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Digital Textile Printing: Status Report 2021

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Abstract

Digital textile printing technology has been considered the preferred textile printing technology since 2003, when production digital textile printers were first introduced at ITMA (International Exhibition of Textile Machinery) in Birmingham, UK. However, in 2021, 18 years later, this technology is utilized in fewer than 10% of the entire textile printing industry. In this document, we aim to summarize the state-of-the-art of the digital textile printing industry and to predict its future trajectory.

Market

The printed textiles market size is currently estimated at USD 146.5 billion globally, and this market is predicted to grow at a CAGR (compound annual growth rate) of 8.9% from 2018 to 2025 (Grand View Research, 2020). Similarly, digital textile printing production has reached over 3 billion square meters, and business analysts have predicted that it will grow at a CAGR of 14% (Masuwa,2020) (Allied Market Research, 2021) (Verified Market Research, 2021). Although these business analyses were reported in the pre-pandemic period and Covid 19 has significantly impacted the global textile printing industry, these predictions from business analysts continue to be relevant as they believe in a strong market resilience and a positive future outlook of the industry.

Currently, digital printing technology is utilized in 6-7% of textile printing production comparing to the rest of analog production technologies (Chaouch, 2018) (Aherburne, 2019) (Provost, 2019). Since its technological infancy in the early 2000s, the current technological achievement for the digital textile printing system has reached the benchmark, and it is considered one of the preferable textile printing technologies for commercial viability. Moreover, the digital printing system is consistently being refined and improved to accelerate the technological conversion from analog to digital.

Technology

The development of viable technology has been challenging for the digital textile printing industry. In the initial development of the technology, a few Japanese companies were the early pioneers. As the first innovator in the middle of the 1990s, Cannon developed a textile sample printer with thermal printhead technology for the textile division of Kanebo, one of the largest trading Japanese companies that originated from the textile industry. Then, simultaneously, Seiren, a comprehensive textile manufacturer in Japan, developed Viscotec, a proprietary digital textile printing system with piezo printhead technology (Pond, 2000). Following these early efforts, Reggiani Macchine (currently EFI / Reggiani) of Italy introduced DReAM, the first production digital printer, at ITMA Birmingham in 2003, and this printer was the true benchmark for the digital textile printing industry. Although its printing speed was slow (~2.5 meters per minute), dozens of DReAM printers were installed for production globally.

Since then, digital textile printing has continued to advance and improve. One of the first breakthroughs was single-pass digital printing technology for textile printing, which utilizes a different mechanism from the typical scanning type printing system in which a carriage equipped with multiple printheads moves from the selvage to selvage of the textile substrate and prints a set of information (image data) with multiple passes. With the single-pass system, each information (image data) is printed by a single droplet of ink from the printheads on the continuously moving textile substrates. Structurally, multiple printheads are placed in line without gaps on the long beam extending the print bed's entire width, and these are fixed in position. Each beam is designated for one set of colorants. For printing with seven colorants (e.g., C, M, Y, K, and three extra inks), seven bays are required on the printing system. Italy's MS Industry (currently Dover/MS) introduced the first single-pass printing system, the La Rio printer, in 2011 at the ITMA in Barcelona, Spain. The La Rio had a demonstrated production speed of up to 70 linear meters per minute. This printing speed is compatible with the rotary screen printing technology, the primary analog textile printing system for textile. Four years later, in 2015, several single-pass printers were introduced from various printer manufacturers, including Atexco, EFI / Reggiani, Konica / Minolta, and SPGPrint, at ITMA Milan, Italy. Today, about 30 units from all manufacturers are currently available globally.

Another advance in digital textile printing has been the development of a hybrid printing system. Some digital textile printing machines are now equipped with both a digital printing system for primary colorations and an analog screen printing mechanism for pre-treatment and supplemental printing applications. A hybrid system is useful because digital printing alone does not allow printing of special effects, such as metallic, pearl, functional agents used for flocking, Devoré, and Plissé. When an analog screen printing mechanism is synchronized with a primary digital printing unit, however, enables the printing special effects along with digital printing. In addition, analog screens can be synchronized to print design elements that contain distinctive spot colors (e.g., fluorescent and out of gamut colors), blotch, and large solid-color areas, which are challenging to print with digital printing technology.

Printhead technology

One of the core technologies for inkjet printing is the printhead. To improve digital textile printing, printhead manufacturers have focused on developing more compact and precise printheads. Micro-Electromechanical System (MEMS) technology has enabled the fabrication of miniature printheads, which have finer drop sizes, more nozzle counts, and tighter packing densities for photolithographic and micromachining techniques. Consequently, printhead modules become more compact and precise, and these printheads perform greater color-to-color registration accuracies and reduce manufacturing costs caused by defects.

As printheads and components within the printhead have become more compact, the printheads can accommodate more functional mechanical components. One of the functions is an ink recirculation system, and several printheads have been developed with this addition. In this mechanism, inks continuously recirculate within the printhead to prevent agglomerations of the ink particles. As a result, the latency (the time of dry nozzle) improves, and the temperature is also more controlled to stabilize the ink viscosity. The digital textile industry is just starting to recognize the benefits of ink recirculation technology, which was originally developed for more demanding digital printing systems, such as a digital ceramic printing system. In digital printing for ceramic tiles, inks are made of large inorganic pigment particles from ~250 nm to ~1000 nm, which easily agglomerate and flocculate. Constant recirculation of the ink in the printheads prevents these problems from stabilizing the ink viscosity.

Ink recirculation is also essential to control latency because the digital printing process is typically operated on heated ceramic tile substrates in dusty environments (Zapka 2018). Although some newer digital pigment printing systems have recently started to utilize recirculation print head technology, the benefits of the recirculation system for digital textile printing are questionable and controversial. Nonetheless, the recirculation mechanism can stabilize the demanding ink formulations containing larger particles, including white pigment ink and specialty inks (e.g., metallic, adhesive, varnish) that might be developed for the future.

Ink formulation technology

Another critical factor for digital textile printing is ink formulation technology. Currently, the commercially available colorants for digital textile printing are still limited to the direct printing stage and remain the same as those used in early 2000, including:

1. Disperse dye ink for mostly polyester
2. Reactive dye ink for primarily cellulose fibers
3. Acid dye ink for protein fibers
4. Pigment ink for possibly all fibers and blends

In general, digital textile printing is a more sustainable process than analog printing on textiles with fewer effluents and material resources. Analog printing requires a large amount of viscous print paste (dye staff, thickening, and fixing agents) and multiple screens per each design (and their storage space). After the printing and fixation processes, the print paste needs to be washed off with a large quantity of wastewater. It requires the use of massive material resources and large amounts of effluents into the environment. Conversely, digital textile printing is a screenless process and applies far smaller amounts of colorants on the targeted areas. Therefore, it consumes much fewer material resources, uses less water for the fixation process, and generates fewer effluents.

Today, in the digital textile printing industry, pigment ink's advancement is the major highlight as the most sustainable printing process Unlike the dye process which requires steaming and washing with water in a fixation process, pigment printing is a dry process that does not use water. The fixation is operated only by dry heat. Although printing with disperse dye can also be a dry process with the sublimation transfer method (DyeSub), which does not require any water use, the choice of printable substrates is limited only to polyester and some polyamides. In addition, sublimation transfer printing uses transfer paper in the printing process that must be disposed of or recycled.

Additional advantages of pigment printing are:

1. The pigment system can print on any fiber classes, including blend fibers.
2. Fixation is economical and straightforward with a dry heat unit.
3. Pigment printing is a dry process that does not consume any water in the fixation process.
4. Pigments are solid, consisting of colored molecular aggregates. With a proper binding agent, greater colorfastness can be achieved.

In the current digital textile printing industry, however, the use of pigment ink is very small, comprising only 3% of the total textile ink consumption (Figure 1). One of the reasons for this limited use is the lack of optical density in the pigment formulations and the fact that it cannot achieve the darker and brighter colors required for the textile design markets. While for dye-based ink, the dye particles are entirely soluble in ink (except for disperse dye), pigments are solid and insoluble. Textile pigment particles ranging in size from ~50 nm to ~400 nm are required to be dispersed in ink with colloidal stability for proper jetting property and shelf life. Typically, the conventional pigment ink for digital printing contains pigments at concentrations below 10% w/w, a formulation principle that does not actualize enough optical density for textile printing. Generally speaking, the greater the loading of pigments in ink, the higher the optical density becomes. A higher load of pigments in the solution can, however, create aggregation, which can cause a loss of the jetting property, optical density, and shelf life. (Nagdassi 2010) Furthermore, pigment printing requires dispersion polymer, which acts as a binding agent that polymerizes to form a film to encapsulate the pigments on the substrates. Since textile printing requires robust fastness, particularly wash-fastness and light-fastness, more than other applications, digital textile pigment ink needs a high level of ink formulation with pigments and polymer dispersion.

Pigment ink formulation for digital textile printing, particularly containing pigments and polymer dispersion as binding agents, is a complex task, and the industry still needs more research and development in order to achieve breakthrough innovation.

While the breakthrough innovations are still under development, the current industry has implemented an alternative process to use pigments for the digital textile printing process. Instead of digitally printing with pigment inks formulated together with pigments and binding agents, the printing process is divided into two separate steps of: (1) digitally printing with inks that only contain pigments (with other agents for jetting functionality) and (2) applications of binding agents before or after printing (by padding, spraying, or manual applications). In this method, less demanding ink formulation is needed to achieve slightly better color reproductions.

Disperse dye ink	55%
Reactive dye ink	36%
Acid dye ink	6%
Pigment ink	3%

Figure 1. Global market share of colorants for digital textile printing. Chaouch, M. (2018, July 24) *Global Developments in Digital Textile Printing* [Presentation]. WTiN North America Digital Textile Conference, New York, NY

Design

In the practice of textile design, technological conversion from analog to digital started at the end of the 1980s. To complete the design process, practitioners utilized specialized proprietary textile design software from the input of design sketches to the final output on paper with digital printers. Since the early 1990s, a group of pioneers have been working to integrate commercial off-the-shelf software, notably earlier versions of Adobe Photoshop and Illustrator, into their design processes to replace costly proprietary textile design software (Ujiie 2011). Today, most textile design studios and practitioners utilize Adobe Photoshop and Illustrator entirely or partially, along with specialized proprietary textile design software to create textile designs. Adobe recently introduced textile design plug-ins for Photoshop, called "Adobe Textile Designer," and this has been a positive catalyst to the digital textile printing industry.

Since the inception of digital textile printing in the middle of the 1990s, textile design practitioners have embraced the creative freedom that digital textile printing offers and have developed new styles, including:

- design with millions of colors
- diminutive images with extreme tonal and fine lines
- photographic manipulation
- special digital effects with filters, and
- large, single-engineered images (Ujiie, 2006)

Digital textile printing has also encouraged creative freedom and cross-disciplinary approaches. Conventionally, textile print design practice requires a set of essential skills, including:

- creations of repeated pattern specified by the screens' size,
- creations of systematic colorways for the completed designs by the numbers of the screens used in the designs, and
- understanding of attainable tonal ranges.

Digital textile printing's creative freedom allows design practitioners with diverse training (e.g., graphic designers, illustrators, or any other design practitioners) to produce their designs on printed fabrics without requiring the specific skills of conventional textile design practice. The Center for Excellence of Surface Imaging at Thomas Jefferson University estimates that globally there are 225k textile design practitioners and 1.5 M graphic design practitioners working in their fields (Ujiie, 2019), plus many design practitioners who work outside of the textile design field. Digital printing technology for textiles enables these new design practitioners, who are not originally categorized as textile designers, to print designs on textiles. Consequently, the definition of textile print design needs to be reconsidered.

Volume and flexibility

Digital printing also allows short-run production and design flexibility for quick alterations, in contrast to analog textile printing, which requires a large production volume. This makes digital textile printing particularly valuable for the high-end luxury fashion and fashion accessories markets that require short-run and flexible productions. Among the main pioneers to adopt digital textile printing technology for commercial textile productions are the design studios and printing operations located in the Como region of Italy. In late 1990, Como's printing operations started to produce digitally printed fabrics with a dozen modified textile printers, re-engineered from the paper plotters at a printing speed of a few yards per hour for each unit. As years go by, these printers are being replaced by newer, higher-speed production printers.

Digital printing's popularity has also accelerated the advent of "fast fashion." According to Carlo Mantero, one of Mantero Seta's owners, a printing mill with a design studio in Como, Italy, the high-end luxury brands now expect digital printing processes as a norm for their productions. Furthermore, they anticipate shorter and shorter lead times from designs to productions and any design alternations. This can become a vicious cycle as consumers constantly purchase trendy textile products at economical price points and these products become stock-piles of environmental waste at the end of quickly changing fast fashion trend cycles. The industry needs to address more sustainable business practices for longer product life cycles and less environmental waste.

In contrast, one of the advantages of digital printing is variable data printing, known as personalization and customization in the textile industry. Product customizations with digital textile printing can be an alternative manufacturing and business model to emphasize its longevity and quality.

<u>Business</u>

As engineering and design characteristics for the digital textile printing industry begin to mature and improve, business strategies and models have evolved. Now that the digital printing process from design to final printed products can be achieved quickly, the manufacturing process can become more optimized for the supply chain and workflow management. Significantly, the industry has begun to adopt the theory of Industry 4.0, known as the fourth industrial revolution, into its business strategy.

The fourth industrial revolution is a relatively new theory, introduced to the public around the 2010s. It follows the long history of industrial change starting with the first industrial revolution around the 1770s, which was led by the invention of the steam engines, which enabled machine production. In the second revolution in the late 19th century, the invention of electricity enabled mass production. The third industrial revolution started in the 1960s with the advent of digital technology, from mainframe computers through to the internet in the 1990s. In the fourth industrial revolution, advanced technologies have become the catalysts to interconnect the virtual and physical domains of global manufacturing for customizations and the new operating systems. Moreover, this fourth revolution extends to interconnect physical, digital, and biological space with breakthrough technologies (Schwab 2016).

The supply chain and the workflow of the textile industry are lengthy and complicated system. Before any printing occurs, a print cloth needs to be produced with rigorous processes including:

- extractions of fibers
- spinning fibers into yarns
- plying yarns
- yarn sizing to increase a tensile strength
- fabric formation (by weaving and knitting)

Additionally, these processes are often operated separately in remotely distant factories.

Once greige goods (a cloth in a loom stage without finishing) are produced, these are sent to the printer for additional PFP (prepared for printing) process as following:

- singeing (burning away broken fibers and thread on the cloth surface)
- de-sizing (removal of yarn sizing)
- scouring (removal of impurities)
- bleaching (whitening).

For the analog printing process, printing can resume on the PFP fabrics; however, for digital printing with dye-containing inks, the PFP fabrics need to be processed further by pretreatment with thickening and fixing agents.

In order to optimize to manage the supply chains and workflow, the industry is beginning to consider the use of new technologies, including the Internet of things (to connect humans to “things”), artificial intelligence (AI), and robotics, to enable collaboration between humans and machines as well as machine-to-machine communications for the automation of production and distribution processes. Moreover, cloud computing can allow remote monitoring of all activities. For example, transistors and radio-frequency identification (RFID) can track and monitor supplies and products remotely. Sensors on the production machines can detect operational errors and send messages remotely to the operators. AI technology can then correct these errors automatically and send signals to the robotics handling textiles on the production machines. In this way, traditional textile factories transform into “smart factories” that incorporate a virtual and physical system for the global supply chain and workflow.

Another business model in the digital printing industry is “micro-factory”. Inspired by Industry 4.0 theory, the micro-factory for digital textile printing is a concept for small-scale digital printing and manufacturing factory designed for just-in-time production and mass customizations. It also promotes agile manufacturing with digital textile printing for the on-shore and near-shore production for domestic manufacturing. For example, the micro-factory for digital textile printing of apparel manufacturing can be located in a small urban-industrial space and set up with compact production machines that include:

- visualization software for monitor display
- pre-treatment unit for the printing fabrics
- digital textile printer
- post-treatment unit for the printed fabrics
- cutting (patter cutting unit) and sewing machines.

A customer can select a digital simulation on a monitor before producing a final pattern design on the chosen dress in this micro-factory model. As soon as designs are approved, the digital printing process starts. Afterward, the digitally printed fabrics are cut and sewn together for the final garments in a short amount of time.

In the coming decades, the fourth industrial revolution will impact the automation and robotics for the digital textile printing industry to optimize their production, management of value chain, and workflows. Many new innovations with advanced technologies are underway.

Technology Adoption

Since the introduction of the first production digital textile printer in 2003 (or the first high-speed single-pass printer in 2011), for more than ten years (18 years from 2003 and 10 years from 2011), adoption rates of this technology in the textile industry remain small, in a range of 6-7%. The current technological conversion speed from rotary screen printing to digital printing is questionably sluggish when compared with technological conversion from engraved roller printing to rotary screen printing technology in the 1960s to1970s.

Rotary screen printing technology was introduced in 1963 at ITMA, Hanover, Germany. In about 15 years, a rapid shift of technology took place, and by the late 1970s, rotary screen printing surpassed the utilization of the previously dominant engraved roller printing. For example, in 1979, rotary screen printing was utilized globally for 42% of production compared to engraved roller printing for 32% of production (Burgess, 2004). In the late 1980s, about 25 years after the introduction in the United States, rotary screen printing became a mainstream technology, used for 52% for all textile printing technology, while use of engraved roller printing declined to only 18% (Amidon, 1988).

	15 years 1963 -1978	25 years 1963-1987	37 years 1963-2000
Rotary screen printing	42%	52%	63%
Engraved roller Printing	32%	18%	~0%

Figure 2. Analog printing technology adoption rates between engraved roller and rotary screen printing technology.

Rotary screen printing has significant functional advantages over engraved roller printing that contributed to this technological shift. These advantages include:

- flexibility to print on different surfaces
- ability to print sharp outlines
- tonal effects
- textured effects.
- print small quantities to mass production.

Interestingly, these advantages are now the same functional characteristics of digital textile printing, to a much greater degree, compared with analog rotary screen printing. Nonetheless, these factors have not contributed to a widespread technological shift from analog printing to digital textile printing. It is a perplexing and controversial fact that the industry might require new solutions.

Surface Imaging

One of these new solutions might be *surface imaging*, a concept developed to vitalize the digital printing industry, including the digital textile printing industry. Surface imaging entails democratizing the digital printing systems with comprehensive applications for broader end-users. It is defined as a domain to visualize any imagery on a wide range of substrates, including porous, non-porous, rigid, and flexible surfaces, by advanced digital printing technologies containing direct colorations, deposition, and subtraction printing. Any designs that consist of drawings, paintings, typographies, raster imageries, vector imageries, and photography can be printed digitally onto various substrates of paper, metal, wood, glass, ceramic, and any polymeric surfaces, utilizing the current advancement of specialty digital printing systems including UV, organic solvent, aqueous dyes, pigments, and functional ink.

For example, textile pattern designs can be not only digitally printed on a cloth for a dress or upholstery and drapery in the interior, but also the same designs can be printed directly on wooded doors, glass windows, metal cabinets, ceiling panels, outdoor walls, flooring materials, or on any other surfaces. While textiles can be printed with a roll-to-roll digital printing system, a similar printer with compatible ink-sets can be used for printing on paper, polymeric films, and any other flexible materials. Comparably, current flatbed digital printers can easily accommodate the ridged substrates in the standard construction material size (4 feet by 8 feet with several inches thick) and print imagery on a vast choice of hard surface materials. Therefore, what was once called "textile design" now is transformed into "design for surface imaging," providing more possibilities for a wider range of applications and functions.

At the same time, s*urface imaging* not only focuses on design or engineering development alone, but it also emphasizes an entire system that consists of design, engineering, and business entities in a digital printing domain. One of the current problems in the digital textile printing industry is a lack of understanding and communication among machine manufacturers, software developers, printing operations, and application end users. Design, engineering, and business entities in the industry have not been properly integrated. It is necessary to understand and implement systems thinking in the industry.

Systems thinking is the core concept for surface imaging to integrate design, engineering, and business components. For example, a typical product development cycle can consist of: (1) ideation, (2) development, (3) production, (4) distribution, (5) marketing, and (6) sales. For the initial development stage of (1) ideation and (2) development, a domain of "design" is the main contributor. Secondly, in the middle stage of (2) development, (3) production, and (4) distribution, the "engineering" domain becomes a primary driver. For the final part of the product development cycle of (4) distribution, (5) marketing, and (6) sales stages, "business" becomes a key stakeholder. Three design, engineering, and business stakeholders need to be well-integrated to develop a successfully manufactured product.

DESIGN ENGINEERING BUSINESS

ideation– development– production– distribution- marketing- sales

Figure 3. System thinking diagram

Since the late 1980s, when a computer was recognized as *metamedia* that can dynamically simulate and customize any other medium's contents, the concept of *metamedia* has broadened in scope to influence any digital applications and processes (Kay, 1984) (Ujiie 2015). Today, the word "digital" represents obscuring the original definition and boundaries of specialized systems for numerous interdisciplinary outcomes (Kane 2016). Accordingly, surface imaging is a *metamedia* for the digital printing system, catalyzed by a "digital" system. Unlike the conventional specialized disciplines, surface imaging encourages transdisciplinary approaches to expand its possibilities.

According to Ron Gilboa of InfoTrends KeyPoint Intelligence, for specialty digital printing technology, the market can be categorized into four segments of (1) graphic communication, (2) packaging, (3) decorative, and (4) functional (Gilboa, 2014). Digital textile printing is positioned in the decorative market along with the rest of the printing material segments, including ceramic, glass, wallcovering, automotive, wood products, laminates for floor and tabletop, and architectural materials. Adopting the transdisciplinary approaches of surface imaging, the design, engineering, and business applications originally developed in the textile market can expand to the rest of the decorative product market segments. Furthermore, the transdisciplinary approaches can broaden the graphic communication, packaging, and functional printing markets, outside of the originally positioned decorative market.

Similar to "T-shaped skills" used to describe desirable workers' specific attributes, transdisciplinary applications for surface imaging can represent "T-shaped approaches." The vertical bar on the letter T represents the depth of skills and expertise in a specific field, whereas the horizontal bar represents the ability to expand across disciplines with experts in other areas beyond the primary field. Thus, surface imaging is a versatile discipline that consistently seeks opportunities for future innovations.

Conclusion

Digital textile printing is becoming a commercially viable textile printing technology, and the future outlook is optimistic. Digital textile printing offers a preferable printing technology over analog printing technology in terms of new design styles, mass customizations, just-in-time productions, agile manufacturing, and sustainable systems. However, the industry is challenged by a flux of technological conversions from analog to digital printing technology. Instead of implementing digital textile printing technology into a new business model, the current technology utilization has retrofitted its system and processes into preexisting workflows. It is a time to shift a paradigm in the digital textile industry. *Surface imaging* is one solution to disrupt the current textile printing industry system to create a prosperous and holistic digital printing system for the future.

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