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Constraint Solving for Inkjet Print Mask Design

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Abstract

We present results in a constraint solving approach for automatic generation of Inkjet print masks. Print masks are used to control the firing of the nozzles, that is, to determine which nozzles on an Inkjet printer cartridge are to spit an ink droplet at each particular instant in a multiple-pass print mode. Many design rules for print masks can be modeled in terms of constraints and cost functions. For example, if adjacent nozzles are fired simultaneously, printing artifacts often result. Therefore, spatial adjacency constraints with respect to horizontal, vertical and diagonal neighbors are modeled with various cost functions; print masks are then generated by minimizing the associated, total costs. Initial solutions are found by a greedy algorithm with some randomization; then neighborhood search techniques are applied to find local near-optima. Our approach can generate masks for Inkjet printers in multiple-pass print modes for multiple-level, multiple-drop technologies. It has been used to design the print masks for Hewlett Packard's wide format printers (DeskJet 2500C and 2500CM). This approach can shorten the turn-around time for print mask design in a systematic and methodical way.

1. Introduction

In the thermal inkjet printer technology, an inkjet printer cartridge, an inkjet *pen*, contains arrays of nozzles such that an ink droplet is spit from each nozzle when a micro explosion occurs if the ink chamber is heated. Print masks are used to control the firing of the nozzles, i.e., to determine whether one particular nozzle is to spit an ink droplet at one particular instant.

There are various kinds of print mode in thermal inkjet printing technology. The most basic one is the single pass, single drop print mode. The pen sweeps across the media and puts a drop on the pixel if and only if there is a data point at the pixel location that needs to be marked. Afterwards the media is advanced exactly the pen length. Therefore, there is only one chance that each pixel location is visited by the pen. Furthermore, there is at most one drop to be put on the media per visit. Therefore, it is a single level printing. In this type of print modes, there is no need for extra control logic to control the firing of the nozzles.

However, many things can go wrong. For example, the media advance error can produce misalignment in the output. Ink coalescence can be an unpleasant artifact which is caused by the fact that ink may migrate before it is completely dried. Firing the nozzles at higher frequency than they can handle may cause puddling around the nozzle opening which can create the satellites.

Multiple-pass print modes are usually used to avoid these printing artifacts. In a multiple pass print mode, each pixel location is visited by the pen more than once. Therefore, extra logic control is required to determine whether the pen should put a drop in this pass when this pixel location is to be marked. Print masks are applied to provide this extra logic. They are usually coded in an array of 0's and 1's. 1 indicates firing the nozzle if there is a data point needs to be marked. 0 means no firing regardless if there is a data point. The size of the array varies from one pen architecture and writing system to another. The arrays tile up to cover the printable area of the media. Each array element has direct correspondence to a particular pen nozzle in a particular pass, controlling the firing as the column of pen nozzles sweeps across the media.

Figure 1 shows an example in a two-pass print mode, with print mask width four and length eight. As this mask array is tiled over the media, the pen sweeps across the media and marks every other pixel location if there is a

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data point there, in a checkerboard pattern. This alternating fashion is to avoid consecutive firing of the same nozzle. Afterwards the media is advanced half of the pen length and the printing resumes. Notice if we label the lower half of the array as $M1$ and the upper half $M2$, then $M1$ and $M2$ should be complementary to each other. In other words, all the entries that are missed by $M1$ the first time when the pen sweeps along are picked up by $M2$ during the second time when the pen visits again.

The print masks are important because they directly affect the print quality. They provide the necessary logic control in multiple-pass print modes. They enforce hardware limitations on firing frequency. This can be modeled as a spatial adjacency problem. In case one wants to further avoid the adjacency between different passes, then it is a temporal adjacency problem. If there is a defective nozzle, one can shift its printing responsibility to another nozzle by specifying exactly that in the print masks. More aggressively, we have proposed to apply halftone patterns for print masks [1]. By introducing an invisible halftone pattern or a less objectionable pattern, one can disrupt the unpleasant, existing pattern, or cover up by the new pattern.

2. Problem Formulation

Mask arrays are used to tile up the entire printable area on the media. Since the logic in 1 means firing at this pixel location when the pen sweeps across the media, we could have marked the non-zero entries by the *pass number* instead of 1. Looking from the pixel's point of view, these two have one-to-one correspondence. Furthermore, we could combine the upper and lower into one since they are complementary. And these two have one-to-one correspondence. This representation is more compact and yet complete (Figure 2).

Now the task for mask generation is to fill up the mask array with numbers subject to the adjacency constraint. The notion of a Constraint Matrix was invented for this purpose (Figure 3) [2]. Each time when we are to decide the number to be filled in this entry, we know that it has to be at least a distance away from its left neighbor, b distance from its upper neighbor and c distance from its upper left neighbor, and so on. This representation is simple and effective. The masks generated by this method have been used in HP's large format printers.

All these have worked fine in single-level printing. Now we have to extend it to handle multiple-level print modes. The difference here is that in single level printing, among multiple visits of the pen over the media, one and only one of the visits will the pen put a drop on the pixel location. However, with diluted ink, or smaller drop volume, one could put a drop for more than one of the visits during multiple passes.

Here is a practical example (Figure 4). We conduct our feasibility test on one of HP's prototype printers which uses the 64-nozzle color pen. The print mask has length 8 and width 4. In one particular print mode, it is 8-pass, with 3 levels. For example, if the image data at the pixel location corresponding to the first entry is level 1, then the pen puts one drop, in pass 2. If the image data here is level 2, then the pen puts three drops, one in pass 2, one in pass 4 and one drop in pass 7. If the image data here is level 3, then the pen puts eight drops, one drop for each pass (there is no need for logic control in level 3).

3. Constraint Modeling

The entry of the mask array is extended to a cell (Figure 5). In the previous example, all the pass number appear in the top row in level 1 are always included in the second row in level 2. This dependency property is not unusual in many practical cases. It is also possible that same pass number may appear more than once within a row. The repetition of the same pass number actually means more than one drop can be fired at each pixel location per pass. This is called the multiple-pass, multiple-drop, multiple-level print mode.

Therefore, a cell is a structure such that there are at most DPP rows, where DPP stands for drop-per-pixel. Each row is a bag, a collection of pass numbers in which some of them may repeat up to MFP times, (Maximal Firing Per pixel per pass). The dependency in the previous example can be achieved by assigning portion of the solution as input to the constraint solver.

The total cost will be the composite costs of the adjacency constraints, the evenness of the mask, and the halftone coherence. The cost of the adjacency constraints are the sum of the costs of the constraints that are false in the mask. The evenness encourages the number of occurrences of values to be as even as possible. The cost associated with the halftone coherence is intended to disrupt the halftone pattern in the output [3].

We now have a list of the input parameters. P is the number of passes. The dimension of the mask array is the pen length divided by P. The width is a user input, dependent on the particular writing system. It can be a two-dimension mask array, one for each particular color. It can also be layers of mask arrays such that we may or may not want to enforce constraint across the layers. The DPP, drop per pixel, corresponds to the number of levels. The MFP is the maximal firing per pass per pixel. A set of weight tables defines the costs. A partial assignment (maybe a halftone pattern) to the solution may also be specified.

The solution is a mask array of given dimension such that each entry is a cell. A cell contains at most DPP bags

of different size. Each slot of the bag is assigned an integer between 1 and P such that there are at most MFP occurrences of any integer in the bag. The mask array is a near-optimal solution to the global minimization of the total cost.

4. Constraint Solving

The constraint solving strategy is based on a greedy, randomized, adaptive search procedure (GRASP) [4] followed by a repair phase. The greedy phase computes a solution by filling in one cell at a time while minimizing the accumulated cost. Alternative values are chosen with a probability that is proportional to their benefit to the total solution. The degree of randomness can be tuned by the user.

The repair phase uses the solution computed by the greedy phase as a starting point for a neighborhood search. We have currently implemented a simple hill-climber that stops when it has found a solution with locally minimal cost, but other options are possible, e.g. simulated annealing or taboo search.

By repeating the greedy and repair phases, the constraint solver generates a stream of proposed, locally optimal solutions. An interesting idea is to use the greedy phase to produce an initial population of solutions, and then use a genetic algorithm to let the population evolve towards better fitness values.

Details on the constraint modeling and the constraint solving are described in a technical report [5].

5. The Results

We have implemented a constraint solver, in TCL/TK, a script language, as the input interface, and a text file as the output.

An input script file in TCL can be found in Appendix A. The programmable support routines are included in the file ”support.tcl”. A random seed is generated for each instance. By recording this seed and setting the random seed accordingly, one can repeatedly generate the same mask array. This example is a spatial adjacency problem (SAP) with a mask array, of width 4 and height 8, one layer (one color plane), for an 8-pass, 3 drops-per-pixel (3-level), single-drop technology. The evenliness is in full weight (1.0) and the attenuation about the halftone coherence is set to be 50%. The mask array should be considered as wrapped-around in all directions because, for example, its top most row is actually immediately adjacent to its bottom most row when it is used to tile up the image. The default cost is ranged from 0 and 15. No horizontal adjacency is allowed, i.e., the cost is infinity if the left neighbor is the same as the current entry. Vertical or diagonal adjacencies are allowed, but not without some penalty. Some GRASP selections can be specified also, for instance, greedy search and hill climber, and so on. A sample output can be found in Appendix B. Sometimes one has to translate the mask array into an internal hexadecimal representation which is specific to the prototype printers to be tested. A number of enhancements and extensions have been made since the preliminary implementation. For example, a newer version of our constraint solver handles a special variation [6], i.e., using print masks in 300 dot-per-inch (dpi) resolution for printing 600dpi data by extending each pixel into four quadrants.

6. Summary

Print masks are always among the last to be finalized before the manufacturing release. They are always under severe limitations. However, miracles are always expected to fix problems at the last moment and miracles are always expected in a very short time. The main objective of this work is to shorten the turn around time for print mask design.

Not all of the desirable characteristics can be modeled as constraints and cost functions easily, if at all. There are still too many possibilities to test. A strategy is in need to produce a collection of representative masks within the solution space. It is fully understood that there will always be inconsistency across pens and across different printers. Therefore, even optimal solutions are never guaranteed to produce the best print quality.

More and more complicated pen architecture will be introduced. The expected life span of pens will be much longer with the new, off-axis-ink technology. Manufacturing cost cutting will end up with cheaper and less accurate parts such that error-hiding will be more and more important. Therefore there is a need for an automated tool for print mask design. We believe that constraint solving suits this type of problems.

7. References

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Biography

Jonathan Yen is a member of technical staff in the Imaging Technology Department, Computer Peripherals Laboratory, Hewlett Packard Laboratories. He is currently a member of the Halftoning and Image Processing project. He got his M.S. and Ph.D. in Computer Science from the University of Utah. His primary research areas include information embedding, digital photography, image processing and printing systems optimization.

Appendix A: A Sample TCL Script

```
#!/bin/sh
# Switch to Tcl/Tk \
exec ./hpcs -f $0

#supporting stuff in tcl
source support.tcl

#find a random number
set random [expr int(rand() * 100000000)]
SetRandomSeed $random #set the random seed

# Create a problem instance.
# syntax:
# SAP <name> <width> <height> <depth>
#     <#passes> <list of levels> <mfp>
#     <evenliness> <attenuation>
#     <wrapx?> <wrapy?> <wrapz?>
SAP sap 4 8 1 8 {3} 1 1.0 0.5 yes yes yes

#set a range for the default cost
sap default 0 15
# forbid horizontal adjacencies:
sap repetetive -1  0  0   inf
# avoid other adjacencies:
sap repetetive -1 -1  0   1 5
sap repetetive  0 -1  0   3 10
sap repetetive -1  1  0   1 5

# Create a printmask
Printmask printmask sap
Greedysearch printmask
Hillclimber printmask

# Print output
set output [printmask get]
PrintMatrix $output$

exit
```

Appendix B: A Sample Output Mask

```
8    2    4    5
148  257  148  357
3    2    5    6
357  246  357  168
6    2    3    5
367  245  136  258
1    2    7    3
167  248  167  358
4    3    6    7
468  357  168  237
8    4    1    2
138  247  158  246
4    3    1    6
247  356  124  368
6    1    4    5
346  125  347  158
```

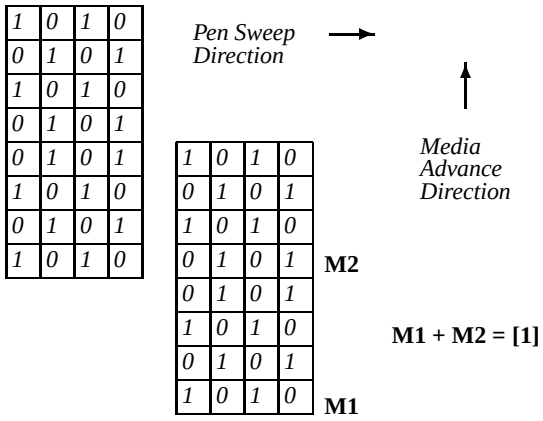

Figure 1: A two-pass print mode

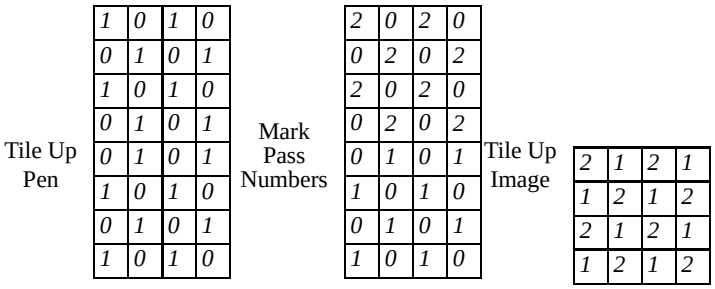

Figure 2: Problem formalization

c	b	d
a	?	X
X	X	X

$|? - Left| \geq a; |? - Upper| \geq b;$
$|? - UpperLeft| \geq c; |? - UpperRight| \geq d;$

Figure 3: Constraint Matrix

Level 1: 1 drop
Level 2: 3 drops

2 247	6 356	4 124	8 358
6 368	2 127	8 568	4 147
4 124	8 358	2 247	6 356
8 568	4 147	6 368	2 127
6 368	2 127	8 568	4 147
2 247	6 356	4 124	8 358
8 568	4 147	6 368	2 127
4 124	8 358	2 247	6 356

Figure 4: A multi-level example

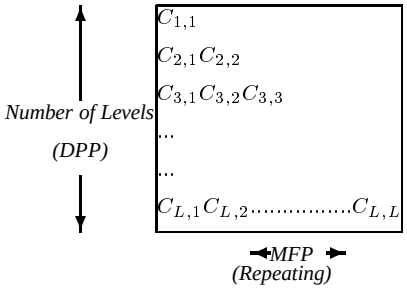

Figure 5: A cell