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Image Analysis and Rating of Ink Jet Printing

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IMAGE ANALYSIS AND RATING OF INK JET PRINTING

By

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Wendy S. Woodbury

IMAGE ANALYSIS AND RATING
OF INK JET PRINTING

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Correlation between image analysis measurements and visual ranking of ink jet printing was established. Human rating was determined by the use of an all-pair comparison. A camera driven image analysis system and NIH image analysis software with a scanner was used to analyze printed samples. Three sets of printed samples were evaluated for print density and single dot attributes.

Analyzing the mean gray scale value (GSV) as a tool for evaluating ink jet print quality is limited. Large differences between samples will contribute to the perception of quality, but small differences are overruled by other factors.

Using the standard deviation of the mean GSV to incorporate mottle effects into image analysis is promising. However, a small amount of mottle will not correlate to print quality.

Object area may be a useful tool for evaluating print quality. Sample set 1, where the printer was held constant, showed decent correlation. This relationship should be further explored.

Perimeter is another good tool for interpreting print quality. As a direct measure of feathering and

wicking, perceived print quality has a direct relationship of measured print quality. Once again, the set of samples in which the printer was held constant showed good correlation.

Roundness, being a normalized parameter, is a good indicator of print quality if there is a noticeable variation between different samples.

A rating equation was established which gave excellent correlation between measured print quality and perceived print quality. The equation is as follows:

$$R_1 = \left(\frac{1}{P} + \frac{1}{SD}\right) \times C_1$$

$$R_2 = \left(\frac{1000}{P} + \frac{1}{SD}\right) \times C_2$$

Where: P = perimeter

SD = standard deviaiton of the GSV

C_1, C_2 = scaling constants

When applied to data gathered during the course of this project, the regression analysis, when compared to the all pair comparison values, generated an r^2 value of up to 0.92. When applied to literature values, the regression value was 0.96.

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INTRODUCTION

Ink jet printers are becoming more widely used in businesses, homes, and in industry. Ink jet print quality depends on the paper it is printed on. In order to provide paper suitable for ink jet printing, a method of analysis and rating print quality is needed.

Current methods exist to analyze print quality. These methods are subjective to human perception. A quantitative method that could be used throughout the industry would be beneficial to those attempting to make paper acceptable for ink jet printing. The quantitative method of choice is image analysis.

Past image analysis studies have analyzed ink wicking and feathering, character area, color bleed, and optical density, among other properties. Using these characteristics in a quantitative fashion to rate the print quality has not been fully realized.

BACKGROUND

Ink jet printing is a non-impact method of printing; very small drops of ink are sprayed onto a paper (or other) surface at a very high velocity (1). The printer, ink and paper form a printing system. As these components vary, ink jet print quality may change.

The printer serves to place ink drops on the substrate, usually paper. Ink parameters such as viscosity, surface tension, pH, etc. are important to the performance of the ink (4). The paper accepts the ink, prevents spreading of the drop, and helps the ink to dry (1).

Different papers may exhibit different print qualities. Ink jet print quality is a function of edge blurriness and raggedness (also termed feathering and wicking), optical density, color bleed, and show through, among others. As these qualities are maximized or minimized, the print quality changes. Good paper can create an image that approaches laser printer quality. Paper producers strive to manufacture paper with excellent ink-jet printability.

Much research has been done in industry on the factors that effect ink jet quality. Studies have used different methods of analysis and different quality parameters.

Lee, et al, analyzed the image quality of plain papers (2). Test prints were evaluated by judges; the rated papers were examined for edge raggedness, a line spread function, and a modulation transfer function. These image quality metrics helped characterize the properties contributing to the print quality (2).

Another study analyzed print quality based on the area and perimeter of a printed character. As the wicking of the character increased, the area and perimeter increased. A linear relationship was found between the character area and wicking. These measurements were made using a camera-driven image analyzer (3).

A third study, conducted by Hewlett Packard, defined a set of quality parameters contributing to overall print quality as seen by the human eye. These parameters are based on character hue and darkness, edge smoothness/roughness, character edge contrast, artifact presence, and area fill uniformity (5).

Hewlett Packard also published a set of criteria for evaluating ink jet printing (9). The different tests generally rate samples as "acceptable" or "unacceptable." Human subjectivity plays a large role in sample rating. Tests include rating feathering, wicking, color bleed, mottling, etc.

A study conducted by Wågberg and Wågberg (8) concluded that feathering is the most important quality factor with perceived ranking, however, when a level of mottling is too high it may overrule this.

The interaction of colored inks with each other can be observed by color bleed, or the spread of one color into another across a distinct boundary (6). The way ink colors blend or bleed contributes to the perceived quality of the printed paper.

The areas of the colored characters (black, composite black, and black on yellow) have been measured with a camera-type image analyzer. A densitometer measured the optical density of the black and composite black characters. These tests were performed to study the effects of sizing on color bleed and print quality (6).

Apogee Systems, Inc. has recently developed a scanner-driven method of analyzing ink jet print quality (10). Western Michigan University has the Apogee system and reports software limitations, such as base stock interactions (shadows, color, etc.) with the rating process. Many different paper factors can alter the results of the print analysis.

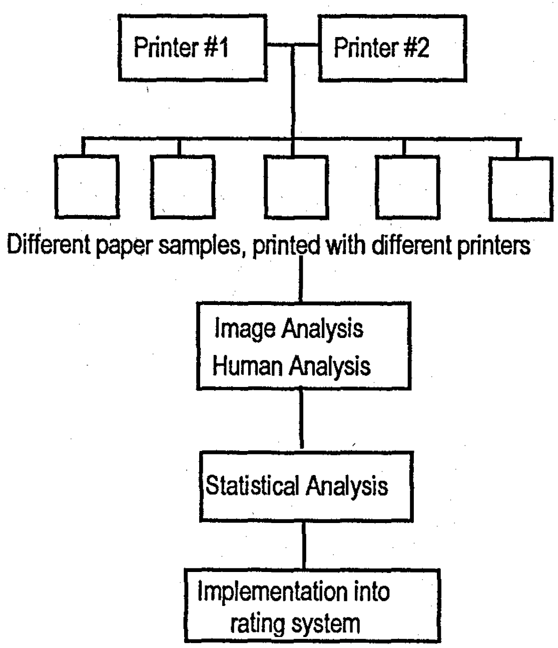
Methods for analyzing ink jet quality vary from using a panel of judges to using a camera or scanner driven system to create a digital image for analysis. Image analysis results can vary significantly from human evaluation. Human rating is slow and imprecise. Image analysis equipment and methods exist, but no industry standard has been created. The design of a rating system would provide a standard in which to compare printed samples to each other.

EXPERIMENTAL DESIGN

Different paper samples were printed with different ink jet printers and analyzed with current image analysis systems to determine a correlation between human rating and image analysis. A sample of the test pattern can be found in Appendix I.

Camera-type image analyzers and a panel of judges were utilized. Criteria for analysis included variations on edge roughness and blurriness, and optical density.

One to four printers were utilized to provide a variety of printed samples. A range of paper types were also be used to produce different printing results. A flow chart follows:



Three sets of samples were analyzed. The first set consisted of a variety of papers produced at Western Michigan University's paper pilot plant. All samples were printed with the same printer.

The second and third sets contained a wider variety of paper types and printers. Paper produced in the pilot plant was used, as well as different commercial paper grades. In total, 4 different printers were used to print test patterns of different paper types.

Image Analysis

Two image analysis systems were used to obtain measurements; a scanner-based system and a camera-driven system.

The scanner system measured parameters related to the gray scale. The mean gray scale value, standard deviation, minimum and maximum gray scale values were obtained by digitizing an image with a scanner and analyzing with software developed by the National Institute of Health.

A system utilizing a live camera image was used to obtain data relating to the area, perimeter, and roundness of a single dot.

Human Analysis

Human analysis was determined by use of an all pair comparison (11). An all pair comparison (APC) is designed to compare different samples in pairs. The rationale behind this method is the idea that human analysis will be more accurate when comparing two samples at once, instead of eight. A sample of the form used to make comparisons can be found in Appendix II.

Ten different people judged each of three different sample sets; each containing eight samples. The decisions of the judges as to which samples were better than other samples were statistically analyzed and a relative ranking scale was calculated.

Statistical Analysis

Correlation can best be determined by evaluating the linear regression of the measured parameters in comparison with all pair comparison scale. A perfect set of data would yield a regression (r^2) of 1. The fit of the data diminishes as the regression decreases to zero.

Data was treated in this manner, and the regression was determined. Consequently, the correlation of the different parameters with the APC scale was evaluated.

PRESENTATION AND DISCUSSION OF RESULTS

Results from image analysis and the all pair comparison, as well as regression analysis can be found in Appendix III. For the regression analysis, each parameter was individually plotted against the corresponding APC scale (0 = worst, 10 = best). In addition, the regressions of the standard deviations of the parameters were calculated.

Gray Scale Value (GSV)

The gray scale is a numerical method of indicating the relative lightness or darkness of a gray tone. The scale ranges from 0 (pure black) to 255 (pure white).

NIH image analysis software was used to determine the mean gray scale value from "area A" (denoted in Appendix I).

Figure 1. Regression analysis of the mean gray scale value

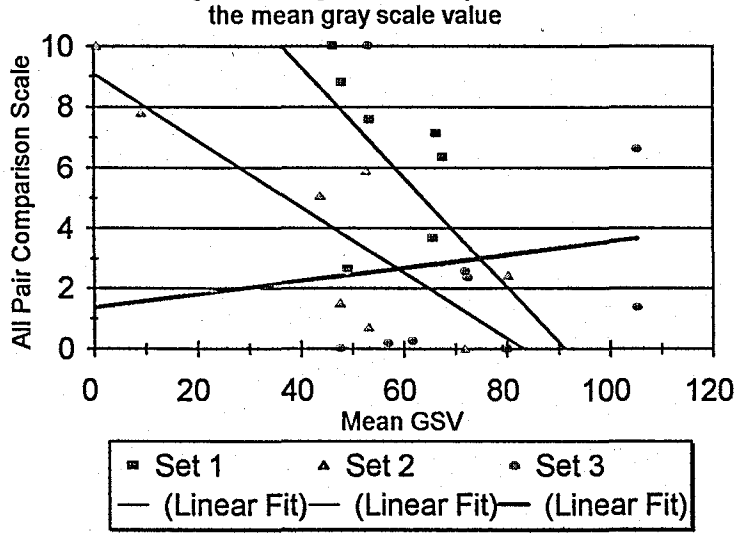


Figure 1 illustrates the relationship between the mean GSV and the APC scale. The regression values are 0.424 for set 1, 0.707 for set 2, and 0.339 for set 3 (remaining data can be found in appendix 3).

The regression ranges from slight to moderate. The idea that color richness having a relationship with print quality is admissible. If color is rich and vibrant, while other parameters show little variation, human analysis would rank it higher than a sample in which the color is lighter, or more washed out.

Although the mean GSV does not make the largest contribution to perceived print quality, there is a relationship.

Standard Deviation of the Mean GSV

Using the standard deviation of the mean GSV incorporates the effect of mottle into the quantitative analysis of print quality. Because mottle is the point to point variation of ink density, the standard deviation should reflect the amount of mottling of a sample.

NIH image analysis software was also used to determine the mean gray scale value from "area A" (denoted in Appendix I).

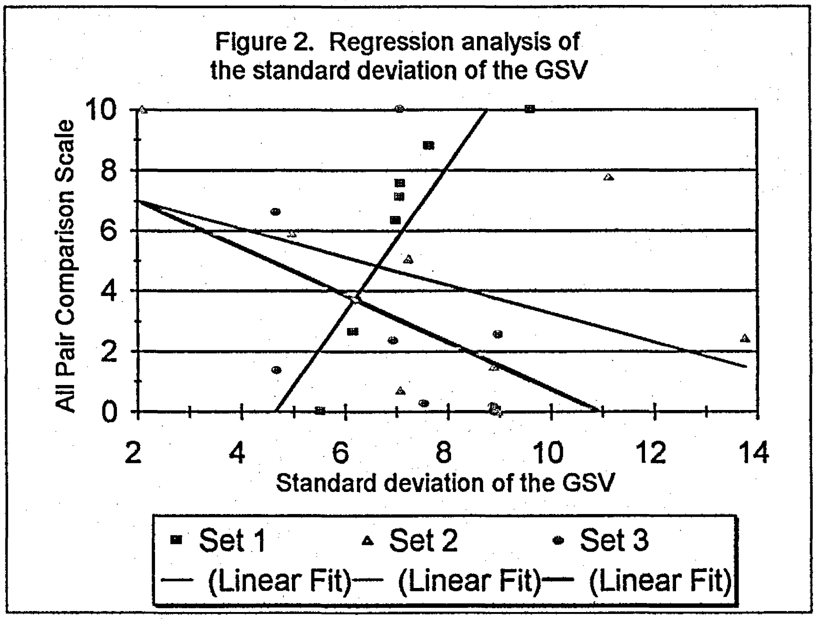


Figure 2 shows the relationship between the standard deviation of the mean GSV and the APC scale. The regression values are 0.791, 0.219, and 0.233 for sets 1-3, respectively.

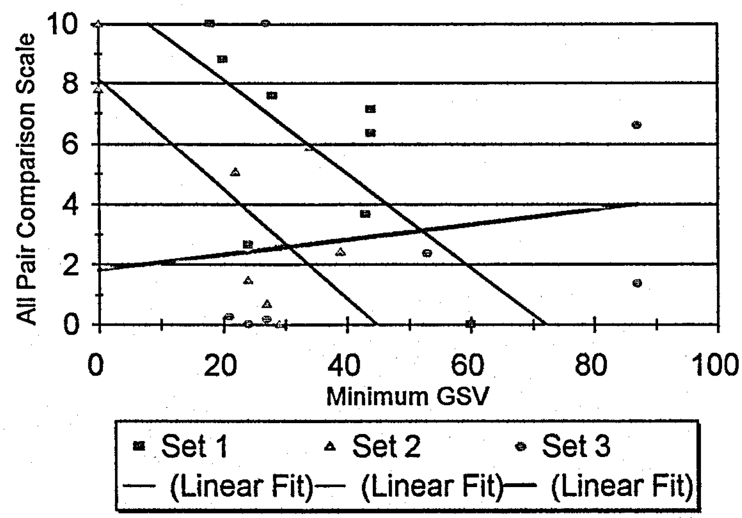
Set 1 showed the highest correlation for the three sets, but this is misleading. Upon examination of the data, the standard deviation increased linearly with the APC scale. The APC scale ranges from worst (0) to best (10). The spread of the standard deviation is not great for set 1, ranging from 5.5 to 9.6. Visual evaluation of the samples did not detect large mottle variation between samples.

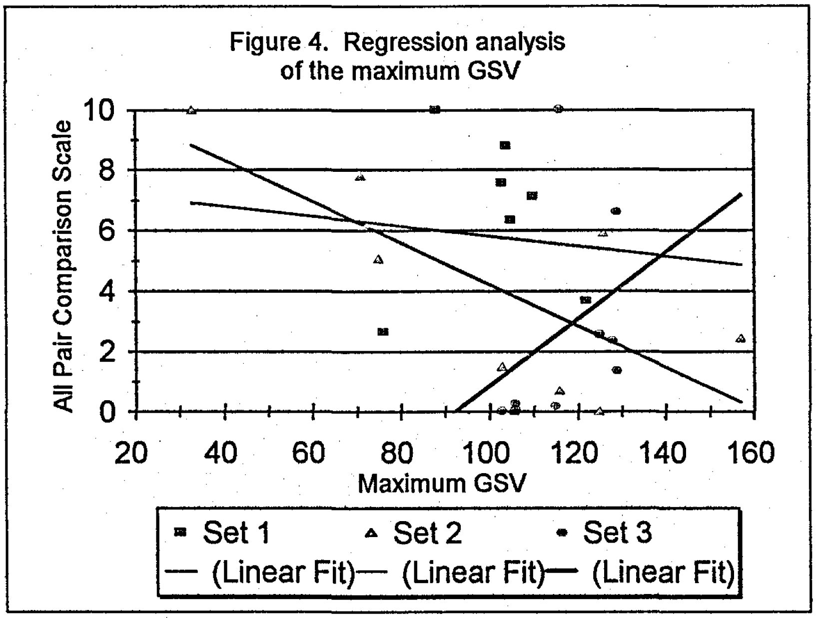
Sets 2 and 3 showed relatively low correlation between the APC scale and standard deviation of the GSV. From this data, it is reasonable to deduce that large mottle variations will correlate reasonable well with the APC. However, the mottle variations in this study were not distinctly different, leading to poor correlation. This theory is backed by research performed by Wågberg and Wågberg (8), as mentioned in the background.

Minimum and Maximum GSV

The minimum and maximum gray scale values were detected by using the NIH image analysis software on Area A.

Figure 3. Regression analysis of the minimum GSV





Similar to the mean GSV argument, it was hoped that by examining the minimum and maximum gray scale values, a correlation would be observed based on color vividness. However, this was not observed, as can be seen in figures 3 and 4.

The regression values for figure 3 were 0.467, 0.539, 0.093 for sets 1, 2, and 3. For figure 4, the values were 0.005, 0.562, and 0.295. Perhaps this information would be useful if there was a gross difference between samples. Using the minimum and maximum GSV does not prove to be a useful evaluation of print quality.

Artifact Area and Standard Deviation

The area of a dot, or artifact, (area B, appendix 1) was detected using a camera driven image analysis system. Four different measurements were taken of four different dots for each sample.

Figure 6. Regression analysis of the standard deviation of area

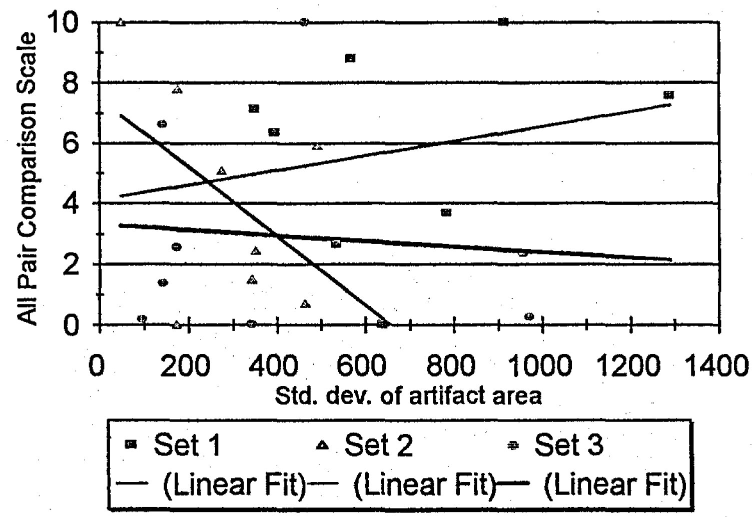
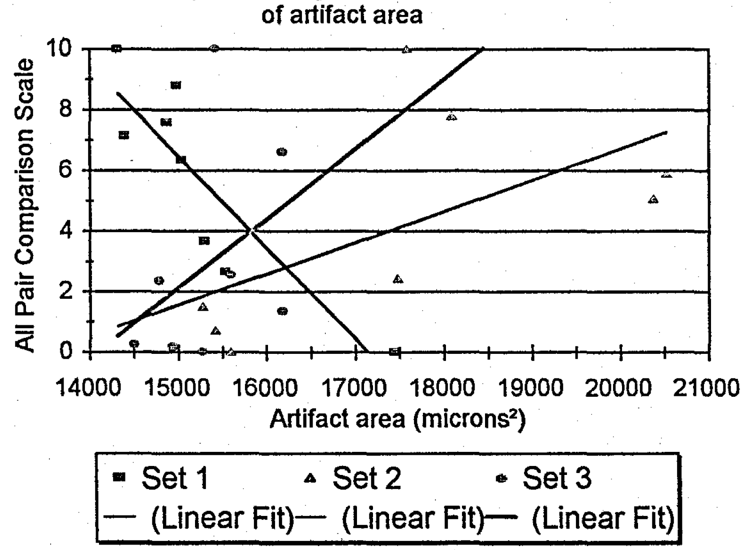


Figure 5. Regression analysis of artifact area



Figures 5 and 6 show the relationship between the artifact area and standard deviation of area with the APC scale. For the area, the regression values are 0.769, 0.361, and 0.261 for sets 1-3. For the standard deviation of area, the regression values are 0.049, 0.232, and 0.145 for sets 1-3.

The relationship between the artifact area and APC scale varies from slight correlation to moderate correlation. Theoretically, because all samples were printed from the same size pattern, as the area of the dot increases, the print quality should decrease. The area measurement should pick up wicking and feathering variations.

For set 1, the correlation is noticeable. These samples were all printed from the same printer. Sets 2 and 3 showed diminished correlation. These sets also used more than one printer to prepare samples. Qualitatively, these samples in the latter sets seemed comparable in print size, but quantitative differences were observed when using image analysis.

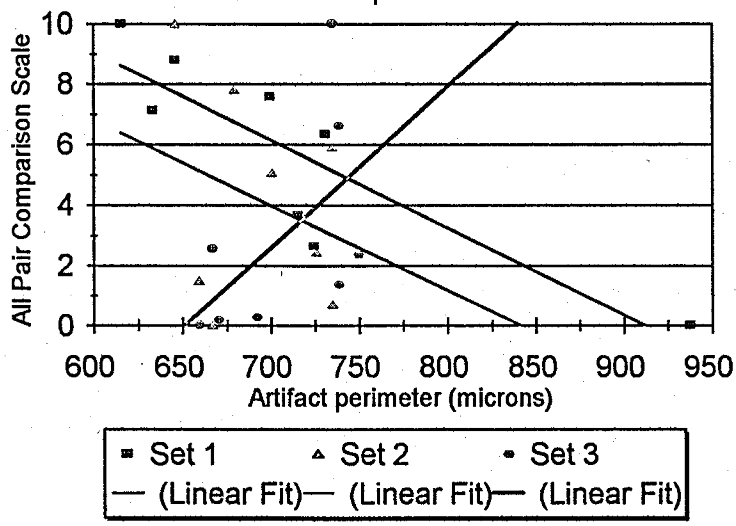
Standard deviation is a sign of non-conformity. Ideally, all printed dots should be the same size. Hoping that the standard deviation would show deviation from the "ideal" dot, this parameter was examined to determine if any correlation existed with print quality.

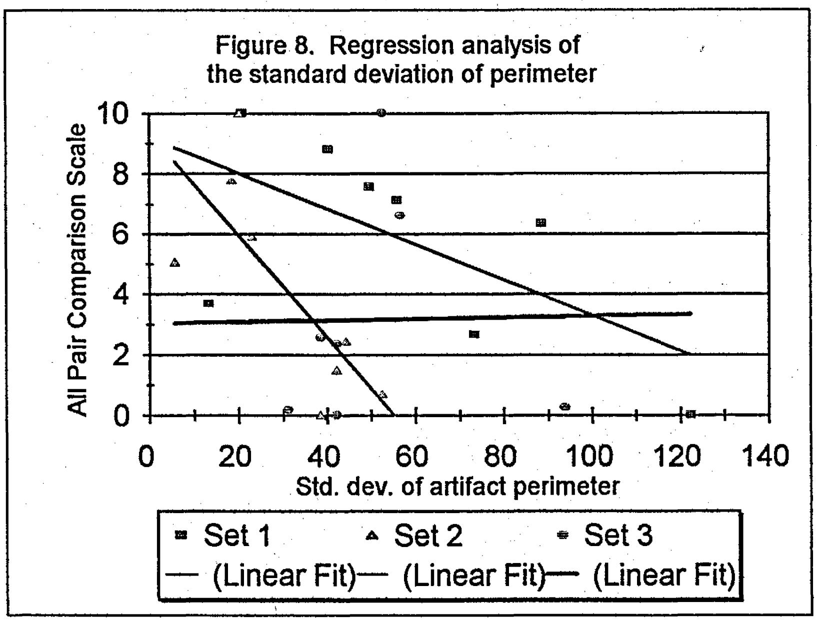
As can be seen from Figure 6, and the regression values, essentially no correlation existed between standard deviation of area and perceived print quality. Perhaps gross differences in this parameter would correlate to print quality; this was neither proved nor disproved.

Artifact Perimeter and Standard Deviation

The perimeter of an artifact was measured using a camera driven image analysis system. Four different measurements were taken of four different dots for each sample.

Figure 7. Regression analysis of the artifact perimeter





Figures 7 and 8 show the relationship between the artifact perimeter and standard deviation of perimeter with the APC scale. For the perimeter, the regression values are 0.754, 0.078, and 0.002 for sets 1-3. For the standard deviation of perimeter, the regression values are 0.397, 0.570, and 0.069 for sets 1-3.

Similar to the arguments analyzing the relationship between artifact area and area standard deviation, perimeter should show evidence of feathering, wicking and other quality deterrents. The regression analysis is very similar to the results observed for the analysis of artifact area.

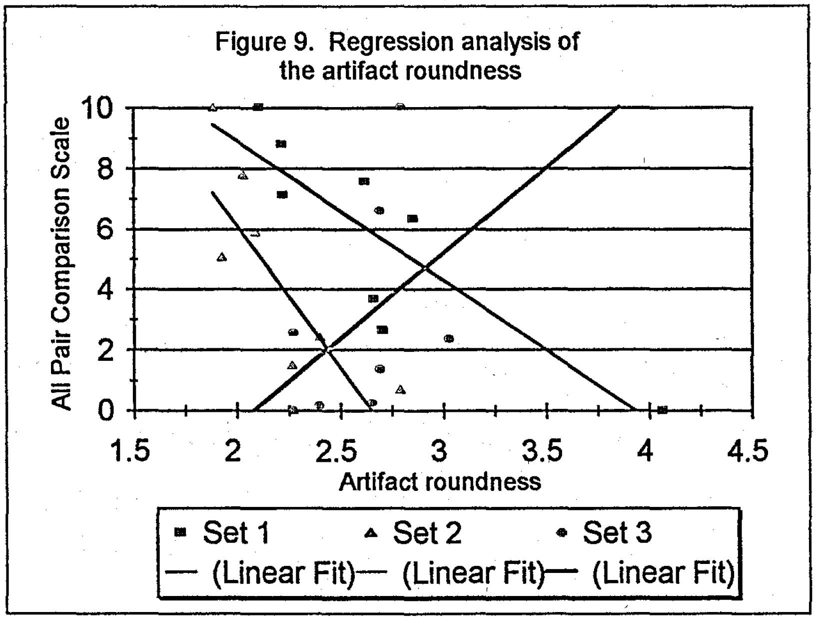
Set 1, as previously mentioned, contained samples printed from the same printer. This set has the highest correlation between human analysis and image analysis, when compared to the other sets. This trend is expected and understandable. As the feathering and wicking increase, the corresponding quality should decrease.

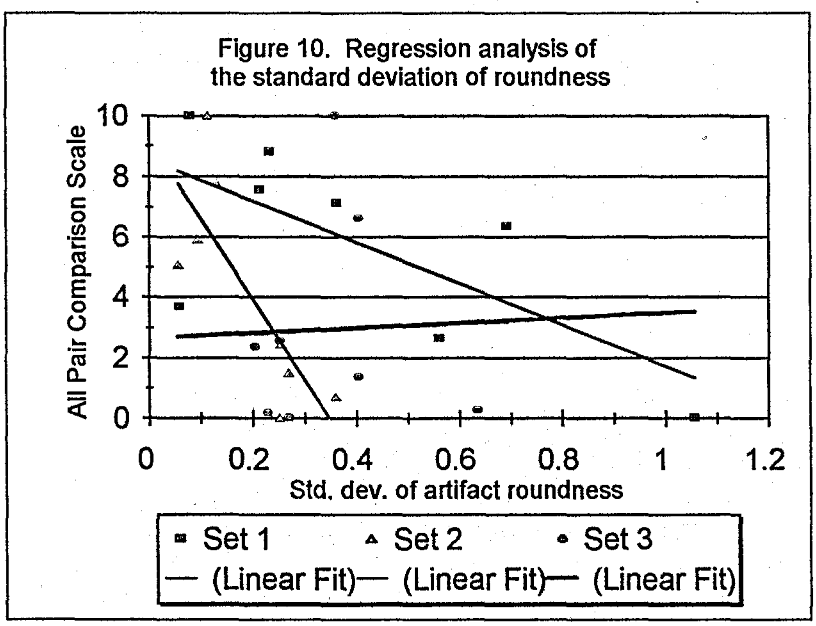
Sets 2 and 3 show no correlation between the quantitative measurement and the perceived print quality. This most likely due to the introduction of different printers into the system.

Analyzing the standard deviation of the perimeter does not show any significant relationship the perceived print quality. When measuring units on a microscopic scale, even large deviations in the parameter do not appear to affect overall print quality.

Artifact Roundness and Standard Deviation

The perimeter of an artifact was measured using a camera driven image analysis system. Four different measurements were taken of four different dots for each sample.





Figures 9 and 10 show the relationship between the artifact roundness and standard deviation of roundness with the APC scale. For the roundness, the regression values are 0.722, 0.599, and 0.071 for sets 1-3. For the standard deviation of roundness, the regression values are 0.485, 0.623, and 0.081 for sets 1-3.

Roundness is a measure of how close an object is to being a perfect circle. As numerical value of the roundness increases, the object becomes less round. In other words, prefect roundness has a value of 1, imperfect roundness has a value greater than 1.

Roundness can be used as a normalized indicator of print quality; roundness is not dependent on sample size. As the roundness value increases, the print quality subsequently decreases.

This relationship is observed for sample set 1, which was printed with the same printer. The correlation between roundness and the APC was noticeable. For set 2, the relationship is still evident, although not as strong. Set 3 shows no correlation, however, the spread of roundness values is not as great (from 2.3 to 3.0) as the previous two sets (from 2.1 to 4.1, and 1.9 to 2.8). Thus, roundness is a good indicator of print quality when there is a large variation in roundness values.

Enforcing the same rationale for analyzing the standard deviation of the roundness as the previous analyses of area and perimeter, it could be hoped that with increased variation, the print quality diminishes.

This effect is not particularly strong, as regression values are not very high.

Rating Ink Jet Print Quality

The ultimate goal of this thesis is to define a rating system that may be used for the characterization of ink jet print quality.

Two methods of correlating measured print quality to perceived print quality have been examined (denoted R_1 and R_2). They are as follows:

$$R_1 = \left(\frac{1}{P} + \frac{1}{SD}\right) \times C_1$$

$$R_2 = \left(\frac{1000}{P} + \frac{1}{SD}\right) \times C_2$$

Where: P = perimeter
SD = standard deviaiton of the GSV
C_1, C_2 = scaling constants

Rating system 1 and 2 utilize the object perimeter and the standard deviation of the GSV. As the perimeter and standard deviation of the GSV increase, the quality decreases. Consequently, the numerical rating decreases, indicating poorer quality. Each equation is paired with a constant, (50 and 5 were used during this experiment for C_1 and C_2) used to scale the numerical rating to a reasonable value.

For rating system 2, an attempt is made to weight the importance of the different attributes. As previously discussed, perimeter is thought to be more important in perceived quality, followed by mottle effects (8).

Data and regression analysis can be found in table 5, appendix 3.

Figure 11. Regression analysis of rating system 1

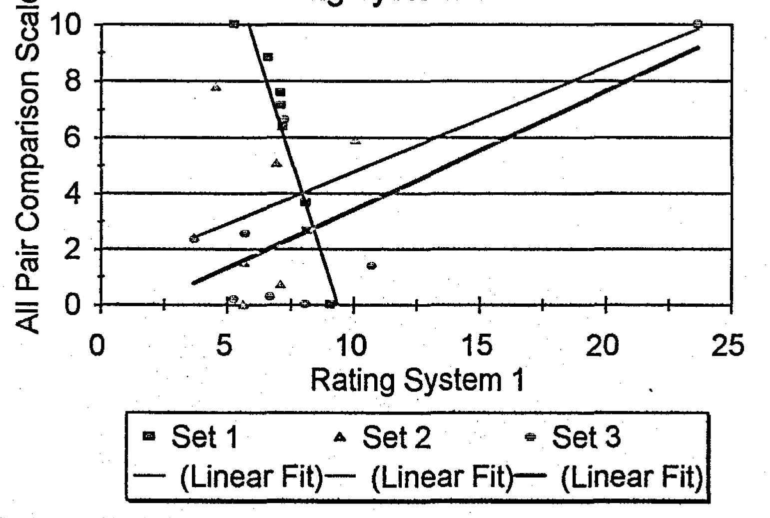
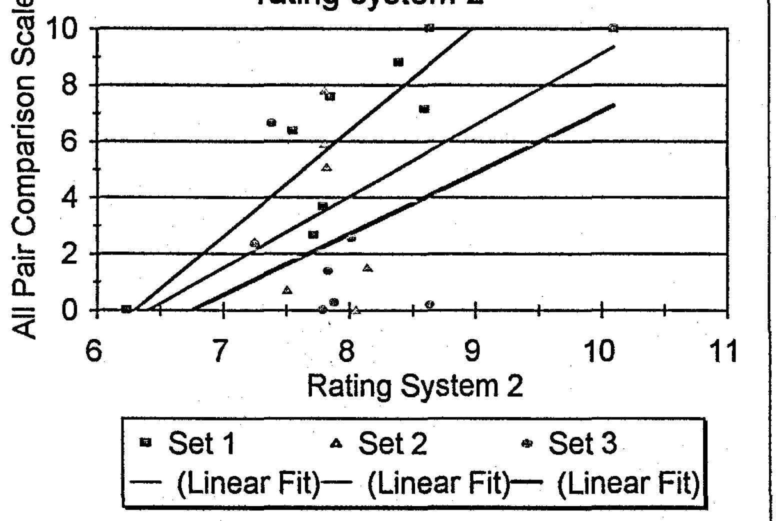


Figure 12. Regression analysis of rating system 2



Figures 11 and 12 detail the relationship between the proposed rating equations and the all pair comparison values.

Regression analysis for rating system 1 yields the values 0.916, 0.444, and 0.554 for sets 1, 2 and 3. This is a considerable improvement over any of the individually analyzed parameters.

For rating system 1, no attempt has been made to weight either factor as more important. As it stands, the mottle effect will have a larger effect on the overall rating due to the magnitude of the terms involved. For this study, perimeter measurements ranged from approximately 600-900 microns, while the standard deviation of the GSV ranged from roughly 2 to 14.

In figure 11, set 1 has a negative slope when compared to the proposed rating system. Ideally, the slope should increase as the rating system increases. For set 1, the standard deviation of the GSV varies only 4 points from high to low, with the highest standard deviation being paired with the best perceived print quality and vice versa.

The variation between samples was not large enough to affect the perceived print quality, but it did create a negative slope, as observed in figure 11. Because the all pair comparison scale is scaled from zero to ten, the differences in actual print quality may not be reflected in the APC scale. For example, if the print quality difference is small, the rating system may or may not reflect perceived differences. This issue can be seen from the vertical line for sample set 1 in figure 11. This effect may be reduced by incorporating standard samples of the extreme ranges of good and bad print quality to fix the APC scale.

Regression analysis for rating system 2 yields the values 0.735, 0.378, and 0.301 for sets 1, 2 and 3. These values show no improvement in correlation (in the case of set 1) to only slight improvement (sets 2 and 3) when compared to the individually measured parameters. It was hoped that weighting the equation in the favor of the perimeter term would improve correlation between perceived print quality and measured print quality; the desired effect was not observed. However, this equation may to be a better "real world" treatment of data. Further consideration should be considered.

Rating Ink Jet Print Quality of Literature Values

Applying the above equations to literature values helps to prove the validity of the proposed rating systems. Data was taken from a study conducted by Wågberg and Wågberg (8) and the equations for rating print quality were applied (units were not detailed for the perimeter or mottle measurements):

Sample ID	Human Rating	Mottle, Large	Peri-meter	Rating 1	r²	Rating 2	r²
C	9.8	51	53	1.92	0.96	98.13	0.45
A	8.3	50	64	1.78		100.08	
B	7.7	48	64	1.82		104.24	
D	4.5	54	130	1.31		92.63	
E	4.2	172	51	1.27		29.17	

Table 6. Comparison of rating systems to literature values.

Figure 13. Comparison of rating system 1 to literature data

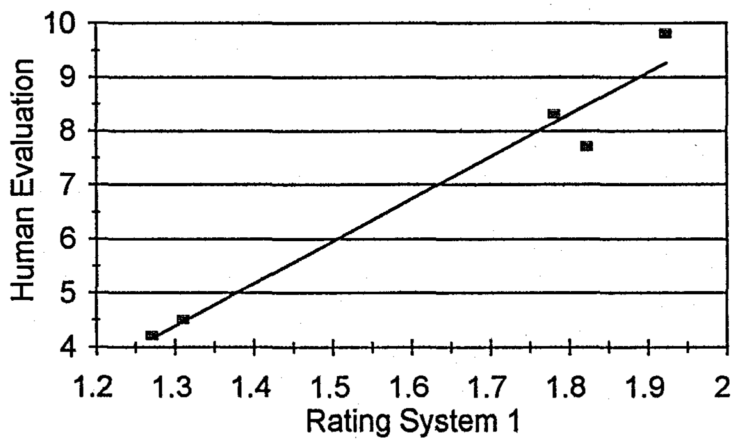


Figure 14. Comparison of rating system 2 to literature data

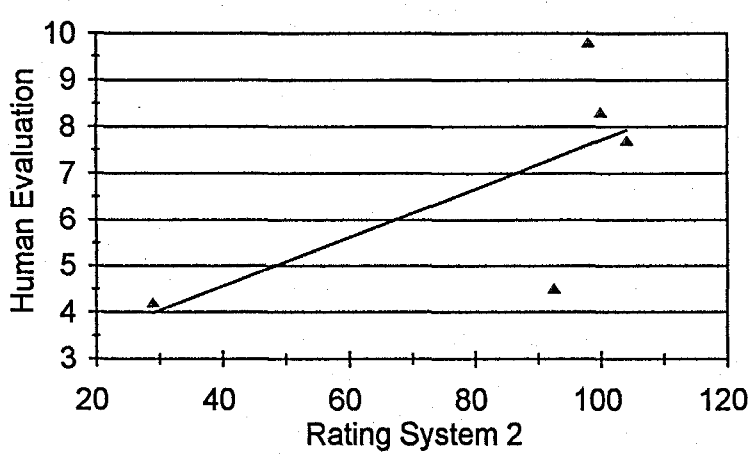


Table 6, in addition to figures 13 and 14, detail the relationship between the rating equations and perceived print quality.

Clearly, the correlation between the first, unweighted equation, and perceived quality is very good. The second rating equation does not provide results as sound as the first equation.

An explanation for this decreased correlation be offered when examining the magnitude of the variables. The values reported for both perimeter and mottle range from roughly 50 to 170 units.

When previously examining the samples generated for this study, a large difference existed between the different parameters. The perimeter was measured from 600-900 microns, and the mottle (standard deviation of the GSV) was measured from 2 to 14 GSV units.

CONCLUSIONS

This project is useful in reinforcing previous ideas concerning ink jet print quality and also providing new avenues for exploration. The following conclusions can be made:

- Analyzing the mean GSV as a tool for evaluating ink jet print quality is limited. Large differences between samples will contribute to the perception of quality, but small differences are overruled by other factors.
- Using the standard deviation of the mean GSV to incorporate mottle effects into image analysis is promising. However, a small amount of mottle will not correlate to print quality.
- Evaluating the minimum and maximum GSV is not a good means of addressing print quality. Large differences may affect print quality, but small differences do not.
- Artifact area may be a useful tool for evaluating print quality. Sample set 1, where the printer was held constant, showed decent correlation. This relationship should be further explored. The

analysis of the standard deviation of the artifact area is not meaningful.

- Perimeter is another good tool for interpreting print quality. As a direct measure of feathering and wicking, perceived print quality has a direct relationship of measured print quality. Once again, the set of samples in which the printer was held constant showed good correlation. The evaluation of the standard deviation of the perimeter is not particularly useful.
- Roundness, being a normalized parameter, is a good indicator of print quality if there is a noticeable variation between different samples. The standard deviation of the roundness shows some correlation, but not strong enough to use as a gauge of print quality.
- The differences in sample sets was evident in the regression analysis. Sample set 1, printed with one printer, showed the best correlation to any of the measured properties. The correlation between the APC scale and properties decreased as more printers were added to the experiment.

- A rating equation was defined which gave excellent correlation between measured print quality and perceived print quality.

SUGGESTIONS FOR FURTHER WORK

Throughout the course of this project, some suggestions for further work in this topic area were determined:

1. Continue to apply rating equation to more printed samples to confirm validity.
2. Determine the best factor with which to weight the effects of perimeter and mottle against each other.
3. Keep the number of printers used constant, as much variation was observed due to the used of different printers.
4. Determine how to measure object perimeter with the image analysis software designed by the National Institute of Health.
5. Design a software macro to use with the NIH image analysis software to measure and rate print quality based on the findings of this project.

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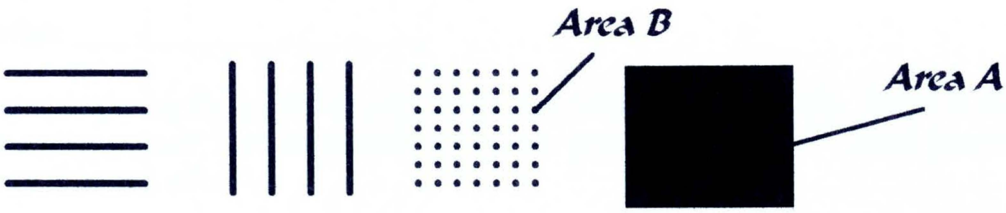
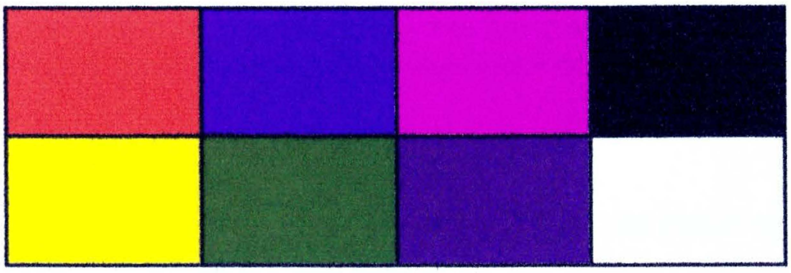
APPENDIX I: Sample Print Pattern





There once was a girl with a curl,
right in the middle of her forehead.
When she was good, she was very good.
but when she was bad she was horrid.

EEEEEE EEEEEE EEEEEE
EEEEEE EEEEEE EEEEEE
EEEEEE EEEEEE EEEEEE

APPENDIX II: Sample All Pair Comparison Form

ALL PAIR COMPARISON
EVALUATION OF INK JET PRINT QUALITY

Judge: ______________________

I am comparing the quality of samples printed with an ink jet printer. There is no right or wrong answer; I am interested only in your personal preference. Thank you for your time and effort!!

W = higher number sample is ***worse*** than lower number sample
B = higher number sample is ***better*** than lower number sample.

	1b	2b	3b	4b	5b	6b	7b	8b
1b								
2b								
3b								
4b								
5b								
6b								
7b								
8b								

← this cell = B if 2b has better quality than 1b

Comments:

Table 1. Results from sample set 1.

Sample ID	Mean GSV	Std. Dv.	Min GSV	Max GSV	Area	Std. Dv.	Perimeter	Std. Dev.	Roundness	Std. Dev.	APC Scale
A	46.41	9.63	18	88	14321	915.5	616	20.9	2.108	0.079	10
B	48.07	7.66	20	104	14983	568.5	646	40.3	2.220	0.233	8.798
C	53.48	7.1	28	103	14876	1289.5	700	49.8	2.621	0.213	7.574
D	49.17	6.17	24	76	15533	535.1	724	73.5	2.709	0.561	2.652
E	67.67	7.01	44	105	15035	394.5	731	88.8	2.859	0.693	6.347
F	65.92	6.23	43	122	15301	783.6	716	13.4	2.665	0.059	3.674
G	79.99	5.53	60	106	17437	638.5	938	122.4	4.069	1.057	0
H	66.51	7.09	44	110	14399	349.3	633	56.1	2.227	0.364	7.129

Note: Area is measured in μm^2
Perimeter is measured in μm.

Table 2. Results from sample set 2.

Sample ID	Mean GSV	Std. Dv.	Min GSV	Max GSV	Area	Std. Dv.	Perimeter	Std. Dv.	Roundness	Std. Dv.	APC Scale
1b	43.99	7.26	22	75	20374	274.5	701	5.9	1.931	0.056	5.068
2b	52.9	4.99	34	126	20518	491.4	735	23.3	2.094	0.094	5.898
3b	53.3	7.1	27	116	15417	464.0	735	52.5	2.796	0.361	0.703
4b	9.44	11.14	0	71	18091	176.9	679	18.6	2.032	0.129	7.789
5b	47.8	8.9	24	103	15276	342.3	660	42.2	2.271	0.270	1.498
6b	0.69	2.12	0	33	17591	49.8	646	20.2	1.889	0.114	10
7b	80.32	13.78	39	157	17480	351.4	726	44.4	2.403	0.254	2.428
8b	71.99	8.99	29	125	15597	173.7	667	38.7	2.275	0.252	0

Table 3. Results from sample set 3.

Sample ID	Mean GSV	Std. Dv.	Min GSV	Max GSV	Area	Std. Dv.	Perimeter	Std. Dv.	Roundness	Std. Dv.	APC Scale
10	72.43	6.95	53	128	14784	956.8	750	42.2	3.031	0.204	6.605
11	57.13	8.89	27	115	14940	95.6	671	31.2	2.402	0.229	2.554
12	65.92	6.23	43	122	15301	783.6	716	13.4	2.665	0.059	0
13	0.69	2.12	0	33	17591	49.8	646	20.2	1.889	0.114	10
14	80.32	13.78	39	157	17480	351.4	726	44.4	2.403	0.254	2.346
15	46.41	9.63	18	88	14321	915.5	616	20.9	2.108	0.079	0.17
16	61.77	7.55	21	106	14502	970.9	693	94.0	2.658	0.636	0.249
17	105.46	4.69	87	129	16180	142.8	739	56.7	2.696	0.405	1.357

Table 4. Results of regression analysis, parameter vs. APC s°cale

Set ID	Mean GSV	Std. Dev.	Min GSV	Max GSV	Area	Std. Dev.	Perimeter	Std. Dev.	Roundness	Std. Dev.
Set 1	0.424	0.791	0.467	0.005	0.769	0.049	0.754	0.397	0.722	0.485
Set 2	0.707	0.219	0.539	0.562	0.361	0.232	0.078	0.570	0.599	0.623
Set 3	0.339	0.233	0.093	0.295	0.261	0.145	0.002	0.069	0.071	0.081

Table 5. Data and analysis of proposed rating system.

	Sample ID	GSV Std. Dev.	Perimeter	APC Scale	Rating 1	r^2	Rating 2	r^2
Set 1	A	9.63	616	10	5.273	0.916	8.641	0.735
	B	7.66	646	8.798	6.605		8.393	
	C	7.1	700	7.574	7.114		7.852	
	D	6.17	724	2.652	8.173		7.714	
	E	7.01	731	6.347	7.201		7.553	
	F	6.23	716	3.674	8.096		7.791	
	G	5.53	938	0	9.095		6.236	
	H	7.09	633	7.129	7.131		8.599	
Set 2	1b	7.26	701	5.068	6.958	0.444	7.825	0.378
	2b	4.99	735	5.898	10.088		7.807	
	3b	7.1	735	0.703	7.110		7.506	
	4b	11.14	679	7.789	4.562		7.808	
	5b	8.9	660	1.498	5.694		8.143	
	6b	2.12	646	10	23.662		10.099	
	7b	13.78	726	2.428	3.697		7.250	
	8b	8.99	667	0	5.637		8.052	
Set 3	10	6.95	750	6.605	7.261	0.554	7.385	0.301
	11	8.89	671	2.554	5.699		8.014	
	12	6.23	716	0	8.096		7.791	
	13	2.12	646	10	23.662		10.099	
	14	13.78	726	2.346	3.697		7.250	
	15	9.63	616	0.170	5.273		8.641	
	16	7.55	693	0.249	6.695		7.882	
	17	4.69	739	1.357	10.729		7.833	