Excerpts from co-authored article

Coatanéa, E., Kantola, V., Kulovesi, J., Lahti, L., Lin, R., & Zavodchikova, M. (2009). Printed electronics, now and future. In Neuvo & Ylönen, (eds.), Bit bang – rays to the future. Helsinki University Print, Helsinki, Finland, 63-102. ISBN 978-952-248-078-1.

Following sections of the article are written individually by Lauri Lahti:

3.1 Standards

[In subchapter "Manufacturing standards"]

PE [printed electronics] is expected to have a great impact on the traditional product development process of the computer industry. Software is going to manage functions that were previously handled by hardware and vice versa. A new kind of collaboration in design and production is needed.

PE will provide a large variety of interactive components and sensor networks that are capable of collecting, holding, processing and sharing data. This also implies a radical change in programming paradigms related to communication without interference, concurrently running programs and complex management systems to monitor and adjust the overall operation. Developing devices with a miniature size will bring challenges with respect to computational efficiency, limited energy and bandwidth, heat balance and the changes in electromagnetic phenomena on a small scale, fault tolerance and error recovery. Knowledge of embedded systems can valuably support developing technology of PE.

Since the store of information is becoming more affordable and the amount of information grows constantly, it poses new requirements for managing the history of data. Many devices benefit if data can be updated frequently to reflect changes in the environment. In many cases, historical data has a specific value for predicting and adjusting future functionality. In the future, official documents will likely record a detailed log of the events in which the document has been involved.

Thus, the authenticity of electronic documents and their usage history could be verified in a new manner and with particular detail, for example with trade treaties, health statements, insurance agreements, degree certificates and diplomas. Many of these types of information could have a significant economic, political and strategic value. Society might become largely dependent on the reliability of electronic documents.

There is a need to store data in such formats and encodings that remain compatible and easy to interpret even in the far future. Metadata and redundant variants of the original data can help to accomplish this aim while still trying to keep the data in a compact form.

Electronic documents also require encryption techniques, but, due to their small scale and limited computational power, the structures might not easily al- low suitable complexity for encryption. Also disposable documents pose a challenge to security.

An access rights management system could provide different kinds of rights for perceiving the data, modifying it and deleting it, making copies or transmit- ting the contents elsewhere.

Formerly, it was usual in product development to implement prototypes and to perform user testing, and with the gained results to iteratively develop better prototypes until an acceptable level was reached. With PE it is no longer so easy to control prototype testing since the spectrum of new devices is becoming more complex and can consist of many interacting components. Therefore, the user experience is reaching forms that are difficult to describe and measure. Many new services will be provided in a constant beta testing manner like currently many of the products of Microsoft and Google.

5.1 Roadmap for Future Development

Adoption Proceeding from Industry to Consumers There are many dif- ferent predictions concerning the future development of printed electronics. With respect to the emergence of new applications that can be adopted to everyday life, it is hard to estimate the trends. It is probable that many applications first will be used in the industrial domain, then adopted by some individual professionals and only after that will they become an active part of life for normal consumers [11].

This report has given specific emphasis to RFID [radio frequency identification] tags, PV [photovoltaic] cells, OLEDs [organic light-emitting diodes] and e-paper [electronic paper]. The first round of products will still be rather modestly intelligent and provide the services of simple hybrid media. In the industrial domain, RFID tags can help in monitoring logistics. Printed PV cells can secure energy supply in critical devices and OLEDs and e-paper can provide energy-efficient lightning and displays. At first products will also carry a higher price to cover the initial development costs. Creating efficient standards and environmental strategies may help in successful adoption.

Due to extra investment and limited robustness printed electronics will probably enter the market most strongly with RFID tagging. When compared to the other three main product categories, RFID gets special attention by offering a new type of functionality that has not been achieved with older technology (wireless tracking of objects) whereas conventional technology has been able to produce solar cells, lighting devices and displays.

New printed products will probably arrive first in restricted application do- mains in industries that focus on mass production and logistics. They benefit from predictable environments and activities. Even a small amount of printed devices can provide valuable support for industrial processes in well-chosen control points of an assembly line or at a gateway of transportation. Investment is easy to amortize since it provides a significant competitive advantage relative to more conventional manual labour.

The success of organic light emitting diodes and photovoltaic cells depends a lot on how easily they can be added to different surfaces and applied to various forms. Also the efficiency of the light emitting process and the photovoltaic process determine their usability. In large and dense sets of these devices efficient passage of light and managing heat becomes crucial. It would be favourable that the photovoltaic process could be added on top of any kind of printed electronics, especially on electronic paper and other displays. Also the ease of recycling, maintaining or updating old devices becomes increasingly important as volumes of the market increase.

Gradual Evolution of Functionality on the Market It has been predicted that the cross-influence of printing and electronics industries will produce a variety of intelligent and affordable PE devices that will heavily penetrate the markets of everyday life as mentioned in the introduction to this report. Kleper [12] suggested one future roadmap for PE that explains how, due to intensive research, the functionality of new products gradually rises during the subsequent decades, as shown in Fig. 12.

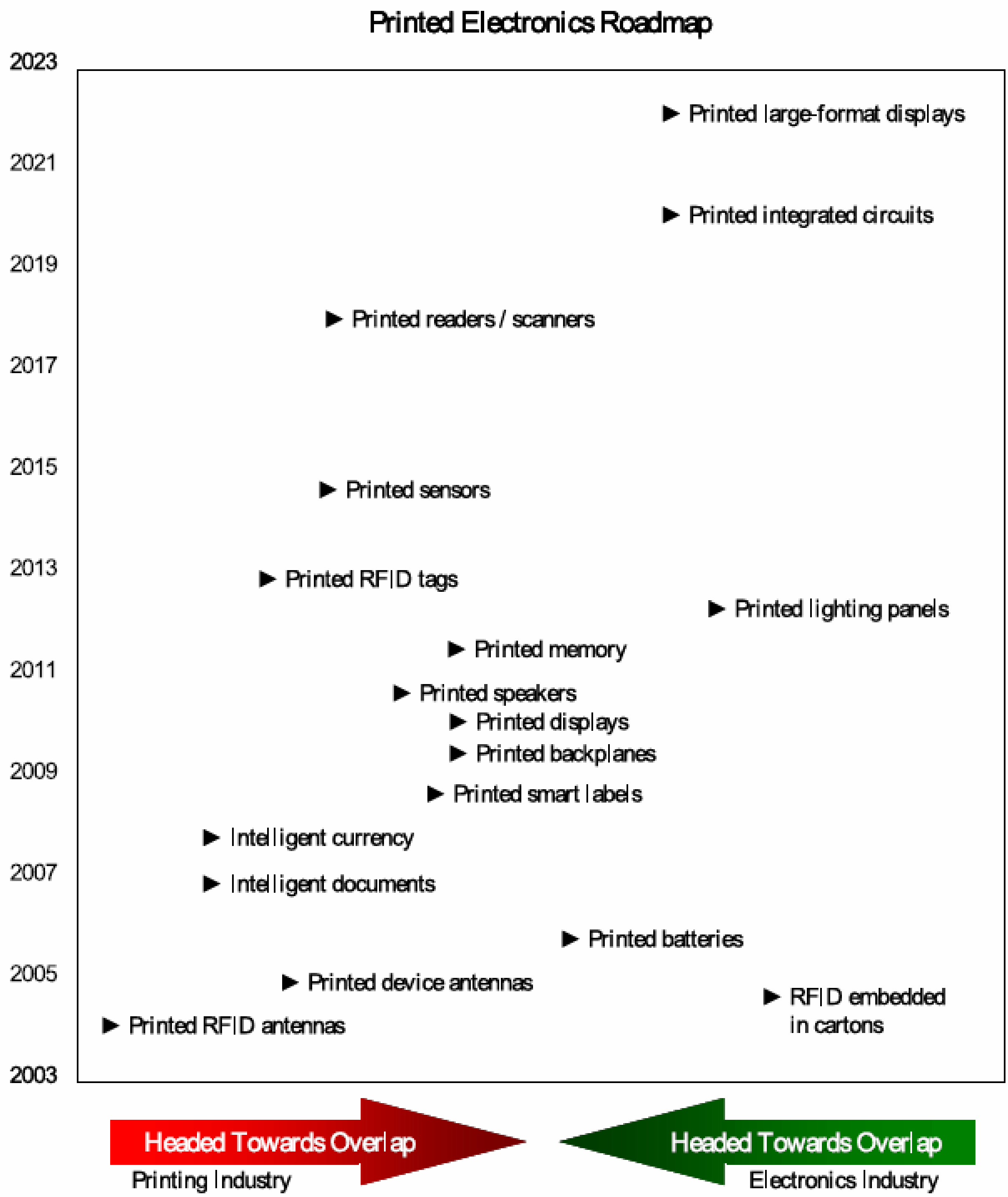

Figure 12. The cross-influence of the printing and electronics industries will likely produce an impressive array of low-cost, intelligent devices that will infiltrate nearly every aspect of everyday life. (Source: [12])

According to [12], one of the first applications of PE that has already rather actively appeared on the market is RFID embedded in cartons. By 2010, some of the central products to emerge on the market, in an estimated chronological order, include: antennas, batteries, intelligent documents and currency, smart labels, backplanes and displays. Later on, by 2015, the hot novelties are estimated to include speakers, memory and lighting panels. Also printed RFID tags are supposed to be actively launched to the market. Printed sensors are appearing on the market as well. Then, by 2020, readers and scanners should have an increasing role in new products. Readers and scanners can refer to, for example, devices that can gather and analyze knowledge from printed items. Finally, by 2025, it has been predicted that integrated circuits and large-format displays will become widespread on the market. Integrated circuits can refer to a variety of complex devices built using printed components and large-format displays can cover a diverse set of light-emitting surfaces. In this listing photovoltaic cells are not mentioned but they are currently entering the market.

The global economic crisis starting in the year 2008 may give a reason to question the optimism of some earlier predictions concerning the development of PE. Thus, it is possible that development may significantly slow down.

Functional Inkjets as a Driving Technology According to [13], functional inkjet inks are predicted to gain a strong position in the future markets. New materials are supposed to lower costs and increase performance in comparison to traditional methods, such as silicon-based electronics. Jetted metal layers are expected to provide a new level of functionality in many areas. Being fairly inexpensive materials, jetted tin and lead solders have been convenient for fabricating interconnects in rather simple devices, for example resistors and many photonic devices. However, environmental risks due to these substances and in- creasing regulation for example in the European Union force the use of more environmentally friendly materials [14]. Jetted silver and copper can be used to reach smaller features and to provide higher connectivity than in current screen printing techniques used for printed circuit boards.

Many new kinds of inks are actively being developed and they can be, for ex- ample, conductive, photoactive, thermally sensitive, memory retentive or chemically sensitive. Different properties can be combined to provide inks tailored for specific needs but often combinations lead also to some trade-offs in functionality. Since inkjet does not require firm contact with a surface, it is well suited to sensitive and soft substrates, like textiles, boards and even human tissue. Inkjet is also a favourable technique, for example, in the production of wearable electronics, smart packaging, and drug delivery systems. Also products with large surface area benefit from inkjet, for example displays, lighting devices, RFID tags, sensors and photovoltaic cells.

Due to the very small size of the inkjet print head nozzle, producing new biomedical products may become possible. Diagnostic devices produced by inkjet printing could revolutionize the way medical care is provided for everyone. Other application sectors in this field include tissue engineering, drug delivery and screening, genomics, biotechnology and biosensors. One ultimate goal would be organ printing that means computer-aided jet based tissue engineering. The printing process could use specific tissues or cell types to provide required functionality, for example in transplantation and cancer treatments. Finally, organs could be printed using a patient's own cell type, thus eliminating rejection linked with donated organs. Promising results have been already gained with existing off-the-shelf printers.

Today already three-dimensional printing is used by many manufacturers for rapid prototyping [16]. Inkjet technology will offer new cost-effective and fast ways to provide three-dimensional modeling and prototyping. Especially fruitful results can be achieved when combining inkjet techniques with novel photopolymers, ceramics, polymer-clay nanocomposites and polymer blend inks [13].

Tailored Products based on Printed Electronics Products based on printed electronics will likely become tailored to different circumstances like heat, cold, wet or radiating environments. Their functionality and computational efficiency could be boosted for some specific energy consuming situations by adding inks that have an extremely high concentration of ions, good fluidity, low viscosity etc. The ink layers might also automatically adapt to the current environment. In displays the visualizations could be optimized to current lighting conditions and a person's vision. The principles of Gestalt psychology could be applied to visualizations. A display could automatically optimize shapes so that human visual system could use efficiently its innate skills of recognizing figures holistically instead of just as a collection of simple lines and curves. Thus, a person could perceive and learn intuitively as much as possible without even needing to focus attention systematically to collect pieces of information from illustrations.

Degrading inks could be maintained by adding or replacing its components. It might be possible to modify each ink layer separately using enzymes or nanorobots that are attracted only by some specific chemical compounds. An easily removable membrane could be placed between ink layers and removing it could activate new added functionality in the product. This removal of membrane could be applied to some specific areas of the printed circuit thus changing the flow of electrons corresponding to new computational needs. This could be applied to tickets, entrance permission documents, parking tokens and other coupons.

It might be even possible to connect separate printed items together to launch still other functionality. As in building puzzles, it could be possible to gradually expand the functionality of a printed product. Users could customize the de- sired functionality of the product by choosing those components that they need and joining them together with, for example, some kind of paper clips. Later it might be possible to just have a stack of printed cards and shuffle their order to achieve the desired functionality. For manufacturers this could allow easy market segmentation and versioning of products.

The products could hold secured content using confidential electromagnetic properties of the printed surface. The printed surface might also show visual notation that could be interpreted with some secret code. The printed surface could provide varying content and functionality depending on the access rights of the user. These access rights could be wirelessly indicated by holding another printed item beside the surface. While maintaining the trustworthiness of an official document, it would be useful to support making corrections and commenting. For this purpose, people might use specific devices to modify the functionality of a printed item.

Production of Printed Electronics Arriving at Home Wide-spread adoption of printing has had a large cultural impact. Due to cost-effective printing techniques, a broader range of readers has got access to knowledge and also has been able to build on the intellectual work of earlier generations. Printing has provided new possibilities to analyze knowledge by offering a sustained and uniform reference for it and furthermore by easing comparison between conflicting view- points. Consumer-driven adoption of printed electronics can possibly accelerate this positive trend.

Until the late 1980's, printing at home and in offices was not very common, or it was done with limited quality compared to publishers, the main technology being often monochromatic matrix dot printers with low resolution. In the mid- 1980's the first inkjet printers aimed at ordinary consumers were introduced. After the initial investment, inkjet technology enabled people to produce prints at home at relatively low cost, competing with the quality of publishers, especially in text and later in graphics. The development of the inkjet narrowed the quality range of publishers, express on demand print shops, and home printers. In two decades home printers more or less reached the level of print shops and photography laboratories. This evolution challenged seriously the business model of printing industry.

It is possible that in the production of printed electronics, progress will follow the same path as ordinary printing. In the first stage, consumers can acquire printed electronics mainly as the products of large-scale industrial manufacture. These products can be fabricated in a large variety of versioning but they are not printed on demand or specifically tailored to the needs of an individual consumer. In the second stage, printed electronics can be produced at local photography laboratories in customized formats on demand. At this point, the technology is still so expensive and complex to maintain that it is economical to keep these services centralized. In the third stage, producing printed electronics will become possible with consumer technology that is easy to use at home and is reasonably priced.

For instance, in 2030, a consumer can possibly download design templates for printed electronics from a network and modify and test them virtually to meet her needs of functionality. Then she can produce a corresponding artefact with a home printer that operates in the nanometric scale of the substance. In this situation, the uniqueness of an object begins to loose its meaning also affecting patents and immaterial rights. This resembles the visions of moving matter from one place to another instantaneously (teleportation). Instead of sharing just knowledge, also real-world functionality of context-aware artefacts could be easily duplicated all over the world.

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