

# Roadmap Printing

## “From the World of Print to the Printed World”

December 7th, 2011

-- Summary --

### 1. Societal and economic relevance

The global graphical printing industry is 440 Billion€. Today, still only 5% of all printing is done digitally, with inkjet becoming the dominant printing technology. As the digital age advances, the transition from traditional analog printing techniques (such as offset) to digital printing offers huge growth opportunities. Digital production printing is forecast for a compound annual growth rate of 11.5% until 2015.

Next to graphical printing, also new printing applications offer growth opportunities in a field called “Industrial Printing”. First commercial applications are found in textiles, packaging, display graphics and printing of colour filters and coatings for displays. An almost unlimited number of new applications have been identified in areas like printed electronics, solar cells, displays, food and nutrition, 3D printing, medical diagnostics and even printing human tissue and organs. Printing is evolving from “printing of information” to “printing of things”. In the “printed world”, printing is to be considered as a versatile digital manufacturing method.

Digital printing technology may help to revolutionize the manufacturing industry. After the industrial revolution and the digital revolution, we are at the dawn of a “digital industrial revolution”. This transition is enabled by a new manufacturing paradigm called “Digital Fabrication” which entails on-demand manufacturing, zero-waste, no stocks, high flexibility, fast turnaround, small series, personalization, mass customization and very short distribution and supply chains. In this new paradigm, *designs* rather than *products* will be distributed around the globe as digital files and manufacturing can be done local. Implications will be profound, with clear positive contributions to major societal issues as scarce resources and environmental impact (low/zero waste, lower energy and material use, shorter logistic chains). Building on a strong track record in manufacturing innovation we need to anticipate and prepare for the next wave of innovation that will once again fuel future growth, and commit to an effort to reclaim part of our manufacturing heritage.

The market for digital inkjet printing grows rapidly. With knowledge and experience available within the Dutch HTSM industry, and the excellent international position of the Dutch academia in related relevant scientific areas, we are well positioned to capture a significant part of this growth.

Industry size digital inkjet printing (B€)	World 2010	World 2013	World 2016	NL 2010	NL 2016
Graphics	16	24	36	2	4
Industrial	3	15	60	0.1	4
<i>Total</i>	<i>18</i>	<i>39</i>	<i>96</i>	<i>2.2</i>	<i>8</i>

Total Dutch R&D expenditure (M€)	2010	2016
Dutch R&D expenditure	180	240

## 2. Applications and technology challenges

For further development of industrial printing and in targeting the most promising application domains, it is paramount to leverage on technology developed for graphical printing, such as inkjet technology. Specific characteristics and advantages of inkjet printing technology for manufacturing purposes are:

- Highly efficient use of material (additive process);
- Contactless material deposition on substrates & no masks required;
- Very accurate deposition of materials on micron scale (in quantity as well as in position);
- Possibility to create complex 2D patterns, 3D structures or objects consisting of a range of (mixed) materials.

With its roots in graphical printing, inkjet technology has rapidly progressed over the past two decades. However, major further technology advancements are required to match the far more stringent requirements for applications in industrial printing. In addition, application research and development is also essential.

### 2.1 Application domains

#### *Graphics industry*

It is believed that the transition from black and white towards color printing and increasing pressure on costs will eventually result in inkjet becoming the core technology in small as well as wide format digital printing. The shift from analogue printing (offset, flexo, screen printing) for graphics applications (advertisements, books, brochures, packaging, labels) towards digital printing (print on demand, just in time) will also fuel the transition towards inkjet as core technology for these markets. The latter will create opportunities for existing and new Dutch companies, with inkjet technology being developed further for new applications and increasing knowledge and expertise within the Dutch printing ecosystem. For graphical applications increasing speed and reliability at a cost effective level are main technology challenges.

#### *Textiles*

Digital inkjet printing of colors and graphics on textiles replaces part of the analog printing done traditionally with rotary screen printing. Speed and reliability and the range of printable dyes need to be improved for further penetration. A further step includes adding high tech functionality to textiles. Wearable electronic functions are expected to reach the market in the next decade, such as solar powered personal electronics, wearable displays or lighting for emergency purposes, electronics for safety and integrated health monitoring devices. Next to electronics also applications will emerge from adding tailored and controlled substances to fabrics for example as insect repellants, anti-bacterial agents or to provide active self-cleaning properties. Tuning of printheads and advanced materials is a key challenge for this field.

#### *Decoration and printing of security features*

Decorative layers or patterns can be applied using inkjet, not only on 2D but also on 3D surfaces. Inkjet advantages in this field will allow mass customized solutions for various 2D and 3D products and packaging: mobile phones, objects for sports, smart phones, cars, etc. Printing of security features on documents, packaging or other products for anti counterfeiting is also an emerging and fast growing market opportunity.

#### *3D printing & additive manufacturing*

Complex 2D patterns and 3D structures can be produced from mixed materials using inkjet or other digital methods and this will open up new markets in high tech manufacturing. Unique products can be made of very complex structures with different materials deposited on micro-scale at the same time, without using production tooling like moulds or masks. Complex shapes that are impossible to achieve with present techniques are feasible by 3D-printing. A step further could be precision optics by printing lenses. Today Rapid *Prototyping* already exists and technical progress is steadily made. Rapid *Manufacturing* encompasses the move to using fully functional materials so that 3D printed

objects will have a full set of end requirements. For this the range of materials that can be processed as well as the maximum build size and production speed need to be enlarged. This step still requires technological breakthroughs in for example speed, precision, cost and quality.

#### *Printed electronics*

Using inkjet as a manufacturing method for electronics will create huge opportunities for existing and new industries. Examples are printing of etch resist patterns for PCBs (Printed Circuit Boards) or antennas. A further step may be printing of conductive 'inks' on flexible foils for OLED displays, large area OLED lighting panels or RFID-tags. Printing conductive tracks under atmospheric conditions as well as masks or other functional material on solar cells also offers a huge market potential. A different approach to creating conductive patterns could be to print metal tracks or circuits directly from the pure metal vapor or liquid phase. An interesting application for the semiconductor back-end industry is filling of holes in silicon wafers with conductive material to accomplish so called TSVs (Through Silicon Vias) for interconnections in stacks of chips or for cooling of high brightness LED's. Another opportunity is jetting of fine structures of conductive or other functional material on plastic foils that have a patterned wetting/non-wetting surface resulting from a patterned pre-treatment with an atmospheric (micro) plasma. Similar as for printed circuit boards, printing technologies are and will be used more and more in manufacturing of large area electronics as encountered in organic LED, photovoltaics and new generations of (thin, flexible) displays. The difference between PCB's and large area electronics might be the ultimate drive to high-speed roll-to-roll printing.

#### *Food and nutrition*

Jetting of very small droplets in huge quantities is an interesting new option to produce spray-drying powders for food or foodstuffs. Also jetting layers or patterns on solid, jelly or fluidic masses will allow new features for food products that can be produced in large quantities, but with high variance (small series, or even unique samples). It is envisioned that inkjet printing will be used for adding very small personalized quantities of vitamins or other food additives to daily meals. In the somewhat more distant future it might be envisioned that complete meals can be inkjet printed, taking into account nutritious value as well as texture for achieving both the required taste and bite experience. Within the above mentioned application areas it is to be expected that connections between HTSM and the Food and Nutrition programs will emerge.

#### *Biomedical & healthcare*

Complex 3D biomaterial structures, like heart valves, organs or bones for human implants that are printed exactly customized to a patient's need can be envisaged for the future. Issues like the influence of shear stress on biological material when it is ejected from an inkjet printhead will become important when this field advances. Also dental applications like printing layers or components, even inside the mouth, have already found their first commercial applications.

Inkjet printhead technology is also under investigation for edible or implantable disposable micro drug dosing devices or for use in micro dosing equipment that can enable fast and large scale titrations for advanced screening of effectiveness of new drugs. Printing of very thin and localized coatings on bio-implants is also an exciting opportunity. Using inkjet to position magnetic or other functional 'marker' particles, cells or drugs also holds a great promise for the healthcare industry, for instance for MRI imaging techniques or very localized or controlled drug deployment. Inkjet can also be used to produce complex bio-array chips with hundreds or thousands of different spots of DNA or markers for diagnostic purposes (lab-on-chip).

## 2.2 Common scientific & technological challenges

In terms of public private partnerships, inkjet printing provides a challenging and promising platform where fundamental research and product development really come together on the many topics mentioned in this roadmap. For new applications in the domains described above, comprehensive research and development activities have to be executed. Major application bottlenecks today are related to speed, reliability and a still too limited range of materials. Common major challenges have been identified in the following three fields.

### *Printing process fundamentals*

Complex interactions between the core components of a printing system have to be investigated and thoroughly understood. Physical studies are needed towards smaller droplets, higher jetting frequency, higher accuracy, tuning of droplet size and shape and drying/fixation/curing on the substrate. In addition, the effects of viscosity and many other fluid parameters on the printing process are still poorly understood. All these areas require in depth fundamental and applied research on micro fluidics, ink-chamber and channel acoustics, thin film piezo actuators and sensors, wetting & non-wetting behavior of fluids on surfaces, surface modification and characterization, material and microstructure related topics, drop positioning and drop formation, feedback principles and the like. In general, there are still many aspects of the inkjet printing process of both low as well as highly viscous liquids or complex liquids such as suspensions which are not sufficiently understood. Further extensive research remains of great importance. The same holds for ink jet printing processes in which phase transitions and heat transfer play a role. Chemistry-oriented studies should focus on the development of a much larger variation in stable surface modifications/coatings of nozzles given the rapidly increasing variation of materials that need to be printed (from DNA via reactive inks to semiconducting materials and edible components), and the study and reduction of fouling or blocking by such inks of the increasingly smaller nozzles. Given the ever increasing integration density of inkjet printheads, where nozzles become increasingly smaller, there is a clear need for 'mild' yet effective and precise coating techniques.

### *Core components: printheads, fluids and substrates*

New generations of printheads need to be developed, enabling smaller feature sizes (from 10 micrometer down to 1 micrometer range or even smaller), higher jet frequencies (from kHz to MHz range), wider range of fluids to be jetted (higher viscosities, polymers, suspensions, metals), higher integration densities (more nozzles per mm<sup>2</sup>), added sensors, intelligence and control principles to increase reliability, accuracy and lifetime. A transition towards fluidic MEMS technology is expected to open up an increasingly wider range of functionalities and applications combined with lower cost for next generation MEMS based printheads. At the same time this transition will bring its own set of technological challenges. There is a strong link to the theme nanotechnology.

In cases where the 'functional' (mechanical, physical, chemical) properties of the printed fluids after deposition and drying/fixation are important, e.g. in printed electronics, their dependence on the chemistry of the fluids and the processing conditions during and after printing are often poorly understood.

Finally, understanding and controlling the behavior of fluids on substrates has been shown to be of great importance. Many of the relevant substrates have a complex microstructure (e.g. a fibrous network) at scales comparable to that of the droplets and therefore cannot be regarded as simple continua. The interaction of the 'ink' with this microstructure is poorly understood. It may however result in significant dimensional changes which compromise the accuracy of the 'print' and the shape of the product. Similarly, fluctuations in ambient conditions (in particular relative humidity) may have a significant impact on the substrate's properties and therefore also needs understanding and control.

### *System platforms: advanced mechatronics and embedded control*

New mechatronic machine platforms and modules are needed which are faster, more accurate, more reliable, use less energy to operate, have wireless (remote) control, use less and environmentally

friendly material and are easier to configure, install, operate and maintain. Embedded system design will need to focus on smart system integration of printheads and scalable printhead arrays, substrate handling and flexible engine architectures. Regarding reduction of energy-use, smart machine platforms should support or enable the roadmap towards increasingly more 'green machines'.

New smart platforms and modules are needed that offer added intelligence, flexibility, real time feedback control loops based on vision and acoustic sensing principles, image quality optimization, lower energy consumption, automated operation, remote monitoring and smart self-diagnostics to reduce downtime.

### **3. Priorities and programs**

The pursuit of opportunities in industrial printing is a global race and collaboration and focus is key to address major common challenges. These challenges have been grouped into three main domains.

#### **3.1 Printheads & functional materials**

Current inkjet technology has limitations in jetting of fluids in terms of viscosity range, chemical properties and maximum allowable dispersed solid particle sizes and fluids with non-Newtonian behavior. In research worldwide, it is common practise to modify functional liquids to match with existing inkjet printheads. Unfortunately, this often means sacrificing optimal functional material properties. Changing this paradigm will mean that printheads need to be modified or developed to match the materials instead.

Interactions between jetted droplets and substrates on which they are printed can also limit the usability for certain materials. In some cases, jetting of droplets 'into air' offers an interesting alternative. The challenge is to subsequently 'dry' liquid droplets in a controlled way to end up with powders exhibiting unique properties for application in for example fields as food & nutrition, (bio)medical and chemistry.

Printing of biological material (DNA, peptides, lipids) requires specific surface modification of nozzles and thorough understanding of interactions with nozzle coatings (adhesion properties, "bio-compatibility").

Scientific and technological challenges associated with printing of new functional inks for printed electronic devices or micro- and nano-sensing structures include understanding of micro-droplet formation, interactions with nozzles, environmental conditions, substrate and new printheads concepts.

All of the above will require the design, modeling and validation of new types of nozzles and printheads, structure miniaturization and implementation of suitable sensing and feedback principles.

#### **3.2 Reliability and advanced sensing & control**

For inkjet to evolve towards a true digital manufacturing technology, reliability and robustness needs to be significantly improved. In many cases it is necessary to be able to apply defect free layers and patterns. This implies stringent demands on all levels: printheads, material interactions and integrated system level. An integrated approach is foreseen in which 4 approaches towards 'zero-defect' printing require evaluation: prevention, prediction, detection and correction. Advanced sensing and control mechanisms are key aspects as well as smart print strategies centered around nozzle failure prevention and compensation. For micro-dosing applications (in areas such as biomedical and food & nutrition) it is often necessary to control the exact and constant dispensing of very small amounts of liquids. For this micro-flow sensors should be developed as part of a closed loop system.

#### **3.3 Print Platform Architectures**

Many printing system architectures are possible and so far roll-to-roll (R2R) and flat-bed architectures have gained the most attention. As both R2R and flat-bed systems have limitations, it is important to conceive and evaluate new approaches ('beyond R2R'). The aim is to offer flexibility and modularity through development of 'print-system building blocks' for factories of the future. Envisioned architectures and platforms may first use hybrid solutions where printing will be complemented by traditional technologies, such as pick and place systems for integration of inserts such as chips or LEDs

or the use of lasers. As technology advances, more and more production steps will be replaced by printing technologies. New mechatronic platforms need to offer flexibility, modularity and integration options for flexible on-demand manufacturing lines for small series of (individualized) products made from multi materials. New design tools are needed to fully benefit of design flexibility and tackle the complexity of 3D, multi-material, 'freeform' design problems. A better understanding of the substrates' response to printing, handling and ambient conditions is also required to guarantee dimensional stability and quality.

New industrial applications require new high-level control systems that support machine operators and the production infrastructure to achieve the highest possible productivity.

## **4. Investments**

### **4.1 Themes for PPS initiatives & TKI's**

Taking into account priorities and programs of chapter 3, technological and scientific challenges from paragraph 2.2 and application areas from paragraph 2.1, a total of eight key themes for promising public private partnerships have been derived (summarized in table 4.1):

1. Printheads & functional materials
2. Advanced sensing & control
3. Print platform architectures
4. Substrates & coatings
5. Droplet visualisation & modeling
6. Fluid - substrate interaction
7. Printed Electronics
8. Printvalley 2.0

### **4.2 Initiatives & programs qualifying for TKI status**

#### *Printed Electronics & Holst*

Many application domains and technology challenges described in this roadmap are topics or program lines that are part of the current program of the Holst Centre. Combined with the functional printing program of TNO this is an excellent base for establishment of a TKI centred around a topical theme "Printed Electronics". This would include current activities in large area OLED lighting, OLED displays, printed electronic functionalities and components, printed sensors & actuators, solar cells and more generic roll-2-roll or other printing platforms for future manufacturing. A program under this envisioned TKI on Printed Electronics would redefine/reposition Holst and its program and would address large parts of the printing roadmap as well as covering significant parts of the solar roadmap, the lighting roadmap, the healthcare roadmap and the mechatronics & manufacturing roadmap.

#### *PrintValley 2.0: Dutch Centre for Industrial Print*

In the successful High Tech Top Project PrintValley, an ecosystem of 23 Dutch parties from industry and knowledge institutes has been created. Within this ecosystem, collaboration, sharing of challenges and finding of new opportunities turned out to be of great value. Next to the 14 business cases that were defined up-front, the true value has been in having a network through which new collaborations and business opportunities can be explored. It also offers an inspiring environment for young people during their studies by offering a window to real world applications and challenges.

To develop the next steps in industrial printing, a multidisciplinary approach is very important. The infrastructure to execute research and development projects for new applications has to be built up and extended. This includes investments in facilities, measurement and test equipment, tooling and prototypes, in order to be able to execute the programs described before. It is apparent that the costs for such facilities are often very high, which can turn out to be a major bottleneck for starting new initiatives.

An initiative where resources and opportunities can be shared is something that we propose to explore in what is called "PrintValley 2.0". It will lower investment barriers, increase opportunities for collaboration and cross-fertilization and provide an excellent research and incubation environment. Since the involvement of SME's in the original PrintValley project was very substantial, we expect that PrintValley 2.0 would again be of great benefit for SME's. Besides the option of having all equipment and infrastructure in one physical location, it is envisaged to set up collaborations through which access to eachothers shared resources becomes possible. Also shared facilities for MEMS prototyping and pilot-scale production facilities for inkjet printheads is envisaged. In the collaboration agreement the guiding principles for exploring new opportunities and low-threshold collaboration need to be defined.

### **4.3 Stakeholders involved in this roadmap**

CCM, NTS, TU/e, TUD, RUG, UT, TNO, Holst, OTB Solar, Holst Center, Norma, Sioux, OLED Technologies, Océ, Vision Dynamics, Innophysics, Demcon, MA3 solutions, Bronkhorst, MI partners, Lionix, Reden, RM Center, Chematronics, Joh. Enschede, Stork SPG Prints, Liquavista/SNRC, Ten Cate, Wageningen University, SurfiX, Aquamarijn, ASML, Philips, NXP, Medspray, Thales, Solmates, Wavin, DSM (Neoresins), Luxexcel, Bruco, Noviomems, Solvay, BASF, FESTO

#### 4.4 Financial overview

2012

Finance ? ? Execution	Comp	State Holst/TNO+	State /NWO	State /other	Univ	EC	Further funding
Univ /TKI	2		2	3	2		
University							
TNO+ /TKI	2	2					
TNO+NLR							
Comp /TKI	19						
Comp							
Int'l R&D	2	1		1		3	
Total M€/yr	25	3	2	4	2	3	0

- ❖ State /other: nationale subsidies, TTI bijdragen, RDA+, etc. (niet WBSO en RDA)
- ❖ University: betreft ook vergelijkbare onderzoekscentra, zoals AMOLF en SRON
- ❖ Further funding: regiobijdragen, overheidstaken (bv defensie), SBIR, etc.

Cash

In-kind

2013

Finance ? ? Execution	Comp	State Holst/TNO+	State /NWO	State /other	Univ	EC	Further funding
Univ /TKI	2		2	3	2		
University							
TNO+ /TKI	3	2					
TNO+NLR							
Comp /TKI	19						
Comp							
Int'l R&D	2	1		1		3	
Total M€/yr	26	3	2	4	2	3	0

2014-15 per year

Finance ? ? Execution	Comp	State Holst/TNO+	State /NWO	State /other	Univ	EC	Further funding
Univ /TKI	3		3	3	2		
University							
TNO+ /TKI	3	3					
TNO+NLR							
Comp /TKI	17						
Comp							
Int'l R&D	5	2		3	1	7	
Total M€/yr	28	5	3	6	3	7	0

**Printing roadmap**  
*From the World of Print to the Printed World*

PPS / TKI topics -->	Next generation 3D printing (additive manufacturing)	On Demand Digital Production Print	Printed electronics Possible TKI	Printheads & functional materials	advanced sensing & control	Print Platform Architectures	Substrates & coatings	Droplet visualisation & modeling	Fluid - substrate interaction	PrintValley 2.0 Possible TKI
	Towards production speed, lower cost, stability/reliability, functional materials multi-material capability, freedom of design, ...	Paper, packaging, foils, board, glass, ceramics, textiles, ...; conversion from analog to digital production	OLED lighting & displays, R2R technologies, smart devices, labels, system-in-foil, medical, sensors, conductive tracks, thin film solar...	Next generation printheads, research on printing processes, drop formation processes, wetting, actuation, acoustics ink-printhead interactions, ...	Sensors, diagnostics, self-sensing, control, reliability monitoring, nozzle failure detection & compensation, ...	Print engine architectures, R2R, flat-bed, beyond-R2R, substrate handling/positioning, ...	Substrate materials, coatings, surfaces, modification, analysis, coatings for printheads, substrate materials, new papers, ...	Advanced droplet visualisation, ultra high speed camera recordings, computational science/modeling, tools, experimental verification	droplet-substrate interaction, wetting, droplet spread, drying/fixation, spreading, coalescence, substrate deformation, ...	sharing challenges, exploring new opportunities, collaboration in joint projects, business case oriented, sharing of facilities and knowledge
<b>Science &amp; Technology themes</b>										
Surface science & coatings										
Reliability, sensing & control										
MEMS devices & technology										
Print platform architectures										
Micromechanics & acoustics										
Fluid dynamics										
Computational science & modeling										
Materials for 'functional links'										

**Table 4.1**

## **Appendix I:**

European projects related to printing with Dutch participation (list to be extended; not complete)

<b>FP7 Stella</b>	<b>Printing of stretchable conductive tracks</b>
<b>FP7 Open Garments</b>	<b>Printing of personalized clothing/shirts/handcuffs</b>
<b>FP7 Phocam</b>	<b>3D printing of micro parts</b>
<b>FP7 Custom-IMD</b>	<b>Custom made implants by Additive Manufacturing</b>
<b>FP7 Directspare</b>	<b>Spare parts on demand by Additive Manufacturing</b>
<b>FP7 Compolight</b>	<b>Light weight products by Additive Manufacturing</b>
<b>FP6 Custom-Fit</b>	<b>Custom made products by Additive Manufacturing</b>
<b>FP6 Metalprint</b>	<b>Printing of molten metallic conductive tracks</b>
<b>FP6 Rama3DP</b>	<b>3D printing of polymer products</b>
<b>FP6 Flextronic</b>	<b>Printing of plateable tracks on foil</b>
<b>FP7 PRODI</b>	<b>Manufacturing and Production Equipment and Systems for Polymer and Printed Electronics</b>
<b>FP7 PolyNet</b>	<b>Network of Excellence (NoE) for the exploitation of organic and large area electronics</b>
<b>FP7 Digitex</b>	<b>Digital Programmed Jetting of Fluids for Multifunctional protective Textiles</b>
<b>FP7 Diginova</b>	<b>Innovation for Digital Fabrication</b>
<b>EU Interreg Sitex</b>	<b>Digital inkjet Textile Printing</b>
<b>EU Crossroads NL-B</b>	<b>New applications of Inkjet technology</b>