et al., 2004)



a) Continuous Inkjet system b) Piezo-Electric Inkjet system

Figure 3. Comparison between continuous and DoD inkjet systems. Data gathered from UniJet.

In inkjet printing the main requirements for the inks are to have homogeneous structure and low viscosity of the range 10-20 cP. The throughput is low, ranging from 50 to 500 picoliters. (Li, Lu and Wong, 2010; Suganuma, 2014)

Nowadays, continuous flow and DoD inkjet systems are used mainly in the graphic arts industry for producing high quality photographs and imagery (Johnson, 2005). Conducted SW analysis on the basis of the studied literature on Inkjet technology (Gamota, et al., 2004; OE-A, 2013) is shown in Table 1.

Table 1: SW analysis of inkjet printing technology for printed intelligence applications. Data gathered from Gamota et al. (2004) and OE-A (2013) publications.

Strengths	Weaknesses
- Reduced process steps; - No use of screens or plates;	- Reduced performance of fully printed circuits;

- Print on demand; - Accurate alignment for multi-layer printing; - Non contact deposition; - Compatible with R2R (roll-to-roll) printing; - Low and medium throughput; - Environmentally friendly due to lesser usage of materials; - Cost effectiveness	- Resolution – estimated range 15 to 100µm (see Figure 1); -Low viscosity inks (presented as weakness for producing components requiring deposition of a thick layer); - Hazardous inks; - Hazardous solvent emissions

Inkjet printing systems are successfully utilized in the production of passive electrical components as well as in research in biotechnology applications (Sridhar, Blaudeck and Baumann, 2011; Lorber, et al., 2013). In a recent paper (Xie et al., 2013), this printing method is considered for production of circuits and integrated humidity sensors on paper substrate. Their results show paper-based printed electronics have potential to be used in the packaging industry as they should be cost-effective and recyclable.

3.1.2 Flexographic Printing

Flexographic printing provides advantages for producing intelligent applications in terms of controlled thickness of the deposited ink film and its high volume printing process. In addition, using rubber plates for transferring the ink allows printing on flexible substrates. (Li, Lu and Wong, 2010)

In flexography, the image is printed on the substrate by a flexible plate (image carrier). The image carrier receives a uniform layer of ink from an engraved roller, known as anilox. The anilox roller is made of small indentations that carry precise amounts of ink. After the doctor blade has removed the excess ink, the anilox roll is adhered to the plate cylinder and the ink is transferred onto the flexible cylinder. The raised parts of the cylinder represent the image and only they receive ink. The image is then printed on the substrate by applying pressure with the impression roll. The pressure can be modified for control over the thickness of the applied film. The process is illustrated in figure 4. (Gamota, et al., 2004, p.246; Li, Lu and Wong, 2010)

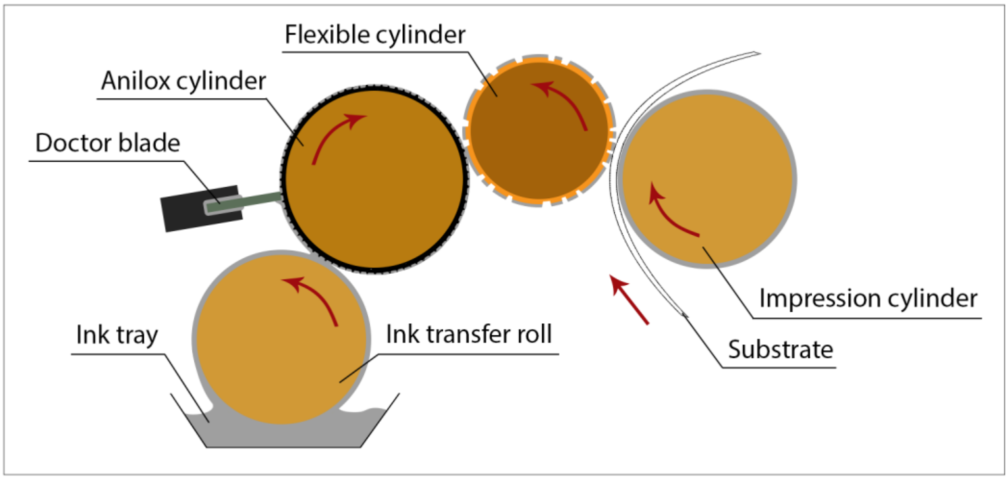


Figure 4. Example of a flexographic unit. Data gathered from PNEAC.

The flexographic inks are usually water based with relatively low viscosity in the range of 50 to 500 cP. The requirement for low viscus inks is a necessity for the ink to enter the indentations of the anilox roll. The throughput for this process is medium to high. (Li, Lu and Wong, 2010; Suganuma, 2014)

Currently, flexography is utilized in packaging industry due to the ability to print on flexible substrates. Conducted SW analysis on the basis of the studied literature on this printing method is shown in Table 2. (Gamota, et al., 2004; OE-A, 2013 Li, Lu and Wong, 2010; Suganuma, 2014)

Table 2: SW analysis of flexographic printing technology for printed intelligence applications. Data gathered from Gamota et al. (2004), OE-A (2013), Li, Lu and Wong (2010) and Suganuma (2014) publications.

Strengths	Weaknesses
- Speed of R2R production is high; - Low to medium ink viscosities; - Accurate layer registration; - Print on different substrates; - Large scale manufacturing;	- Ink splitting between printing form and substrate causes somewhat inconsistent surface; -Medium to high throughput; - Low to medium resolution;

- Fine line silver grid networks for OPV (Organic PhotoVoltaic) manufacturing is promising; - Cost effectiveness (R2R manufacturing); -Recyclable plates	- Complex formulation of inks; - Long plate preparation time; - Hazardous solvent emissions; - Hazardous inks; - High machinery cost

The variety of flexographic plates, anilox rolls and the advances in this technology have contributed to its current usage in smart packaging (Gamota, et al., 2004, p.246; VTT, 2006). At the LOPEC 2014 tradeshow exhibition, ContiTech presented their innovative technique of front side metallization on solar cells applied with the flexographic printing method (ContiTech, 2014). Furthermore, finger electrodes for a humidity sensor have been manufactured using flexography and the results are presented in a recent research paper (Hakola et al., 2014).

3.1.3 Screen Printing

The screen printing method provides the ability to adjust the printed layer thickness from sub-micrometre to hundreds of micrometres. This advantage ensures its place in the printing industry and its flexibility provides a wide range of operation. (Gamota et al., 2004, p.307)

The process of printing the image, as shown in Figure 5, requires a screen printing plate that is patterned with the image, squeegee blade and a substrate. The screen is positioned over the substrate, leaving a gap. The ink is then deposited over the screen printing plate, and by using the squeegee blade it is forced through the screen mesh onto the substrate. (Gamota et al., 2004, p.307)

The unique feature of screen printing is the high aspect ratio of printed components. The thickness of the printed elements can be modified by using different screen meshes. For example, thickness over 100 µm of the printed product can be achieved by using a thick screen mesh. (Suganuma, 2014)

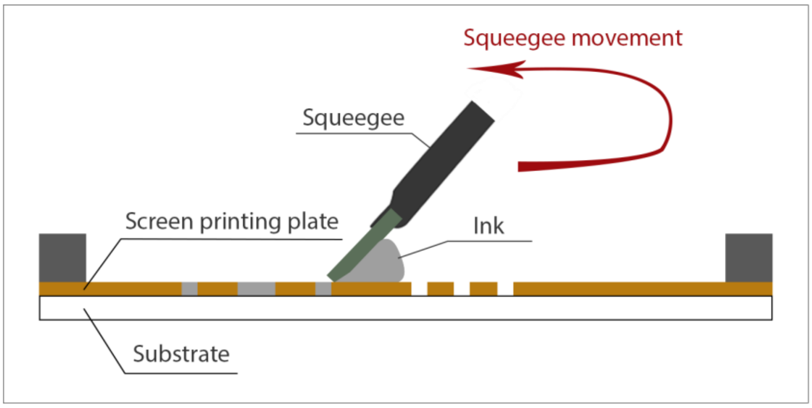


Figure 5. Example of a screen printing unit. Data gathered from Khaleel, Al-Rizzo and Abbosh (2013, p.366).

Screen printing inks have viscosity in the range of 500 to 5 000 cP. The viscosity contributes to the ability of this method to produce high aspect ratio printouts. The throughput is dependent on the screen size mesh. Conducted SW analysis on the basis of the studied literature on this printing method is shown in Table 3. (Gamota, et al., 2004; OE-A, 2013 Li, Lu and Wong, 2010; Suganuma, 2014)

Table 3: SW analysis of screen printing technology for printed intelligence applications. Data gathered from Gamota et al. (2004), OE-A (2013), Li, Lu and Wong (2010) and Suganuma (2014) publications.

Strengths	Weaknesses
- Easy formulation of inks; - Allows printing on textiles and flexible materials; - Ability to adjust the printed layer thickness; - Throughput varies depending on the screen size; - High speed of R2R production; - High potential due to simplicity of the process;	- Low resolution screens – estimated range 50 to 100µm (see Figure 1); - Registration problems in manual screen printing; - Hazardous solvent emissions; - Hazardous inks

- Cost effective	

Screen printing has been used in producing components for electronic products as well as sensors in terms of large format printing. It is the preferred method where the layer of ink is required to be thick and where great precision is needed. (Gamota et al., 2004, p.318) In a recent research paper (Eshkeiti et al., 2015), screen printing is described to be used for manufacturing of multi-layered printed circuit boards (PCBs) on different substrates. The results confirm that the screen printing method has potential to be used in developing light-weight and flexible PCBs.

3.1.4 Gravure Printing

Because gravure is suitable for very large production runs, it is studied in manufacturing intelligent products. The engraved plates can hold up to 900 m/min of throughput. (Li, Lu and Wong, 2010)

The gravure printing method uses a system consisting of an engraved metal image carrier, a doctor blade (essentially a sharp blade) and an impression roll. The printing unit is shown in figure 6. When the ink is transferred to the image carrier, the doctor blade is then used to remove the excess ink from the cylinder leaving ink only in the engraved cells. The next step of the process requires the rubber covered impression roll to press the substrate onto the gravure cylinder and create pressure for the ink to be transferred to the substrate. (Gamota et al., 2004, p.274)

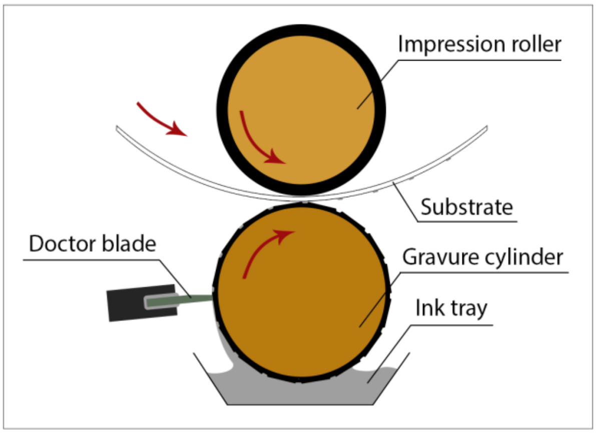


Figure 6. Example of a gravure printing unit. Data gathered from SNE Research (2011).

The inks used in the gravure printing technique are with viscosity ranging from 100 to 1000 cP. For transferring ink in high speed, low viscosity is required. Gravure has been used to produce high-quality photography and art in large quantities. Conducted SW analysis on the basis of the studied literature on this printing method is shown in Table 4. (Gamota, et al., 2004; OE-A, 2013; Li, Lu and Wong, 2010; Suganuma, 2014)

Table 4: SW analysis of gravure printing technology for printed intelligence applications. Data gathered from Gamota et al. (2004), OE-A (2013), Li, Lu and Wong (2010) and Suganuma (2014) publications.

Strengths	Weaknesses
- Speed of R2R production is high; - Reproducing very fine detailed elements; - Uniform thickness layer; - Accurate layer registration; - Medium resolution; - Long runs on R2R printing; - Recyclable gravure cylinders; - Cost-effective in large scale production	- Complex formulation of inks; - Time-consuming preparation of gravure cylinder; - Medium to high throughput; - High cost for fabricating gravure cylinders; - Hazardous inks and solvents

Gravure printing method has potential in applications where high viscosity inks are used and a uniform thickness layer is required (Gamota et al., 2004, p.298). This technology has been researched in production of electrical, optical and optoelectrical components (VTT, 2006, p.8). An OLED (organic light emitting device) based temperature indicator has been successfully manufactured using the R2R gravure printing technique as well as fully printed thin film transistors (Lee et al., 2014).

3.1.5 Offset Printing

The offset technology offers great control and precision in terms of registration of the printed pattern. This benefit favors its usage in printed electronics. (Li, Lu and Wong, 2010)

The offset printing process uses continuous roll of substrate instead of individual sheets and the system contains an inking unit, a plate cylinder, a dampening unit and an impression cylinder. The ink (from the inking unit) and water (from the dampening unit) are transferred to the plate cylinder so that ink is applied on those parts of the plate that form the image, as illustrated in figure 7. The image is then transferred onto a rubber blanket cylinder. Depending on the thickness of the substrate, a variable pressure is applied between the blanket cylinder and the impression cylinder, which results in the image being printed. (Gamota et al., 2004, p.218)

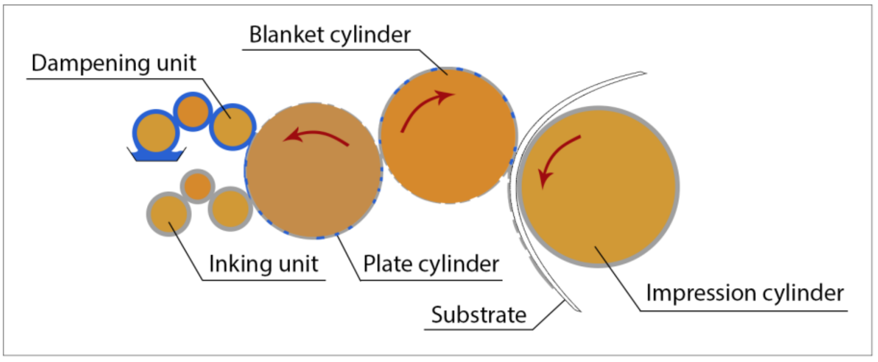


Figure 7. Example of an offset printing unit. Data gathered from SNE Research (2011).

The required ink specification for offset printing is viscosity in the range of 100 to 10 000 cP. The development of waterless /UV ink presents a significant potential for advancements in the offset technology. Conducted SW analysis on the basis of the studied literature on this printing method is shown in Table 5. (Gamota, et al., 2004; OE-A, 2013; Li, Lu and Wong, 2010; Suganuma, 2014)

Table 5: SW analysis of offset printing technology for printed intelligence applications. Data gathered from Gamota et al. (2004), OE-A (2013), Li, Lu and Wong (2010) and Suganuma (2014) publications.

Strengths	Weaknesses
- Fine printing resolution; - High speed of R2R production; - Accurate layer registration; - Cost-effectiveness in high volume production; -Recyclable plates	- Complex formulation of inks; - Water, if used in the process; - No personalization; - Medium to high throughput; - High machinery cost; - Hazardous inks

The offset printing method can be used for producing visible codes and has been studied in the production of indicators, invisible codes, sensors, hybrid media applications and printing with special inks. In order to use this technology effectively in producing intelligent printouts, the particle sizes distribution of the inks as well as the solvent evaporation rate has to be improved. (Li, Lu and Wong, 2010; (VTT, 2006, p. 55)

3.2 Subtractive Processes

Subtractive processing is considered to be a close competitor to silicon as it allows nanoscale accuracy (Chang, Ge and Sanchez-Sinencio, 2012). Photolithography, laser ablation and xerography can be used in producing flexible electronics. The lithography technology was used in manufacturing flip chip substrates. A frequency-selective surface and the resolution capabilities of the system go up to 10 µm. (Jain et al., 2005)

Subtractive processes achieve high precision and therefore most of the printed electronic circuits have been produced with these techniques (Chang, Ge and Sanchez-Sinencio, 2012). Conducted SW analysis on the basis of the studied literature on subtractive processes is shown in Table 6. (Gamota, et al., 2004; OE-A, 2013; Li, Lu and Wong, 2010; Suganuma, 2014)

Table 6: SW analysis of subtractive processing for printed intelligence applications. Data gathered from Gamota et al. (2004), OE-A (2013), Li, Lu and Wong (2010), Suganuma (2014) and Chang, Ge and Sanchez-Sinencio (2012) publications.

Strengths	Weaknesses
- Reproducing very fine detailed elements; -Printing on flexible substrates; - Accurate registration; - High and Medium resolution; -Low throughput; -On-demand printing	- Toner usage; - Complex process; - Non-scalability; - Toxicity; - High machinery cost

4 Application Areas of Printed Intelligence

Applications of printed intelligence technology are visible today – for example, large sensor arrays, touch-screen displays, disposable electronics, biosensors and the need to get familiar with the methods used in their manufacturing process is an increasing demand. This innovative technology allows the development and research of a broad range of products. (OE-A, 2015)

According to an IDTechEx report, the market size for printed, flexible and organic electronics will grow to $76.79 billion in 2023. Figure 8 illustrates the market shares and growth forecast of OLEDs, photovoltaics and conductors as major technologies in development. (Breitung and Hecker, 2013)

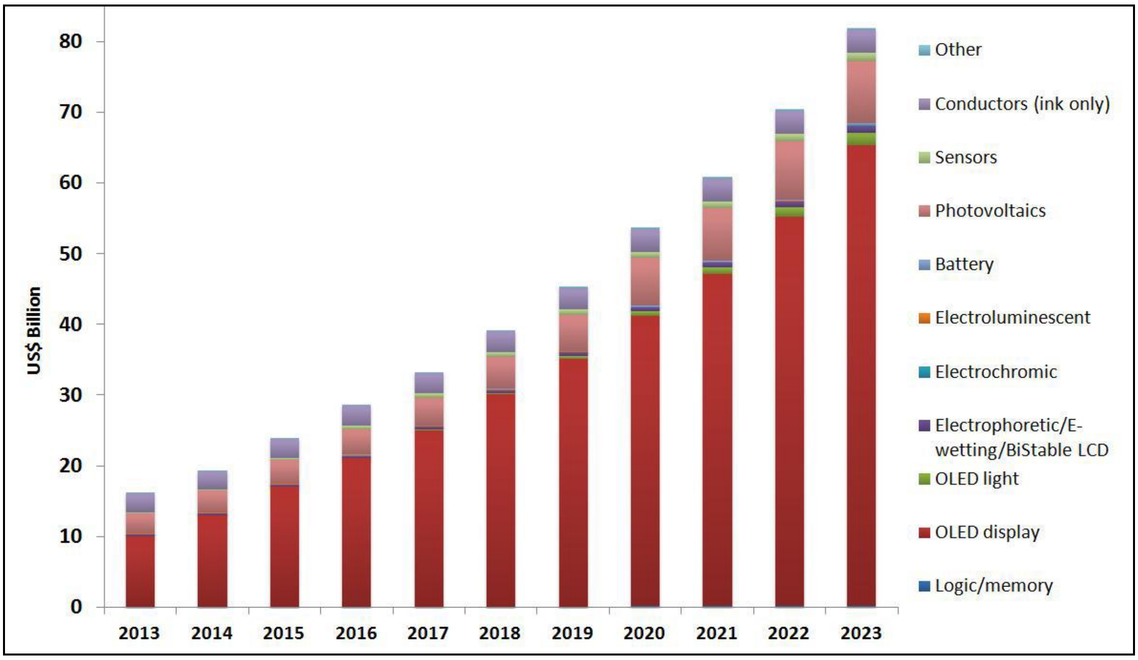


Figure 8. IDTechEx report “Printed, Organic & Flexible Electronics 2013-2023”. Reprinted from Das (2013).

Additive printed methods have great potential for increasing the speed of manufacturing exponentially due to the simplicity of the processes. Although the silicon technology is a main competitor, using conventional printing technologies for producing even only part of the product will increase the efficiency of the workflow.

Applications such as polymer LEDs (Light Emitting Diode) based polymer thin films (gravure-printed) and flexible organic FETs (field effect transistors) are studied for low cost fabrication. FETs have been produced using flexography (patterning) and gravure (coating) printing methods. In addition, research on polymer solar cells, nanostructured memory devices, fuel cells, diffractive optics and holography on product packages has proven that using traditional printing methods for production of these applications is successful. (VTT, 2006, pp. 14-29)

The research on applications in the area of indicators, sensors and packages contributed to the development of printable low-cost indicator systems for packaged food, antennas for RFID (Radio Frequency Identification), disposable biosensors and fibre-based packaging – active communication (sensors and indicators), passive communication (2D codes) and communicative (hologram printing). (VTT, 2006, pp. 30-43)

Bioactive paper integrates materials which can interact with the environment or a target substance and trigger a notification system. Applications of bioactive paper are researched in various areas from fungus detecting wallpapers to indicators for water and air contamination. (VTT, 2006, pp.41-47)

As the need for reliable analysing systems in medical care increases, the research on bioactive hybrid materials focuses on development and production of biosensors. In a study published in a review paper from VTT called “Research and development activities in printed intelligence 2006”, manufactured bioactive materials have been developed and have potential in a wide variety of applications such as point-of-care in medical diagnostics and optical MEMS (Microelectromechanical systems). (VTT, 2006, p. 38)

Foil-based microfluidic chips can be used in medical applications such as point-of-care or point-of-use diagnostics/analytics as personalized medicine, preventive medicine or drug discovery (VTT, 2012, p.33). Medical applications such as printed electrodes, smart blister packaging, smart textiles and products for vital signs monitoring are targeted in the future development of printed electronics (Breitung and Hecker, 2013, p.9).

The results of a new study have shown that it is possible to print two types of cells taken from the retinas of rats using an inkjet printer. Studies at the University of Cambridge have successfully utilized this technology and it has the potential to be used for generating new tissues grown outside the eye and then implanted in patients with retinal damage. (Lorber, et al., 2013).

5 Development of Interactive Metropolia UAS Campus Map

As a result of launching the Hybrid Media Networking project, Metropolia UAS is also contributing to research on printed intelligence. Experimental work had to be done in normal office environment in order to determine whether producing functional printouts in these conditions is reasonable. In order to start the experimentation work, an idea of a product that incorporates a functional printout had to be generated. Several ideas were considered and the one most suitable for the project was an interactive campus map for Metropolia UAS. This idea was chosen because of several factors, including simplicity of the structure, functionality and interactivity.

5.1 Initial Design

The concept design was created using GIMP (GNU Image Manipulation Program) for producing textures and Blender (open source 3D animation suite) for compositing the different components of the map. The information about locations of the campuses was estimated and their main areas of study were gathered from Metropolia's website, a section called Contact Information (Metropolia, 2013). The dimensions of the map were decided to be in A4 paper size.

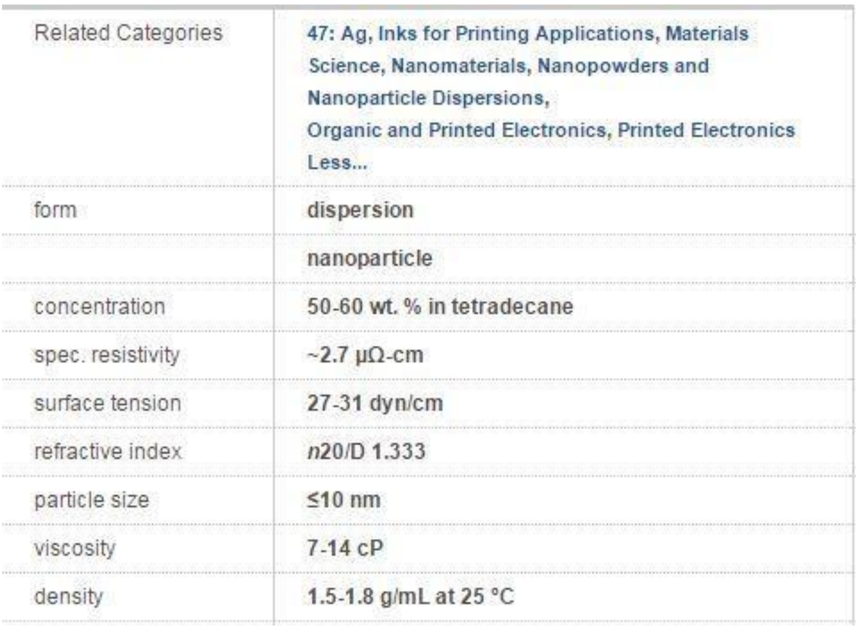
The design had to be scalable and flexible. Accordingly, a battery was positioned on the bottom right corner as illustrated in Figure 9. The top (first) layer was intended to be printed with an inkjet or electrophotography printer available at Digipaino, the digital printing lab of Metropolia UAS. It included a scaled roadmap of the capital region of Finland (Google maps, 2014), the Metropolia UAS logo and four buttons indicating the main fields of study available at the university. The locations of the campuses were designed as circular shapes overlaying the map and they had to be cut off from this layer in order to allow SMD (surface mounted device) LEDs to be visible when the map is assembled.

Figure 9. The first design of the Interactive Campus Map of Metropolia University of Applied Sciences.

The second layer was intended to incorporate parallel circuit design connecting the light elements (SMD LEDs sizes: 1608 and 2012) to the battery. In this initial design, the circuit used the two sides of the paper as illustrated in Appendix 1. The battery in this design was of lithium ion type as it could support the number of SMD LEDs connected. The next step was manufacturing the circuit. Although this design was not optimal, it envisioned the map structure.

5.2 Production of the Circuit Design

The conducted research on printing methods during the first phase of the project led to utilising Inkjet technology in producing the circuit as it was the ideal option for minimizing the throughput of used ink. The available equipment for this step was the OmniJet 100 Mini inkjet printing system. Consequently, the choice of materials was made according to the requirements for the piezo-electric inkjet system. The ink used at this phase was a nanosilver ink with particle size ≤10 nm that was purchased from Sigma-Aldrich – more information is provided in Figure 10. The choice of ink was made also because of its chemical compatibility, adhesion and functional properties that are suitable for producing the wiring.



Related Categories	47: Ag, Inks for Printing Applications, Materials Science, Nanomaterials, Nanopowders and Nanoparticle Dispersions, Organic and Printed Electronics, Printed Electronics Less...
form	dispersion
	nanoparticle
concentration	50-60 wt. % in tetradecane
spec. resistivity	~2.7 μΩ-cm
surface tension	27-31 dyn/cm
refractive index	*n*20/D 1.333
particle size	≤10 nm
viscosity	7-14 cP
density	1.5-1.8 g/mL at 25 °C

Figure 10. Silver dispersion data from Sigma-Aldrich. Reprinted from Sigma-Aldrich.

The OmniJet 100 Mini inkjet printing system allows the usage of four cartridges simultaneously and this provides an opportunity to use different functional inks. However, when this project was carried out, only one cartridge could be applied. The used cartridges were Samsung Mini 030 with a volume of 5ml and 16 nozzles. The printer was situated in the laboratory room, where UV safe yellow lighting is applied.

At the start of the experimental work, a few test prints were made using reused cartridges. In order to minimize the risk of clogging the nozzles from uncleaned ink residue, one cartridge was treated with IPA (Isopropyl alcohol). To preserve the nanosilver ink, it was kept in a fridge, and before testing, the ink was left in room temperature for about two hours. The preparation of the ink included dispersion of the nano particles with an ultrasonic homogenizer and passing the ink through a syringe Minisart filter shown in Figure 11a. The filter was designed to be easily attached onto the cartridge by a luer lock and this made filtering and inserting the ink very convenient and efficient (see Figure 11b). Filtering was a necessary step in order to clarify the liquid and to insure that big particles would not clog the nozzles. After inserting the nanosilver ink (2 ml), the cartridge was attached on the printing head.

a) Minisart filter b) Filter, syringe and cartridge

Figure 11. Materials used with the OmniJet 100 Inkjet system.

The OmniJet 100 Mini printer comes with a software for more precise adjustments of the printing process. The software has “Jetdriver” mode for designing the drop and adjusting the voltage waveform applied to the piezo-electric element in the cartridge. Another important section is the “Print” mode providing settings such as printing pattern, jetting frequency, DPI (drops per inch) calculator, drop size and drop count (drops in a pixel). In the “Jetdriver” mode, a camera is used to inspect and measure the droplets forming from the nozzles. Consequently, it was possible to design the drops for an optimal print quality, meaning that the drop has circular shape and no satellite drops forming from the tail. As illustrated in Figure 12, the droplet from the first test was ejected with a short tail that quickly rejoined it and there were no signs of satellite drops.

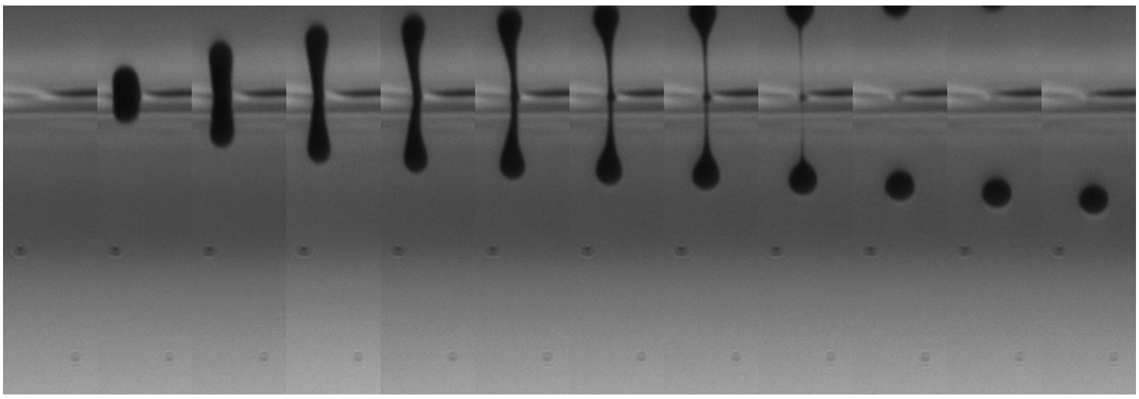
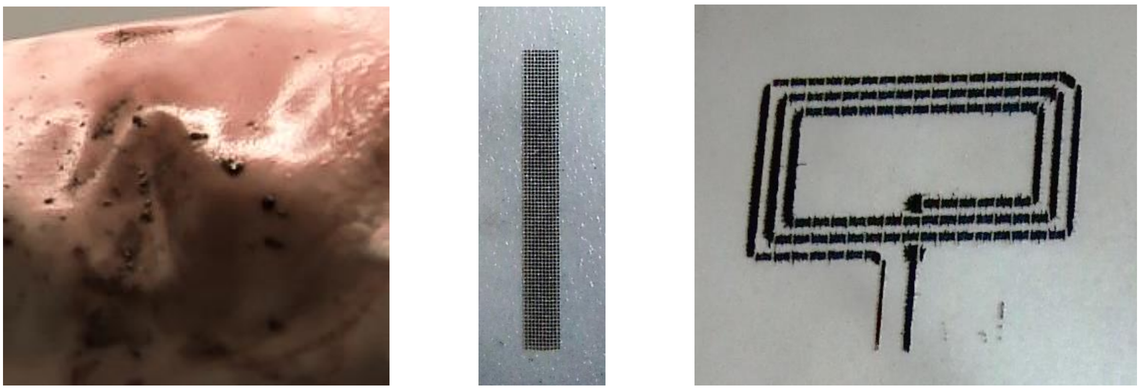


Figure 12. Inkjet printer nanosilver ink drop formation. Images generated with OmniJet 100 Mini inkjet printing system software.

However, during the second ejection, the drops were pulled back and started building on the bottom of the cartridge. That was an indication of a problem. After wiping the nozzles with a cloth soaked in IPA, the ejection was tested again. This time the ink began leaking over the bottom without formation of any drops. Next, the waveform was changed to implement first negative and after that positive voltage in order to give an extra push for the drop to form. Even though this action prevented the leaking of the ink, there were still no drops forming. After a short discussion with the team working on this project, it was decided that the cartridge had to be replaced with a new one. While the used cartridge was cleaned, big particle formations started to appear in the cleaning liquid, as shown in figure 13a. As a result of this, IPA was concluded to be the cause of the nanosilver ink particles to bond together in large masses, consequently, resulting in clogged nozzles.

Considering the effects of IPA on the ink, the next step was to exclude its usage and repeat the process. Two millilitres of the ink were filtered and inserted in the new cartridge. In the “Jetdriver” mode, the first ejected drops produced long tails, which indicated that the waveform had to be adjusted to use lower value for the applied voltage. Adjustments were made until the jetted drops had short tails and no residual satellite drops that resulted in lowering the voltage from 90V to 65V. The following step was to adjust the printing settings according to the size of the drop and substrate as well as choosing the printed pattern. The dimension of the printing plate supports a substrate of a maximum size A4 – paper size. For the purpose of testing, a glass substrate was used as it can be cleaned and reused. The first test pattern was a pixel pattern. The printed shape is shown in figure 13b. Although, the print was successful, the pattern was printed with a distance between the drops thus it did not provide the required structure (drops must connect) for conductivity.

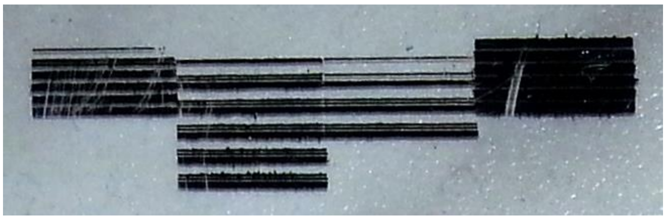


a) Nanosilver ink particles with IPA. b) Pixel pattern. c) Image pattern.

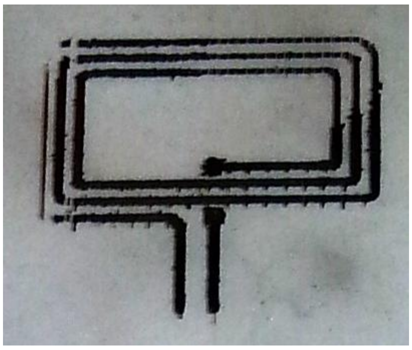
Figure 13. Inkjet test print problems using IPA as a cleaning agent.

After the pixel pattern was analysed, the printing settings were changed to print an image pattern. For the experiment with an image pattern, a monochrome digital image that had straight horizontal and vertical lines made of black pixels (the smallest picture element) with no gaps of white pixels along the shape. The printout is shown in Figure 13c. After a close inspection of the cartridge and the printed patterns, it was evident that there were places along the printed shape, where no drops were jetted. It was concluded that the reason for the misprint was clogged nozzles.

During this experimental stage of the project, the only cleaning solution for the cartridges was IPA. For that reason, the work with the OmniJet 100 Inkjet system was postponed for a few weeks until the arrival of a new substance – Tetradecane (ordered from Sigma-Aldrich) – to clean the ink. Meanwhile, the team had to get familiar with the safety measures for working with this chemical material. Access to the physics laboratory was acquired in order to use the chemical fume hood when working with Tetradecane. When the substance arrived, a new printing session was organised. The nanosylver ink was dispersed with an ultrasonic homogenizer to ensure that it had optimal consistency. A new cartridge was filled with 2 ml of filtered ink and positioned in the printing head. The same printing process steps as before were executed – a good droplet formation, pixel pattern and image pattern test prints. The pixel pattern print settings were set to print one drop per pixel.



a) Pixel pattern (ink surface scratched during testing).



b) Image pattern.

Figure 14. Inkjet test print problems using Tetradecane as a cleaning agent.

As shown in Figure 14, the printouts were misprinted. The differences in the test prints shown in Figure 14a are in the size of the pixel and the pixel count (number of pixels in the printed area) settings. The purpose for changing these values throughout the experimental prints was to produce a rectangular area, where the drops are printed overlapping each other and forming a consistent layer of ink with no gaps. From left to right in the image (see Figure 14a), the first three rectangular areas had the same values set for pixel and drop size and no margin space. The difference between the three areas was in the pixel count value. The fourth rectangular area, however, had a pixel size equal to half of the drop size which resulted in a more consistent printout. After printing the pixel patterns, the experimentation continued with reproducing the image pattern from the previous printing session. Although, the cleaning substance was changed, the printouts showed similar issues as when IPA was used. By examining the nozzles of the cartridge, it was determined that they were not blocked. It was evident that another problem existed, which was causing misprinting. Suspecting an issue with the delivery of the waveform signal to the cartridge, the experimental work was stopped and a specialist was called to check the condition of the printer.

5.3 Second Design

While the inkjet printer was unavailable, the initial design of the map was improved. As illustrated in Figure 15, the new design implemented a thin film battery, a foam layer and EL (Electro Luminescent) elements. The new design layout was improved by using GIMP and Inkscape (a professional vector graphics editor) open-sourced software.

Figure 15. The second design of the Interactive Campus Map of Metropolia University of Applied Sciences.

The thin film battery provides partial flexibility and optimises the thickness of the product. The batteries available for this project were Enfucell soft batteries – regular 1.5V, Mini 1.5V and regular 3.0V. The specifications are presented in Figure 16. If SMD LEDs were to be used in the development of the map, a switch circuit would have been needed with at least two regular 1.5V batteries connected.

SoftBattery	Reg 1,5V	Mini 1,5V	Reg 3,0V
Dimensions			
Maximum thickness	0,7 mm	0,7 mm	0,7 mm
Outer dimensions (± 1 mm)	60 mm x 72 mm	36 mm x 46 mm	60 mm x 42 mm
Maximum weight(1)	2,9 g	0,90 g	1,4 g
Performance(2)			
Nominal voltage(3)	1,5 V	1,5 V	3,0 V
Minimum initial capacity(4)	90 mAh at 0,6 mA	18 mAh at 0,2 mA	10 mAh at 0,2 mA
Initial internal resistance	~50 Ω	~150 Ω	~300 Ω
Maximum peak current(4)	8-10 mA	3-4 mA	3-4 mA

Figure 16. Battery specifications (Enfucell, 2014). Reprinted from Enfucell (2014).

The foam layer was integrated into the design to eliminate the thickness difference of the components as well as to provide a non-conductive gap between the buttons and the circuit on the functional layer. The battery had a maximum thickness of 0.7 mm and in order to neutralize the bending of the top layer, the underlying layer (the foam sheet) had to be 0.7 mm thick as well. Cut-outs for the battery, buttons and light elements had to be made. For creating the prototype of the map, a paper sheet provided from Digipaino was used as an alternative to the foam layer.

The new design included EL light elements instead of SMD LEDs to test if it is possible to produce them in an office environment and use them as location indicators for the map. In addition, the available EL-ink set allowed customization of the shape of the light sources and provided freedom in terms of design. The new light elements were designed in representative shapes in accordance to the four main areas of study as illustrated in Appendix 2. As the emitted light would have had the same properties for all components, a colour filter had to be made. Because the new design implemented EL lights with tailored shapes, the roadmap image on the top layer had to be enlarged so that the size of the lights would be optimized for better visibility and aesthetics.

5.4 Design and Print of the Top Layer and Colour Filters

The design of the top layer was simple and the button colours were consistent with the colour of the fields of study presentation on Metropolia’s website, a section called “About Us” (Metropolia, 2013). The top layer was prepared for print utilising the GIMP software. The initial design was improved by using Inkscape to include additional graphics for the buttons and scaling up the roadmap to its maximum size. These changes enhanced the visual appeal of the map and the overlaid shapes on the buttons provided an artistic logo association with the four main fields of study in Metropolia UAS.

The map was reprinted from Google maps services as its usage was free of charge. The light emitting elements were positioned according to the locations of Metropolia’s premises, as shown in Figure 17. Because this layer was intended for a traditional print, the image was exported as a PDF (Portable Document Format) file with the dimensions of 210 mm by 297 mm and a resolution of 300 ppi. The top layer was printed in Digipaino using the RICOH Pro C751 electrophotography copying machine.

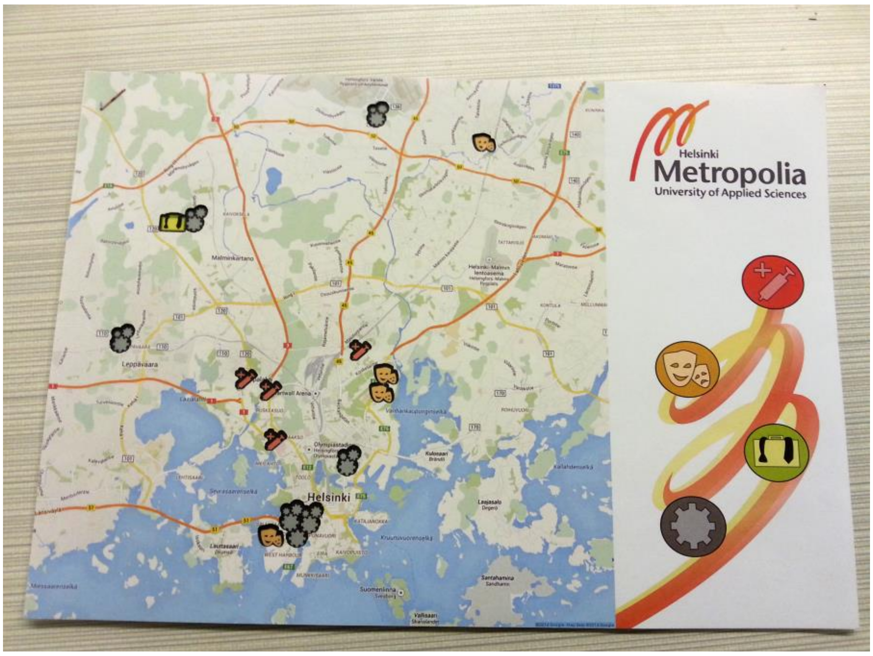


Figure 17. Top layer of the Metropolia UAS campus map. (Electrophotography)

Cut-outs, where the lights were positioned, had to be made so that the elements would be visible. In order to achieve that, the GRAPHTEC cutting pro FC 4510-60 flatbed cutter in Digipaino was used. A vector graphics (graphics comprised of paths instead of pixels) file had to be created containing the shapes that were going to act as guidelines during the cutting process. The software choice for this task was Adobe Illustrator. Since the EL light shapes were already available as vectors (paths) from the second design of the map, the simple solution was to create the guideline shapes by outlining the original ones. When this was completed, the printout was processed in the cutting machine. That was the final step in the manufacturing of the top layer.

The new design of the map required a colour filter to be produced. This layer had to be aligned over the EL light elements in order to deliver the desired colour effect. To create the image to be printed for this purpose, the existing vector graphics were used once more. As shown in Figure 18, the printing substrate was chosen to be a Xerox transparency film for colour inkjet printing.

Figure 18. Colour filter for the EL light elements.

The colour filter elements were outlined with thick black strokes in order to limit the light intensity emitted outside the borders of the shape. The design was inkjet printed in Digipaino.

5.5 Production of EL (Electro-Luminescent) Light Elements

When the new design was accepted from the project team, the development of the interactive campus map continued with research and the implementation of the EL-ink set. The inks were made available for testing purposes as a sample set from ELANTAS Beck GmbH. Guidance about deposition and curing practicalities (hardening of the materials) was also provided. The screen printing technique was used in producing the light emitting elements for the reason that the inks had viscous consistency. The chosen substrate was a polyimide sheet in A4 paper size. The structure of the electroluminescence component is built on several layers as illustrated in Figure 19. The substrate, onto which the EL layers were deposited, was a polyimide sheet of the A4 paper size. The screen printing unit was used for creating the first layer of four light elements using the conductive ink from the set. It was produced with an estimated thickness of 12 µm measured with a paper thickness gauge, and left under a UVA curing lamp for 5 minutes at the UV intensity of 120 mW/cm^2. Meanwhile, the silk screen was prepared to be cleaned. Regrettably, the solution available for cleaning the screen mesh did not remove the conductive ink residue and the remaining layers had to be deposited with an alternative method. In this case, the following technique was a manual application with a small wooden rod.

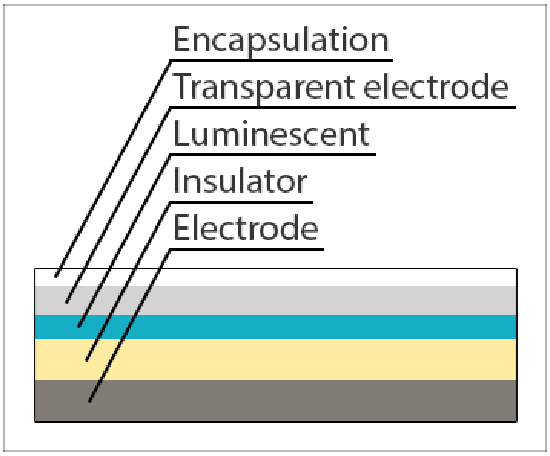
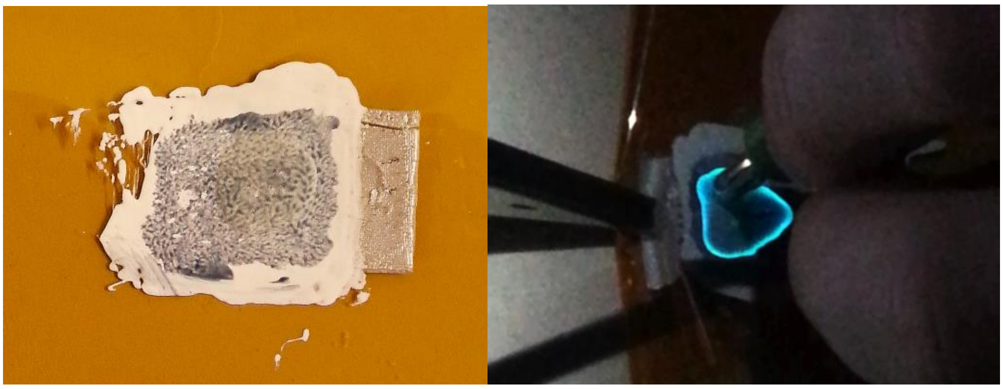


Figure 19. EL light emitting element.

The next layer was produced with the dielectric ink and it had to cover the bigger part of the electrode of each sample. A small line of the conductor, as shown in Figure 20a, had to be left uncovered in order to have a successful connection to a power supply. After the insulator was applied with an estimation of the thickness - 11µm (measured with micrometre), the curing process was repeated by using the UVA lamp for 5 minutes. The following layer consisted of an active luminescent phosphor, which determines the shape of the lit element as presented in Figure 20b. The estimated thickness measured for this deposition was 20 µm; consequently the curing time was 10 minutes. The next layer had to be a transparent conductor applied over the insulator and active phosphor. One millilitre of ink was put onto a wiping towel that was used to transfer small amounts of ink at a time. However, it was not an efficient solution because the towel absorbed the ink and it could not be used again after the experimentation. This method proved to be successful in producing a thin layer. Nonetheless, as seen in Figure 20a, the recommended thickness of under 1 µm was not achieved. In spite of this, the samples were left to cure and later tested.



a) EL printed element. b) EL - 220 Volts applied.

Figure 20. EL light emitting elements.

The produced EL light components were tested by applying AC current gradually. From 0 to 100 volts the samples were not emitting light. When the voltage was increased to over 100 V, a flickering was noticed. The more voltage was applied, the brighter the phosphorous component became. The intensity of the light was increasing up to 220 V. However, as seen in Figure 20b, the active layer was emitting light only at its edges. This indicated that the deposition should be much thinner to allow the whole shape to be lit.

Four EL lights were successfully produced during this experimental work. However, the requirement of such high voltage supply is not feasible for this map concept. Therefore, the implementation of EL light elements was postponed until new experiments are made using different printing techniques.

5.6 BOM (Bill of Materials) for Metropolia Campus Map

During the experimentation phase of this project, various materials were utilized for producing the different components of the map. The choice of supplies was made on the basis of their functional properties. For printing the circuitry, the nanosilver ink was selected for its conductivity and adhesive properties. The EL-ink set was provided as a sample kit from ELANTAS which contained all necessary components for producing EL elements. It is important to note that the BOM calculated in Table 7 does not include the price of the EL-ink set used in the experimental work. However, to determine the estimated BOM for a single print, an alternative EL ink set from KPT is used in the calculations. The KPT inks include transparent conductive ink, electroluminescence paste, insulating material and conductive paste. The two EL ink kits are used for producing EL displays. (OE-A, 2014; KPT)

Table 7. BOM for Metropolia Campus Map

material	price_€	quantity	total	note
silver ink (25g)	293	0.016339869	4.787581699	~15.3 ml per bottle
Polyimide (sheet)	0.029	1	0.029	
Tetradecane (656ml)	236.7	0.015243902	3.608231707	
		sum	8.424813407	
material	price_€	quantity	total_€	
polyimide	0.029	1	0.029	
EL ink set (ELANTAS)	0	1	0	
KPT EL ink set (100g/min order)	366.23	0,02	7.3246	
silk screen	21.5	0.001	0.0215	
Squeegee (Circuitnet)	5.5	0.000002	0.000011	
fat remover (250g)	4.7	0.058333333	0.274166667	
battery			4	
printed map A4	0.6	1	0.6	
		sum	12.24927767	
		Total BOM	20.67409108	

The calculations provided in Table 7 are for one print only. The BOM for producing the interactive campus map indicates that this process is not yet cost-efficient. To reduce the bill, more research and development is needed. Data and calculation are for one print only.

6 Results and Discussion

During the first phase of this thesis project, research was conducted on traditional printing processes and their current usage in producing functional and intelligent printouts. The study led to an exploration of various applications in the field of printed intelligence. It was an important learning experience as it introduced new application areas for printed industry to encounter.

The studied literature provided useful information that was utilised in SW analyses for each additive process and one for the subtractive processes. The analyses were created with the purpose to guide the development of the interactive campus map of Metropolia UAS. In addition, they presented the advantages and disadvantages of the techniques in accordance with cost-efficiency, speed of production and usage of materials. The SW analyses served their purpose as they were used in deciding which printing method to use in manufacturing the circuit design of the map.

In the beginning of the second phase of the project, an initial design was created to present the different layers of the map. The optimal solution for producing the prototype was clear. In the SW analyses, it was indicated that the inkjet technology has most advantages in prototyping and testing. As a result, the decision to use this method was made fast. As the experimental work started on creating the circuitry, some issues started to arise. The first tests were made with nanosilver ink, which has very good properties as a conductor. Although the samples were misprinted, they prove the feasibility for inkjet technology to be implemented in creating functional printouts. After a close examination of the printed shapes, it was evident that not all 16 nozzles of the used cartridge were jetting drops during printing. When the cartridge was cleaned afterwards, it was discovered that isopropyl alcohol changes the composition of the nanosilver ink by causing the particles to bind together thus clogging the nozzles. It is important to mention that IPA was used in preparing the cartridge before the ink was inserted and for wiping the excess liquid that formed when it was positioned into the printing head.

During the following printing session, the printouts were misprinted again, in spite of using different cleaning solution. As the nozzles were not clogged this time, this indicated that there was another issue. Suspecting that the waveform signal was probably being sent inaccurately, the experiments on producing the circuit stopped and

maintenance of the printer was carried out. Although it was not possible to proceed further with this development, the experiments provided a positive answer to the following research question:
- Is it feasible to produce functional printouts using conventional printing methods in an office environment setting?

A limitation was observed, when printing in the uncontrolled environment of the laboratories. Pollutants such as dust could significantly lower the conductivity of printed wires or thin elements. If a dust particle creates a bridge between the ink components, it would affect the electrical properties of the printed matter. During the experimental work done for this project, the deviation in humidity and temperature did not noticeably affect the produced printouts on glass and polyimide substrates.

While the inkjet printer was unavailable, the design of the map was improved by including new design elements, a thin film battery, EL lights, a foam layer and a colour filter. The top and colour filter layers were printed with conventional printing methods.

The experimental work continued with producing four samples of EL light elements. The screen printing kit was used for the deposition of the first layer. Unfortunately, the conductive ink did not get cleaned off and the silk screen could not be used in the following procedures. However, the work continued by implementing an unconventional technique to apply the rest of the layers. The process of producing the samples was complex and time consuming due to the EL element structure being made of five layers. On the other hand, the ability to tailor their shape allowed a more creative and innovative design.

7 Conclusion

The purpose of this thesis was to answer research questions regarding the feasibility of producing functional printouts in an office environment using conventional printing methods and their estimated BOM. As a result of the conducted experiments, it can be concluded that the manufacturing is possible when taking into account the environmental factors of the uncontrolled environment. As for the estimated BOM, the calculations made for the used supplies in producing the interactive campus map shows that the research and development in this area needs to be significantly increased in order to reduce its costs.

The findings presented in this study led to conclude that in order to better understand the properties, composition and behaviour of functional inks and substrates, further experimentations have to be made. The increasing interest towards printed intelligence is evident as the demand for research on different applications continues to grow.

There were a few challenges during this project where an answer to the arisen problem had to be found fast. In these situations, it was important to be able to think “out of the box” and find an alternative solution. This provided a very good learning experience.

This thesis had significance for the Hybrid Media Technology Networking project as it answered the set research questions. It also provided SW analyses with the purpose to be used as guidelines in the manufacturing of printed intelligence applications.

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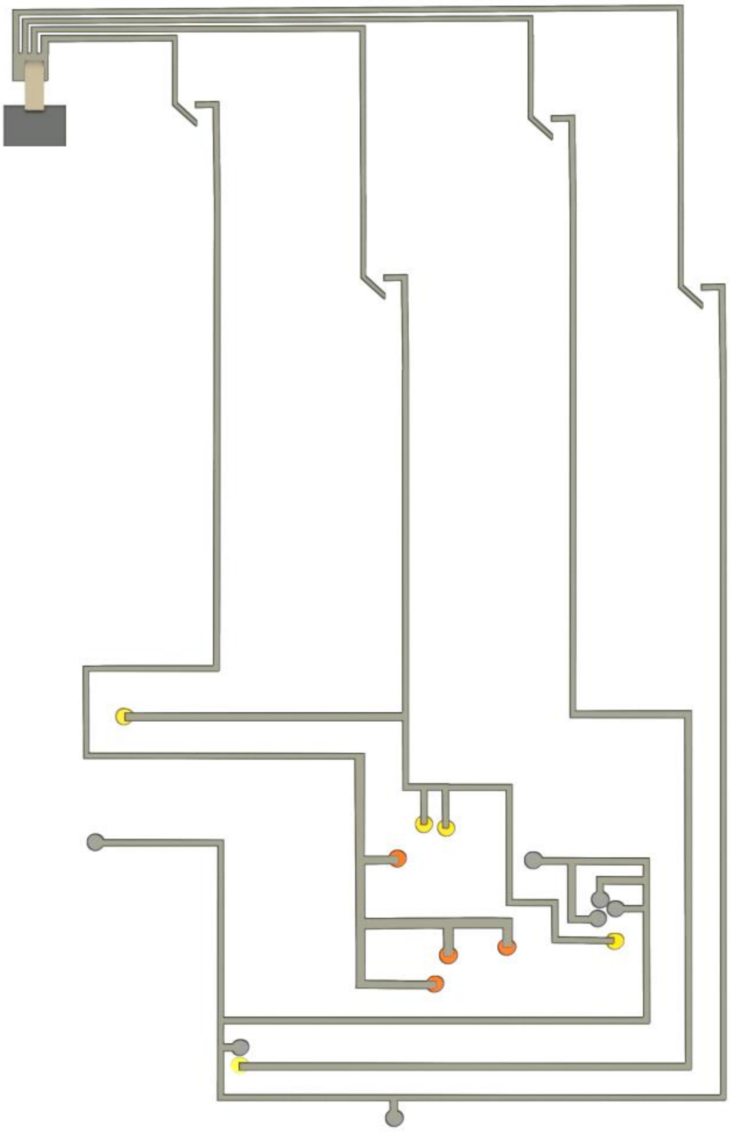
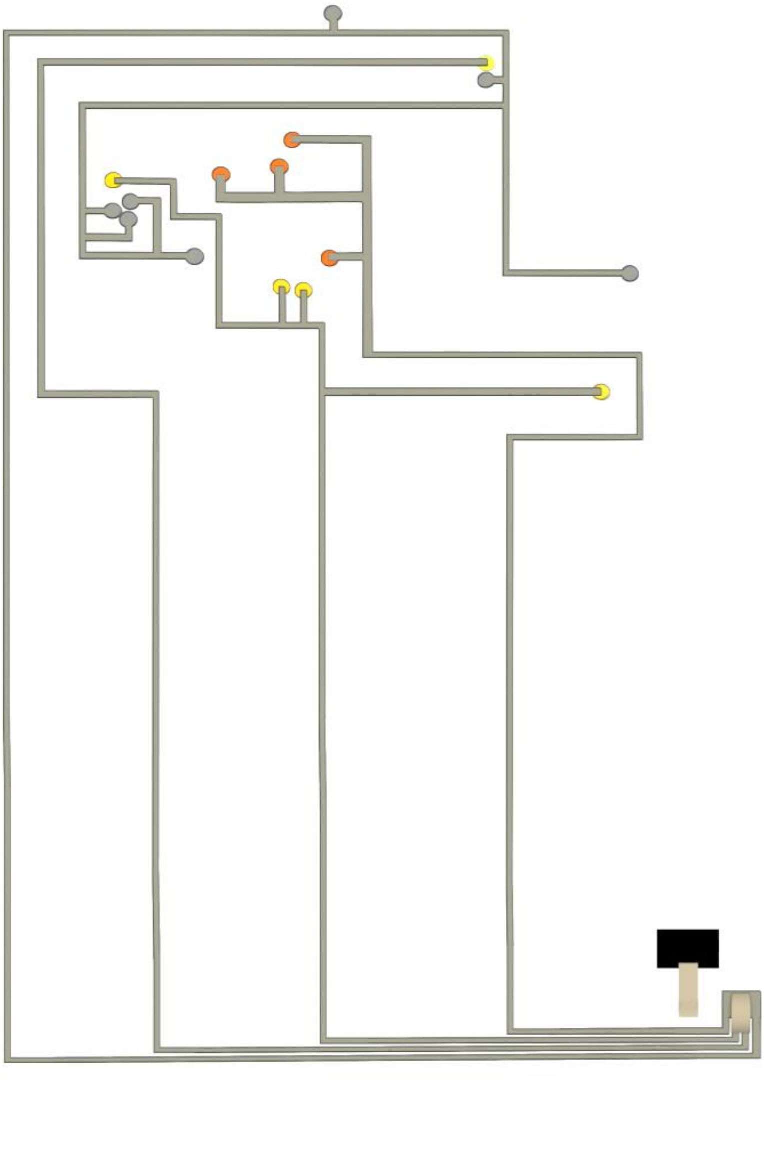
Initial Circuit Design

Top



Bottom



Design of EL Light Elements and Colour Filters