# From DMP to 40" TV – The Challenges of Scaling-Up Inkjet

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## Abstract

*There is much activity on inkjet printing of functional materials, and many very impressive and encouraging results on a small scale have been shown. But the real applications for such achievements will generally require printing at a much larger scale, and there are many challenges in scaling a successful process at laboratory scale to a successful one at industrial scale.*

*Inkjet printing is inherently scalable, which is a key advantage for solution processable P-OLEDs and their use in manufacturing large, commercially-relevant displays. But there are many aspects to consider in scaling up including time, process factors, dealing with large arrays of nozzles and large printers, and robustness.*

*This paper addresses some of these issues, and raises awareness of others with particular reference to display printing - methods to combat swathe joins are still applicable, print strategies can be used to generate redundancy in arrays to mitigate lost nozzles or nozzle variations, and physical structures can be changed to makes processes more tolerant of drop misplacement.*


## Introduction

Inkjet printing has reached far beyond printing of graphical images on conventional media and there are numerous examples of its use for 'functional' printing [1] – printing of materials with a function other than colour, for example OLED materials, metal inks for conductive tracks, etch resists, solder masks, resistive materials, dielectric materials, and colour filters.

Much of the development work on the printing of these materials has understandably been done at a small scale. Print heads with relatively few nozzles are often used, usually singly, in small area printers printing onto small substrates, and usually by scanning the head over the substrate printing in swathes. For example, the Dimatix DMP printer has proved very popular with researchers as a desktop tool for printing a wide variety of materials. But many of the final target industrial applications are either inherently large e.g. 40"+ television panels, or are conventionally processed as a large array of smaller devices to take advantage of parallel processing, or both.

Where inkjet processes are to form a part of such manufacturing lines, they will generally have to work on these large substrates, which is in contrast to the scale on which they were developed. Inkjet is often and rightly described as a scalable technology, but that does not necessarily mean that the process for doing so is trivial.

## Scanning larger substrates

Scanning a printhead over the substrate in a series of adjoining swathes is a commonly used print scheme (figure 1).

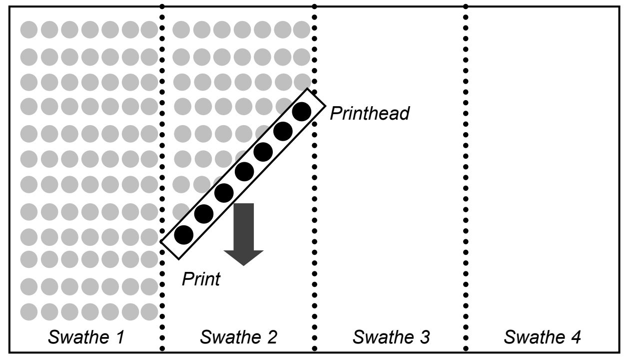


***Figure 1**. Typical swathe printing method*

However, the joins between the swathes can be imperfect and may appear as a line defect on the substrate. An example of this is swathe joins in a printed display resulting in a visible line defect (figure 2). As described previously [2], one cause of such a defect is the asymmetric drying of the printed material at the edge of a swathe due to the asymmetric solvent atmosphere around the join.

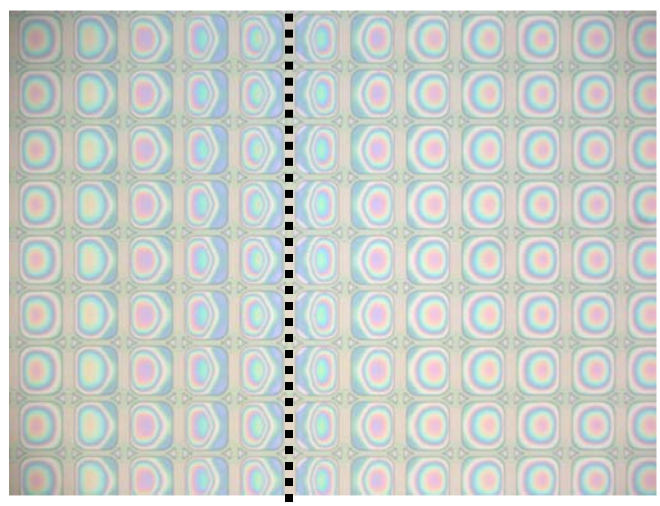

***Figure 2**. Pixels in a display clearly showing asymmetry either side of a swathe join (dashed line).*

The asymmetry is removed once the next swathe is printed, but clearly as substrate size increases, the time taken to print a swathe at a given linear speed increases, and hence the likelihood or magnitude of a swathe edge defect is increased. Previous work [2] has been able to eliminate such effects through changes to ink formulation for example, but as the time between swathes increases, it may be more difficult to do so.

The time taken to print swathes is naturally of interest in its own right. Clearly as the substrate size increases, for a given swathe size and linear print speed, the time taken to print the substrate increases. Substrate surface condition may change with time and so as the time to print a substrate increases, the first printed and last printed areas may behave differently. And at some point the process time will become too long to meet a throughput requirement, perhaps determined by preceding or subsequent processes, and an alternative print scheme will be required.

## Large nozzle arrays

### *Benefits*

The key feature which makes inkjet scalable is that in most implementations it is already a parallel process in that it makes use of many nozzles. Hence in principle the process can be scaled up and/or the process time scaled down by simply adding more nozzles.

At the first level, this might involve using an alternative head with more nozzles or additional heads, but still printing in swathes. This reduces the number of swathes required for a given substrate size, and hence the overall process time, but the swathe time would remain unchanged and swathe join effects will still occur. Therefore, the natural conclusion is for the array to grow to match the width of the substrate, such that it is printed with a single swathe.

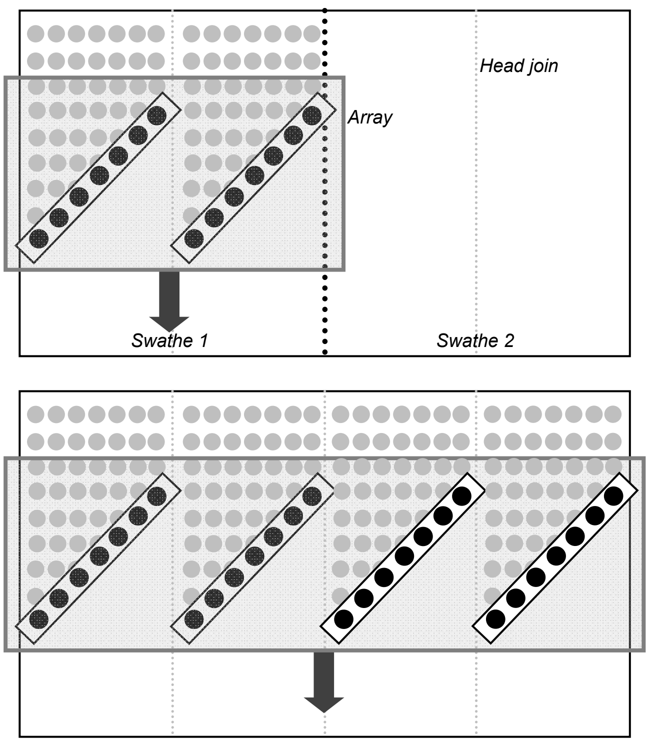


***Figure 3****. A 2 head array still printing swathes (top); a full width array (bottom).*

When a substrate is printed in a single swathe/pass, the issues outlined above and previously [2] relating to multi-swathe printing should largely be eliminated – no intermediate swathe edges are generated on which to have asymmetric drying for example. But a large nozzle array can have its own problems.

Generally a large array would consist of a number of individual printheads mounted together to form the array, and so while they might now print coincidentally, there are still joins in the array between the groups of nozzles from the individual heads which still share some characteristics of swathe joins. It is possible these joins might be affected by physical factors such as the alignment between heads, although a good mechanical design for the head mounting system should allow the alignment to be accurately set. But as shown previously [2], discontinuities in the behaviour of nozzles can become very visible in the printed output, and the join between the nozzles from different heads is a likely place for such discontinuities to appear, just as swathe joins are.

It was shown previously that the profile of, for example, drop volume from nozzles across a head could be related to variations in a printed display, and that by adjusting the volume of drops printed by each nozzle to flatten the profile such variations could be reduced [2]. Others have used multi droplet generation and volume control to achieve a variation of <0.4% in pixel ink volume [3]. Such ideas can of course be applied to heads in a multi-head array to not only reduce variation attributed to a single head, but to reduce discontinuities between heads. In addition, just as swathes can be overlapped and interlacing used to smooth the joins between swathes, heads can be overlapped in the physical array and the common print regions between them interlaced to smooth the joins.

### *Problems*

A large nozzle array can eliminate some of the problems associated with swathe printing, and other swathe problems that remain can in principle be addressed with similar methods to those used for similar problems when swathe printing. In this respect, the inkjet process does indeed seem scalable. But there may be new issues which result from having a large, multi-head array.

While printhead manufacturers strive to produce heads which are as uniform and reliable as possible, printheads may with use develop one or more nozzles which do not jet, or jet poorly. In a single head system it is possible to use only a subset of the available nozzles so as to eliminate missing or defective nozzles from the range of nozzles used. This reduces the swathe width but is otherwise a straightforward adjustment to the print process.

However, where heads are built into an array, reducing the swathe width used from any head in that array would require other heads to be physically adjusted to close the gap left by the removal of those nozzles from the array. Generally a head array fixture would only be equipped with an adjustment capability sufficient to align heads to one another, which may only be a few millimetres and not capable of closing larger gaps. Hence either the requirement for 'perfect' heads becomes greater, or heads are swapped when defects occur, or the system must cope with missing or defective nozzles in another way.

One such way is to build redundancy into the system and into the print methodology. At its simplest, nozzles can be duplicated in line with additional heads such that if one fails, another is already located on the same path to take its place (figure 4(a)). But this rapidly increases the number of heads required and is effectively just delaying replacement of the faulty head. Alternatively, the array could be constructed with respect to the required pattern with redundancy within each head i.e. that in the normal printing of the required pattern, only a proportion of the nozzles on each head are used (figure 4(b)). If one of the required nozzles becomes faulty, the position of the head can be shifted so as to use an adjacent nozzle instead (figure 4(c)).

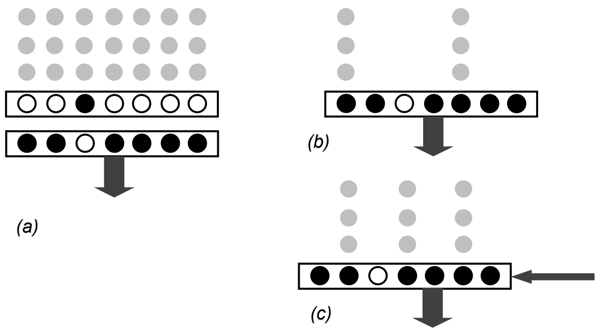


***Figure 4**. (a) Simple redundancy using a second head to replace missing nozzles. (b) Missing nozzle when printing a pattern not utilising all nozzles may be corrected by adjusting head position (c).*

Print strategy can also be used to give compensation for nozzle-to-nozzle variation and nozzle failure. The exact options for different strategies are dependent upon the application, but since it is rare to need to print single, isolated drops in real applications, it is often possible to find alternative ways of printing groups of drops which allow such compensation. If it can be arranged to print groups of drops from several nozzles rather than just one, any variation between nozzles can potentially be averaged out, or missing or defective nozzles compensated for.

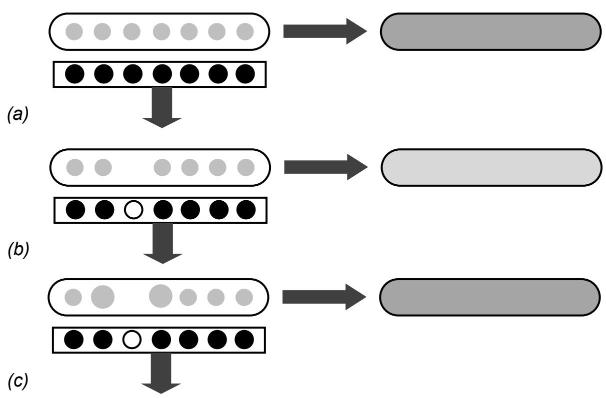


***Figure 5**. (a) Printhead printing across channel printing every drop (left) which fills the channel correctly as drops flow together (right). (b) Missing drop just results in a reduced total volume, which may be OK with enough other drops. (c) Compensation for missing drop with increased volume neighbouring drops.*

Some examples from a display printing application are shown in figure 5. By printing across the line of the channels to be filled, many nozzles are used to print into the channel rather than just one. Assuming sufficient flow of the printed ink along the channel, this not only averages the volume of drops from the set of nozzles, but offers a means of compensating for missing nozzles. If wetting is very good and many nozzles are used, a missing nozzle may simply represent a small reduction in the overall volume of ink in the channel, which may not need any active compensation. The missing drop could be replaced by an extra drop from an adjacent nozzle. And further refinement of this idea is possible with greyscale printing as it may be possible to add the extra volume required by increasing the grey level across several adjacent nozzles to distribute the impact of the missing nozzle.

## Metrology

What is implicit in most of the above is that the condition of the head is known. To compensate for a missing nozzle by switching to another, shifting the head or ejecting more ink from neighbours, the presence of the missing nozzle must be known in the first place. While drop analysis systems to detect missing nozzles and measure the performance of jetting ones are common features on printers, large printers with large arrays of nozzles introduce some issues.

A typical Drop Analysis (DA) system might utilise a camera with strobed illumination to visualise drops in flight from a printhead. By illuminating drops with strobe flashes at two different times after drop ejection, drops can be located at those two points in time and hence the speed and direction of the drop determined for the period in between. The projected area of the drop can also be obtained from images captured and used as a measure of drop volume, although this is not necessarily very accurate as the reported volume is very sensitive to the measured area, which in turn is very sensitive to illumination and thresholding in the image analysis.

Such a system may take 10 minutes to scan and measure the speed, directionality and volume of a 128 nozzle printhead used on a single head, swathe-printing printer. A larger scale printer might instead have many thousands of nozzles and so at the same rate, the DA process if unchanged would extend to several hours. This renders it unviable as a ‘daytime’ process, and while it could for example be run as an overnight process, by the time the process finishes the first data is several hours old. The process time can be reduced by equipping the printer with multiple DA tools to run the DA process in parallel, but this obviously adds significantly to the machine cost.

As reported previously [2], small variations in drop volume between nozzles can result in visible defects in a printed display for example. A volume variability less than 1-2% may be necessary to render the variation invisible in a display, but volume measurement derived from projected drop diameter of drops in flight may only be accurate to around 5%. Therefore besides requiring significant time, a typical drops-in-flight type DA system is probably not accurate enough to measure and allow adjustment of drop volume to the required precision. Printed drop volumes have been measured to sufficient accuracy using a white light interferometry method but this currently requires several hours of measurement for even a 128 nozzle head.

Hence the metrology of large arrays of nozzles would seem to be a weakness in the scaling up of inkjet. Either new faster and more accurate techniques for measuring nozzle performance need to be developed, or print strategies used which accepting there will be a small number of missing, defective or variable nozzles in a large array, are able to cope with them without necessarily knowing much about either their location or degree of imperfection. There are many large scale inkjet printers for graphic applications which are subject to the same potential problems, but smart image processing can render small defects invisible. However in functional printing, single small defects can render a much larger area, or even a whole substrate, useless and so equivalent print strategies are harder to find.

## Machine design and effects of scale

Simply scaling the mechanics of a printer can give many issues to be considered. A process or application may have been developed on a small printer with good drop placement accuracy and that has become a necessary part of the process. Maintaining that accuracy in a much larger machine is not necessarily easy, or achievable.

It may well be that a very small throw distance (nozzle plate to substrate distance) has been used to minimise drop placement errors from angular deviation and drop speed variations. Carrying this forward as the process is scaled up can introduce stiff challenges to the machine designer. For example, if a 300µm throw distance has been used for accuracy, designing a print system to maintain that distance over a large print area and for a large number of individual printheads is not trivial.

Thermal effects become increasingly significant as the print area becomes larger. A 150mm square glass substrate might have a dimensional change of 1µm per °C change in temperature, but clearly that change becomes perhaps 5µm/°C for a Gen4 substrate. But this effect is compounded by the likelihood of a temperature variation in the first place. Maintaining a constant and uniform temperature for that Gen4 substrate is much more difficult than for the smaller substrate because of its size.

Similarly, and often related, the atmosphere around the substrate may require controlling in order to achieve the performance required from the printed item. It may require printing in a clean environment for example which requires a certain air exchange rate which in turn requires flow. That flow, and in particular its uniformity may both be significantly harder to achieve for a larger print area.

As described above, maintaining dimensional tolerances in a large printer can be challenging, and that may lead to a component like the printer chuck on which the substrate sits becoming quite massive to ensure dimensional and/or thermal stability. But that chuck still needs to move precisely under the nozzle array and its mass can cause problems. It may be that the mass is such that more than one linear stage is required, but this introduces further complication and potential inaccuracy from synchronisation of the linear stages resulting in yaw of the chuck as it moves.

Even something as apparently straightforward as printhead maintenance can become significantly more complex for a large nozzle array. Just as for drop analysis procedures, what is a quick process for a single head becomes a significant length of time if applied to tens of printheads serially. While it is much more viable to have a whole-array head maintenance system than a whole-array drop analysis system, time is not the only consideration.

One of inkjet printing's strengths is as an additive process, only putting material where it is required on a substrate and thus being economical with the material. It may well be that maintenance is often required to recover even a single nozzle on one of the printheads, in which case purging ink through every head is not so economical. So while speed may suggest a whole-array maintenance procedure, economy may suggest a head-wise procedure. It may be possible that both could be accommodated in the design of a printer, but more likely a compromise system is required.

Jetting while in an idle state is also a common method of maintaining nozzles in a proper condition. If this function is retained in a scaled-up printer, the relative ink usage of this function may simply scale with the printer size, but in terms of inkjet being an economic, additive process, it's always worth considering just what the fluid demand in idle mode may be. For example, when scaled to a high resolution Gen4 size printer, the idle jetting scheme from the single head predecessor would consume more than 2 litres of ink per day. In many functional printing applications, that quantity of ink can represent a significant cost and while the large printer would also bring significant benefit, being able to reduce that quantity with a revised or alternative method of keeping nozzles in a proper condition could reduce costs. Fluid recycling is one option, or waveforms which exercise the meniscus without producing a drop are another, but avoiding contamination and drying of fluid in nozzles would be respective concerns which may require machine complexity or fluid reformulation.

## Conclusions

At the simplest level, to print a large substrate such as that for a large television screen for example, a large printer is required. But there are lots of considerations on what such a printer looks like and on how it operates and these may be quite different to the small printer on which initial development work was carried out.

A large, substrate-wide array of printheads can eliminate many effects which would otherwise result from a single head or small array scanned over the substrate in swathes. But some 'swathe join' effects can still remain at joins between heads, although these can be addressed with techniques such as interlacing.

However, large arrays bring their own problems, particularly for a functional fluid printer where print defects may be much more critical than for a graphics printer. Some ideas have been presented on redundancy and compensation, but first the array has to be characterised, which itself is a complex task.

Finally care has to be taken in the design of the mechanical system as problems can scale with the machine and if not careful, threaten the fundamental advantages of inkjet printing.

## References


[1] Proceedings of Digital Fabrication 08 (2008)

[2] M.I. Crankshaw et al., Inkjet Printing of Swathe-Free Displays, Proc. DF08, pg. 736. (2008)

[3] S. Seki et al., Current Status of Printing OLEDs, SID 09 Digest, pg. 593. (2009)


## Author Biography

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