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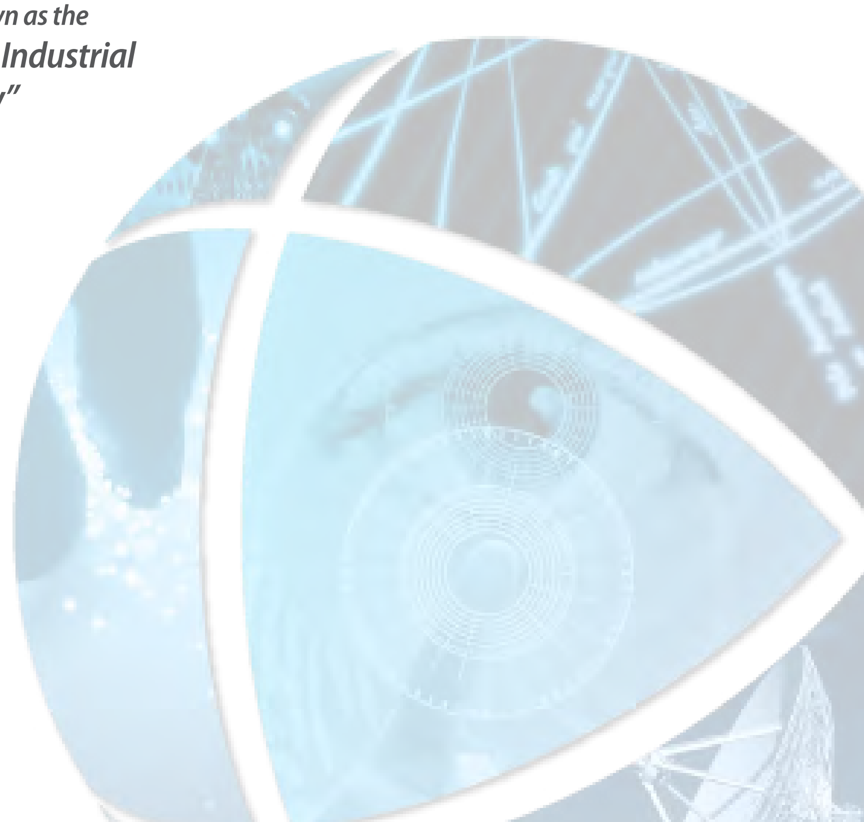

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Dimensional Measurement Variation of Scanned Objects Using Flatbed Scanners

By Dr. Martin P. Jones, Dr. Richard N. Callahan, & Dr. Richard D. Bruce

ABSTRACT

This paper presents a study of the variations in the measured dimensions of objects obtained from their flatbed scanned images. Flatbed scanners have been used by other researchers to measure the dimensions of a wide variety of objects. While there is published research that considers scanner measurement variation, they lack detail on quantifying the effect of several sources of this variation. This paper investigates the effect of the object's position relative to the scanner plate and the effect of scanning resolution on measurement. The object scanned was a high precision glass scale with photo etched graduations. A computer algorithm was developed to automatically measure the distances between the one millimeter spaced graduations on the glass scale based on its scanned images. Results showed that the measured spacing of the graduations varied in patterns depending on the position of the glass scale relative to the scanner and the scanning direction. However, there was not a clear pattern in the measured spacing as a function of scanning resolution even though the probability of detecting the graduations decreased with decreasing resolution. It was concluded that flatbed scanners can measure objects with sufficient accuracy and precision if the sources of measurement variation are quantified and minimized.

INTRODUCTION

It has been over 50 years since the first digital image was produced from a scanner constructed by researchers at the National Institute of Standards and Technology (NIST). That image spawned many other imaging technologies, such as satellite imaging, packaging bar codes, medical imaging, and desktop publishing (NIST, 2007, May 24). Flatbed scanners, also known as desktop scanners, are commonly used for desktop publishing. The first CCD (charge-coupled device) flatbed scanner was developed by Ray Kurzweil in 1976 (Kilbane, 2006). As discussed in the present paper, flatbed scanners have also been used by other researchers for the dimensional measurement of a wide variety of objects beyond desktop publishing. Although previous published research addresses scanner measurement variation, there has been a lack of detail in quantifying the effect of several sources of this variation. The present paper investigates how the position of an object relative to the scanner and its scanning resolution effects measurement variation.

Background

Flatbed scanners have been used for the measurement of a wide variety of objects. Significant medical research has primarily analyzed the grayscale densities of flatbed scanned images to detect tissue anomalies (see for example Rampado, Garelli, & Ropolo, 2010). The present paper focuses on the dimensional measurement of objects. Prior research using flatbed scanners for dimensional measurement are mainly in the fields of construction, food science, and manufacturing.

Construction researchers have used flatbed scanners to measure the amount and size distribution of porosity in concrete and mortars (Miriello & Crisci, 2006; Peterson, Carlson, Sutter, & Van Dam, 2009; Zalocha & Kasperkiewicz, 2005). The selection of gray-level thresholds of the images was a common criterion for proper porosity sizing. These studies generally concluded that flatbed scanners could provide a low-cost and convenient alternative to stereoscopic microscopes for some porosity measurements.

Food science researchers have used flatbed scanners to measure the size distribution of rice and wheat grains (Paliwal, Borhan, & Jayas, 2004; Van Dalen, 2004). Algorithms were developed to automate the inspection of these cereals based on the scanned images. Similarly, Shahin and Symons (2001) developed a neural network system to classify lentils by texture and other characteristics. Their flatbed imaging system achieved a 90% agreement with human inspectors performing similar classification of grains.

Flatbed imaging in manufacturing research seems to have broader applications than in construction and food science research. Korin, Larrainzar, and Ipina (2008) measured the crack lengths in steel specimens based on flatbed scanned images. Ng (2008) developed a flatbed scanner inspection method to detect encapsulation defects in light-emitting diodes. Igathinathane, Melin, Sokhansanj, Bi, Lim, Pordesimo, and Columbus (2009) used flatbed images to estimate dust particle size distributions generated in industrial environments. Kee and Ratnam (2009) developed a flatbed approach to measure the diameters of fine wires used in electronics. Yakovlev and Safonov (2009) used a flatbed method to estimate void size distributions in manufactured foam-rubber. Jones, Callahan, and Bruce (2011) performed a gage capability study on flatbed length measurement of injection molded spirals.

Calibration of the dimensional precision and accuracy of flatbed imaging is the main topic of several prior studies. Seywald (1996) investigated the geometric accuracy of both drum and flatbed scanners. Targets (reference patterns) were designed, scanned, and then automatically measured using computer algorithms to assess image distortion. Poliakow, Poliakov, Fedotova, and Tsvetkov (2007) developed precise glass rulers for the calibration of flatbed scanners used to digitize astronomical plates. Kangasraasio and Hemming (2009) considered several sources of measurement variation associated with flatbed scanners. Two possible sources were identified as stemming from lens distortion and roundness deviation of the drive wheels. Since these represented systematic variations, their measurement distortion effects could be minimized by mathematical subtraction.

Although all of these articles investigated measurement variation due to the position of an object and its scanned resolution, no individual article has investigated the effects of both position and resolution. For example, Seywald (1996) investigated both resolution and position, but the latter did not include measuring objects at heights above the scanner's glass plate. This would be essential in assessing the ability of flatbed scanners to measure the features of objects that cannot be brought into contact with the glass plate. In contrast, Korin, Larrainzar, and Ipina (2008) investigated the position of an object relative to the glass plate (including above the plate) but did not consider changes in the scanning resolution. Since increasing resolution increases scanning time and data storage, assessing this tradeoff could be valuable in the selection of scanning parameters that meet the requirements of specific applications. Furthermore, since the brand and model of scanners (as well as procedure and analysis) varies from study to study, results are less comparable among researchers. The present study therefore, was undertaken to fulfill the need for a single comprehensive study that quantifies the effects of position and resolution on measurement of objects using flatbed scanners.

Purpose

The goal of the present research was to quantify the effects of two key sources of measurement variation in the dimensions of objects using a flatbed scanner. The present research results can assist potential users in deciding whether or not this convenient and inexpensive technique meets their specific measurement needs. Users may decide that they need the accuracy, repeatability and versatility of, for example, a coordinate measuring machine in their particular application. The selected key sources of measurement variation were the position of an object (later described) relative to the scanner plate and the scanning resolution. The position of the object was moved around most of the plate's surface and perpendicularly from the surface to a height well beyond the depth of field of the scanner to assess the ability of the scanner to be used to measure a variety of object sizes and a variety of object attributes not in contact with the plate. Each resolution setting available on the scanner was applied to assess both its effect on sizing of the object and the detection probability of specific object attributes.

METHOD

The Object (Specimen)

A high precision glass scale with photo etched chromium graduations was scanned over 300 times using the flatbed scanner under different experimental parameters. The scale was a PEAK model 1972-100 purchased from Structure Probe, Inc. of West Chester, PA. It had 100 millimeters (mm) of 0.1 mm spaced graduations and was manufacturer calibrated to ±1 μm over a 10 mm distance against NIST traceable standards. Each graduation line had a nominal width of 0.03 mm. The overall dimensions of the scale were 140 mm x 25 mm x 3 mm. A piece of white copy paper was laid on the back of the scale as replacement for the inside white lining of the scanner's lid. The lid was never closed on top of the scale to prevent unnecessary stress on the scale which could lead to damage, distortion, and misalignment relative to the scanning axis.

A scan of the graduations area of the scale is shown in Figure 1. Note the fringes present (shown by arrow and dashed line) on the image which arise from the well-known phenomena which produces Newton's Rings. This indicates small gaps between the glass scale and the glass plate of the scanner in the order of a wavelength of light. Figure 2 shows that the 0.1 mm graduations are distinguishable.

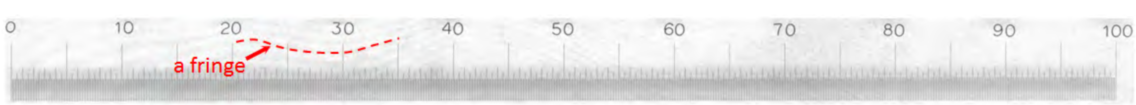

FIGURE 1. **FLATBED SCANNED IMAGE OF A HIGH PRECISION GLASS SCALE WITH PHOTO ETCHED GRADUATIONS.**

Equipment and Software

All data acquisition, processing, and analysis were performed using a laptop computer with a 64 bit Windows 7 operating system, Intel "Core i7" CPU, and 8 GB RAM. A Hewlett-Packard Scanjet 5590 was used to scan the glass scale at each resolution

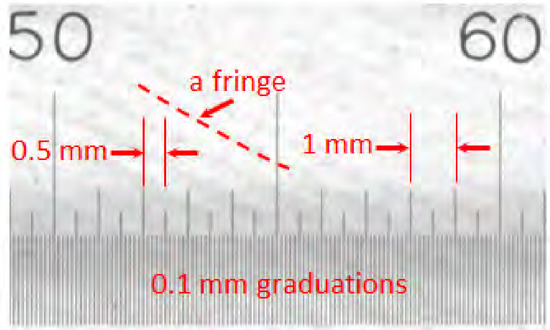

FIGURE 2. **FLATBED SCANNED IMAGE OF ABOVE GLASS SCALE SHOWING DETAIL OF THE 0.1 mm GRADUATIONS.**

available via the scanner's accompanying software. The available resolutions ranged from 4800 pixels per inch (~189 pixels per mm) to 75 pixels per inch (~3 pixels per mm). The hardware optical resolution, however, was 2400 x 2400 pixels per inch. Although the software enabled the scans to be stored in various image file formats, the 8-bit grayscale bitmap was chosen for all scans, since it was the highest bit depth available. For scans like Figure 1, the image file size was typically about 30 megabytes and required actual scanning times as long as 1.5 minutes depending on the selected resolution and direction of scanning. This particular scanner was chosen because it was a common office model used at the researchers' university and represented the typical capabilities of current desktop scanners. The cost of the scanner was about $275.

Scans were imported into "ImageJ" image processing and analysis software to extract data, known as "plot profiles", across the 1 mm spaced graduations on the glass scale. This software was chosen because it is a free download to the public from the National Institute of Health's website (http://imagej.nih.gov/ij/), with a user-friendly interface for writing macros that helped automate the data extraction process. The plot profiles across the 1 mm spaced graduations were then imported into Microsoft "Excel 2010" where they were interpreted as distance measurements via a grayscale criteria and a macro (see Appendix) that automated the measurement process. Excel was chosen because of its widespread public use and compatibility with the ImageJ software. For statistical analysis, IBM SPSS Statistics software was used.

Procedure

Extraction of plot profiles across the 1 mm spaced graduations.

Once a scan file of the glass scale was saved, it was imported into the ImageJ program. A custom macro (see Appendix) was developed by the authors to prompt the user through the several steps needed to extract the plot profiles across the 1 mm spaced graduations. The macro first draws a horizontal line across the entire image as shown in Figure 3. In the next step, the macro zooms to the "drag point" as shown in Figure 4 and prompts the user to drag the line so that it intersects only the 1 mm spaced graduations. Figure 5 shows the line placement by the user resulting in the 1 mm intersections. Note that the user had freedom to place the line anywhere within the zone that is between the 0.5 mm and 1 mm graduations. This was purposefully done to study the effect of line placement on the measurement of the graduations. Another possible effect on measurement was the tilt of the glass scale relative to the plot profile line. In attempt to minimize this effect, care was taken to physically align the glass scale with respect to the scanning axis which is perpendicular to the plot profile line. An estimation of the effect of tilt will be given later in the "Results and Discussion" section.

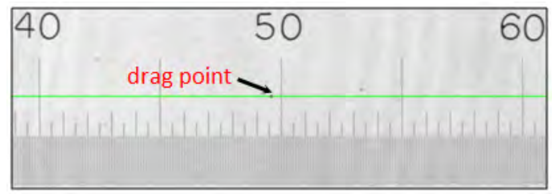

FIGURE 4. **SECOND STEP: ZOOM.**

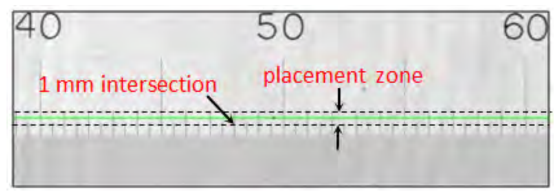

FIGURE 5. **THIRD STEP: USER ADJUSTS LINE.**

Once the user was satisfied with the placement of the plot profile line, the ImageJ command "Plot Profile" was run and the resulting graph was displayed as shown in Figure 6. Each dip in the gray value corresponds to a 1 mm graduation line; therefore 101 dips are present in the figure, marking off the 100 mm of graduations. The figure shows distance in units of pixels and there were

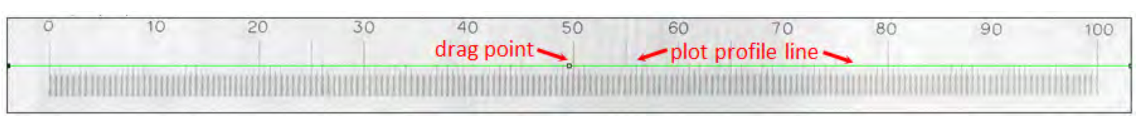

FIGURE 3. **FIRST STEP TO EXTRACT PLOT PROFILE: DRAW LINE.**

about 19,000 pixels across the 100 mm of graduations when the highest resolution of 4800 pixels per inch was used.

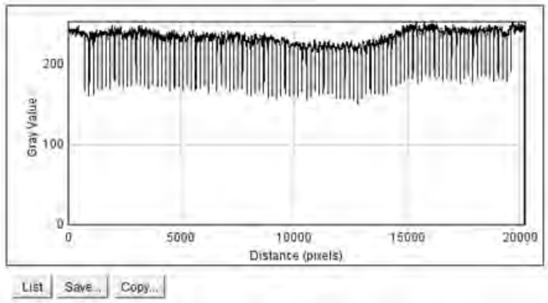

FIGURE 6. **FOURTH STEP: PROFILE PLOT ACROSS THE 1 mm SPACED GRADUATIONS IS GENERATED.**

The locations of the dips were then used to calculate the spacing (distance) of the 1 mm graduation lines. To find those locations automatically, criteria and macros (discussed in the next subsection and the Appendix) were developed in Excel. The data shown in Figure 6 were copied from ImageJ into Excel.

Interpretation and calculation of distance between the 1 mm graduations.

As many as 19,000 data point pairs (gray value and pixel position) were imported from each plot profile into an Excel spreadsheet. The two basic criteria

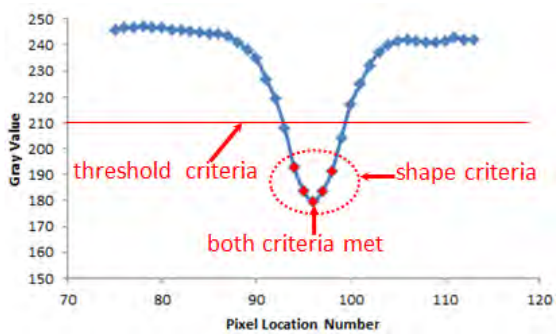

FIGURE 7. **ONE DIP FROM PLOT PROFILE ILLUSTRATING CRITERIA FOR LOCATION OF A GRADUATION LINE.**

used to locate the 1 mm graduation lines were the gray values of the dips (threshold criteria) and the shape criteria of the dips. Under most scanning conditions investigated, the threshold criterion was that any dip with a gray value of 210 or less was considered to be a potential location (pixel) of a graduation line. The shape criteria required the potential line location to be preceded by two pixels of decreasing gray values and to be followed by two pixels of increasing gray values. When both of the above criteria were met for any pixel, a macro identified the location of that pixel as the location of a graduation line. Figure 7 shows detailed data from one of the dips in Figure 6 and illustrates how it met both of the above criteria. The locations of adjacent graduation lines were subtracted from

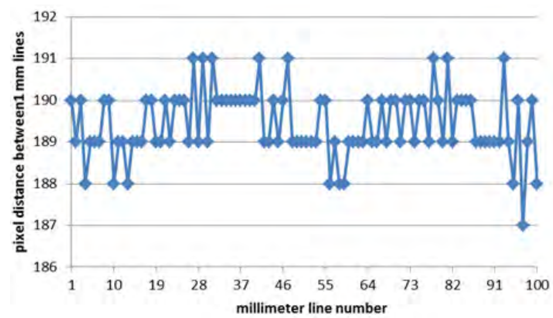

FIGURE 8. **EXAMPLE OF MEASURED DISTANCES BETWEEN 1 mm GRADUATION LINES.**

each other to arrive at the distance between the 1 mm lines in units of pixels.

While it is possible to translate the pixels into metric units, most of the later analysis will be better discussed in terms of pixels. Figure 8 shows an example of the measured distances between 1 mm graduation lines along the 100 mm glass scale using a scanning resolution of 4800 pixels per inch (~189 pixels per mm). The variation of this type of graph as a function of the position of the glass scale relative to the scanner's glass plate and the scanning resolution was the basis for the analysis in the present study.

Orientation of the glass scale in contact with the scanner's glass plate.

The graduation lines are photo etched on one side only of the glass scale. These lines were in direct contact with the glass plate for the following procedure. The glass scale was oriented in two directions relative to the scanning direction: parallel and perpendicular. For the parallel orientation (see Figure 9), the scanning direction was parallel to the graduation lines. For illustration purposes, this figure shows the glass scale in only four of the forty-eight positions it was placed in the parallel orientation. The glass scale was indexed 9 mm in the scanning direction using gage blocks to move a total distance

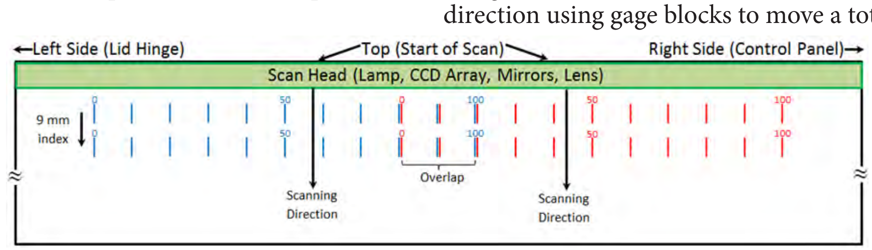

FIGURE 9. **ORIENTATION WHEN SCANNING DIRECTION IS PARALLEL TO GRADUATION LINES.**

FIGURE 10. **ORIENTATION WHEN SCANNING DIRECTION IS PERPENDICULAR TO GRADUATION LINES.**

of 216 mm. The figure depicts blue and red graduations. Blue represents when the glass scale was flush with the left side of the scanning bed and red represents when it was flush right. This resulted in an overlap region where the same area of the glass plate was scanned twice, thus enabling more checks on measurement repeatability. Essentially, the parallel orientation measurements encompassed an area of 216 mm by 216 mm. For the perpendicular orientation (see Figure 10), the scanning direction was perpendicular to the graduation lines. Again, for illustration purposes, this figure shows the glass scale in only four of the forty-eight positions in which it was placed in the perpendicular orientation. The glass scale was indexed 9 mm perpendicular to the scanning direction using gage blocks to move a total distance of 216 mm. The perpendicular orientation measurements encompassed an area of 216 mm by 203 mm.

Glass scale above the scanner's glass plate.

The glass scale was elevated to a height of 12 mm above the glass plate in 1.0 mm increments. Each height increment was reached by propping up the glass scale with microscope slides of nominal 1.0 mm thickness. The microscope slides supported the glass scale only at its ends so that the slides did not obstruct the graduation lines. At each height, the glass scale was scanned in both the parallel and perpendicular directions as defined in Figure 9 and 10, but only at one location for each direction.

Resolution of the scanner.

The scan resolutions used were 75, 100, 150, 300, 600, 1200, 2400, and 4800 pixels per inch. The respective metric equivalents of these are approximately 2.95, 3.94, 5.91, 11.81, 23.62, 47.24, 94.49, and 188.98 pixels per mm. At each resolution, the glass scale was scanned in both the parallel and perpendicular directions as defined in Figure 9 and 10, but only at one location for each direction.

RESULTS AND DISCUSSION

Repeatability

As illustrated in Figure 5, the user had freedom to choose the position of the plot profile which could affect measurement variability since the graduation lines widths are not imaged as being uniform along their lengths. This can be seen in Figure 11 for two adjacent 0.1 mm spaced graduation lines (note individual pixels are distinguishable). For the remainder of the present paper, unless otherwise

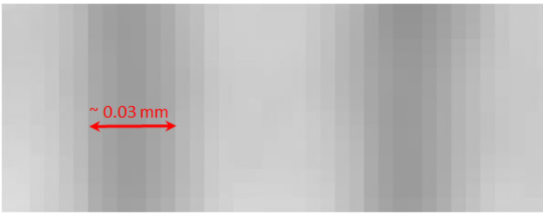

FIGURE 11. **TWO ADJACENT 0.1 MM SPACED GRADUATION LINES IMAGED AT 4800 PIXELS PER INCH.**

specified, the default scanned resolution was 4800 pixels per inch (~189 pixels per mm). In addition to the limitations of the optics and scanning mechanism, this variation may also have been due to the superimposed fringes (see Figure 5) adding darker pixels to the graduation lines. Therefore, five different plot profile lines were chosen to assess this possible effect on measurement of the 1 mm graduation lines. Figure 12 shows the differences between the high and low measured distances (range) using the five profile lines for each graduation line. The mean of the above 500 measurements was 189.98 pixels = ~190 pixels. A one-sample Kolmogorov-Smirnov test (via SPSS software) rejected that the measurements were normally distributed and so the standard error of the mean was not calculated.

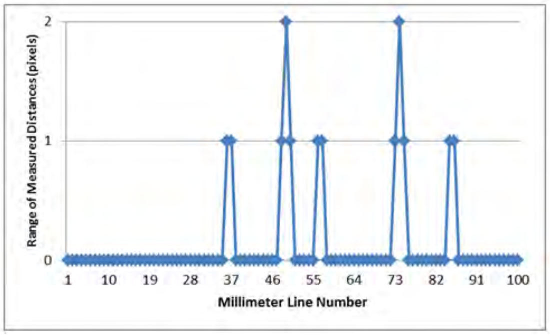

FIGURE 12. **DISTANCE RANGE OF FIVE PROFILE LINES FOR EACH GRADUATION LINE.**

Regardless, note that only 12 of the 100 lines showed any difference among its 5 measurements, of which 10 lines showed only a 1 pixel difference and 2 lines showed a 2 pixel difference. This indicates that the choice of profile line had a small effect on the distance measurements: 14 pixels out of a mean of 190 pixels across 100 lines represents about a 0.074% variation (14/19,000). Another possible effect on measurement was the tilt of the glass scale relative to the plot profile line. Sometimes the glass scale had to be realigned relative to the scan-

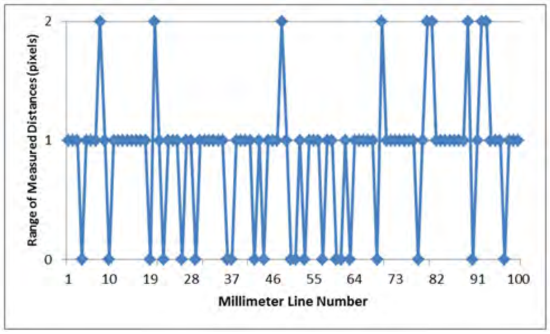

FIGURE 13. **RANGE OF THE FIVE PERPENDICULAR SCANS FOR EACH GRADUATION LINE.**

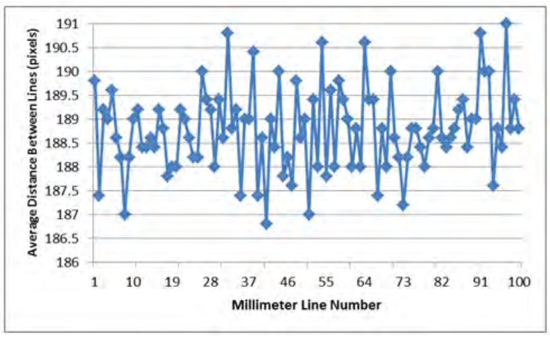

FIGURE 14. **AVERAGE DISTANCE OF FIVE PERPENDICULAR SCANS FOR EACH GRADUATION LINE.**

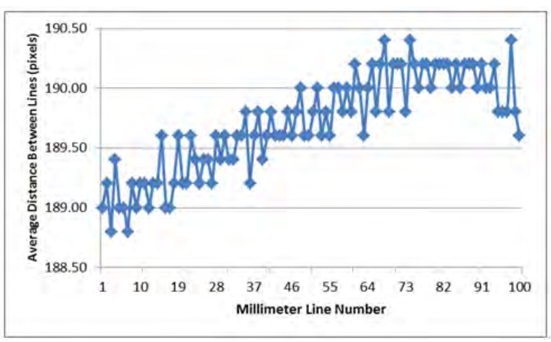

FIGURE 15. **AVERAGE DISTANCE OF FIVE PARALLEL SCANS FOR EACH MILLIMETER GRADUATION LINE.**

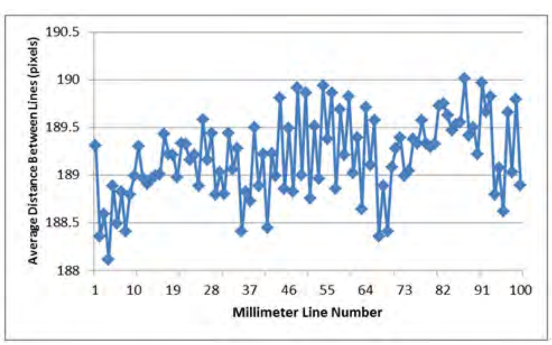

FIGURE 16. **AVERAGE LINES DISTANCES FROM COMBINED PARALLEL AND PERPENDICULAR DATA.**

ning axis because the entire profile line could not be contained within the placement zone (see Figure 5) due to the tilt of the glass scale. This required alignment forced the tilt of the glass scale to be within 0.14 degrees and thereby reduced its effect on measurements to under 0.031%.

A larger effect on measurement was due to mechanical and optical variations. To provide the baseline assessment of these effects on the measurement of the 1 mm graduation lines, the glass scale was scanned five times in succession without moving its position. This was done for both parallel and perpendicular orientations as defined in Figures 9 and 10. Figure 13 shows the differences between the high and low measured distances (range) using the five perpendicular scans for each of the 100 graduation lines. Note that there are more occurrences of nonzero ranges than in Figure 12. This was expected due to variations, for example, in the scan head movement and lamp output from one scan to another. Figure 14 shows the average of those five perpendicular scans for each of the millimeter lines. A one-sample Kolmogorov-Smirnov test indicated the data in the figure were normally distributed with a mean of 188.78 pixels (~189) and standard deviation of 0.88 pixels. The standard error of the mean was then calculated as 0.088 pixels (0.88/1001/2) or about 0.05%. Therefore, a 3σ estimate of the distance between millimeter lines would be 188.78 pixels ± 0.264 pixels. Ideally 1 mm should equal 188.976378 pixels at 4800 pixels per inch resolution, which is well within the 3σ estimate.

Similarly, Figure 15 shows the results for the parallel direction. Note that there is a trend for higher line numbers to have higher measured distances. Later it will be discussed why such a trend might occur. Note this trend is only about one pixel out of 190 pixels across the entire 100 mm of the glass scale. However, despite the apparent trend, a one-sample Kolmogorov-Smirnov test indicated the data in the figure were normally distributed with a mean of 189.70 pixels (~190) and standard deviation of 0.41 pixels. The standard error of the mean was then calculated as 0.041 pixels or about 0.02%. Therefore, a 3σ estimate of the distance between millimeter lines would be 189.70 pixels ± 0.123 pixels. However, the expected distance of 188.976378 pixels is not within this 3σ estimate. These differences between the parallel and perpendicular directions led to the question of whether or not there was a systematic scanner error related to the position and orientation of the glass scale.

Variation Due to Position and Orientation of Glass Scale

As described, 48 scans of the glass scale were acquired in both the parallel and perpendicular directions; totaling 96 scans. Figure 16 shows the average (96 measurements) of each of the one hundred 1 mm graduation lines regardless of the

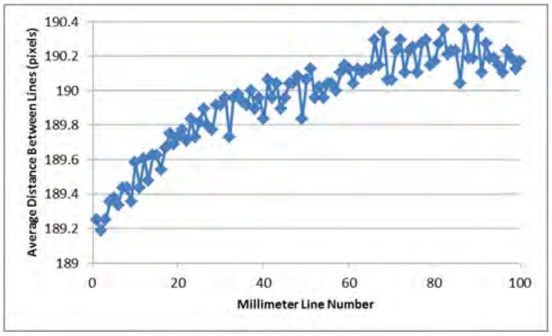

FIGURE 17. **AVERAGE LINE DISTANCES FROM ONLY PARALLEL DATA.**

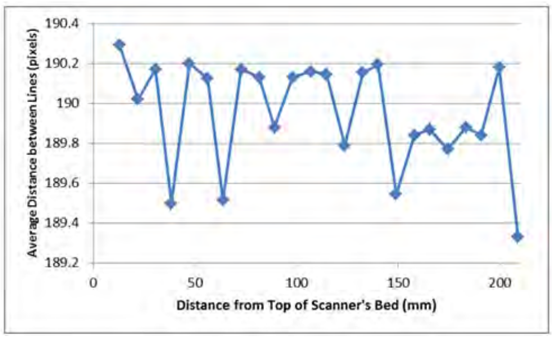

FIGURE 18. **PARALLEL AVERAGE LINES DISTANCES AS A FUNCTION OF DISTANCE FROM TOP OF BED.**

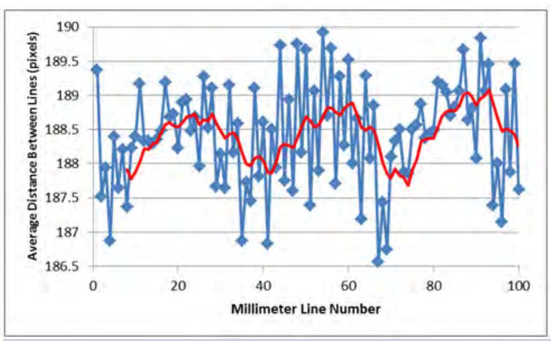

FIGURE 19. **AVERAGE LINE DISTANCES FROM ONLY PERPENDICULAR DATA.**

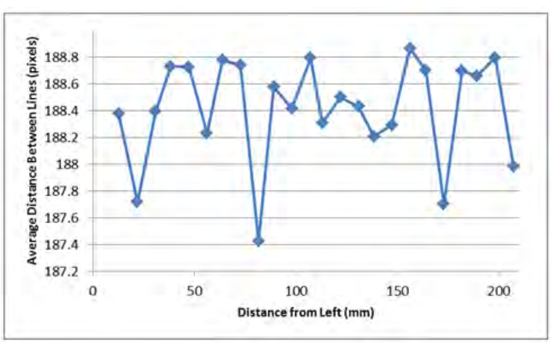

FIGURE 20. **PERPENDICULAR AVERAGE LINE DISTANCES AS A FUNCTION OF DISTANCE FROM LEFT SIDE OF BED.**

position and orientation of the scan. A one-sample Kolmogorov-Smirnov test indicated the data in the figure were normally distributed with a mean of 189.18 pixels (~190) and standard deviation of 0.42 pixels. The standard error of the mean was then calculated as 0.042 pixels or about 0.02%. Therefore, a 3σ estimate of the distance between millimeter lines would be 189.18 pixels ± 0.124 pixels. However, the expected distance of 188.976378 pixels was not within this 3σ estimate. There seemed to be an increasing trend and a periodicity to the data in the figure, which became more apparent when parallel and perpendicular data were analyzed separatelyWhen only parallel data are plotted, the increasing trend is clearer as shown in Figure 17. Note the trend is again only about one pixel out of 190 pixels across the entire 100 mm of the glass scale (~0.5% per 100 mm). One possible explanation is that the glass scale line spacing was actually larger towards the higher line numbers. However, when the glass scale was rotated 180 degrees, the same trend appeared except the measured lines were larger for lower line numbers, thus preserving the left-to-right increasing trend. Another possible explanation for this trend is that the scanner optics images the lines, say towards the left, are at a more oblique angle than those towards the right. An analogy would be if a person was directly in front of a door they would perceive it to be wider than if they stood at an oblique angle to it. The data in Figure 17 were rejected as being from a normal distribution by the Kolmogorov-Smirnov test.

It was thought there might be a similar trend as the scanning head moved from top to bottom of the scanner's bed. Figure 18 shows the parallel averages of the measured millimeter line distances from top to bottom. Note the variation is only about one pixel over the tested 216 mm length of the bed. There seems to be no trend as pronounced as that shown in Figure 17. The Kolmogorov-Smirnov test indicated the data in Figure 18 were from a normal distribution.

If only perpendicular data are plotted, some periodicity can be seen as shown in Figure 19. An 8-point moving average (red) of the data (blue) is superimposed to better see the periodicity, which seems to repeat about every 20 mm. Note, the variation is about two pixels out of 190 pixels across over each 20 mm period (~1% per 20 mm). While this is small, it is nearly twice as much variation than resulting from the parallel data. One possible source for this periodicity is from the scanner's drive wheels being slightly off-center of their rotation (Kangasraasio and Hemming, 2009).

It was thought there might be similar periodicity or another trend as the scanning head moved from top to bottom of the scanner's bed. Figure 20 shows the perpendicular averages of the measured millimeter line distances from the left to the right side of the scanner's bed. Note the variation is only about

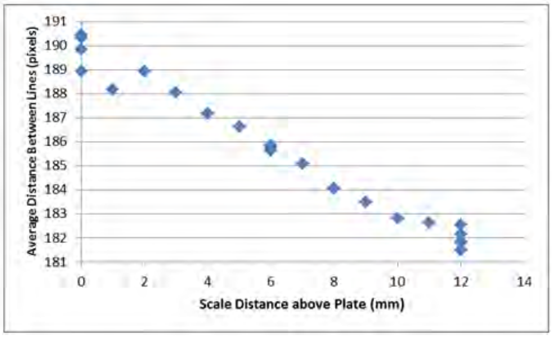

FIGURE 21. **PARALLEL AVERAGE LINE DISTANCES AS A FUNCTION OF DISTANCE ABOVE GLASS PLATE.**

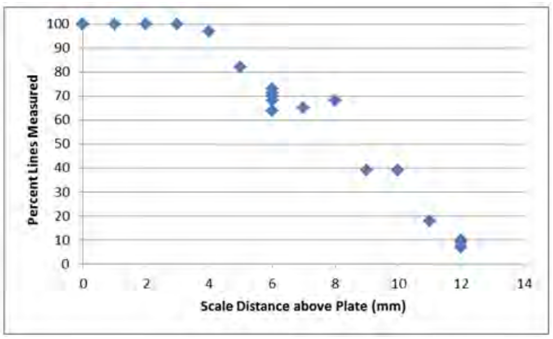

FIGURE 22. **PARALLEL PERCENT OF LINES MEASURED AS A FUNCTION OF DISTANCE ABOVE GLASS PLATE.**

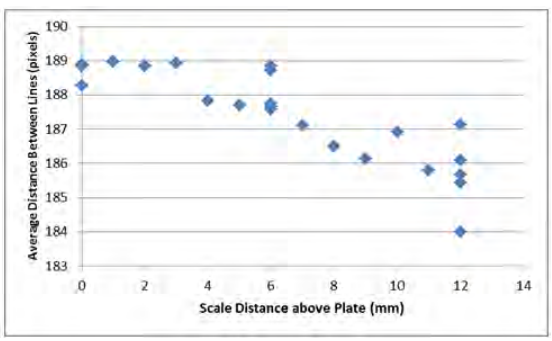

FIGURE 23. **PERPENDICULAR AVERAGE LINE DISTANCES AS A FUNCTION OF DISTANCE ABOVE GLASS PLATE.**

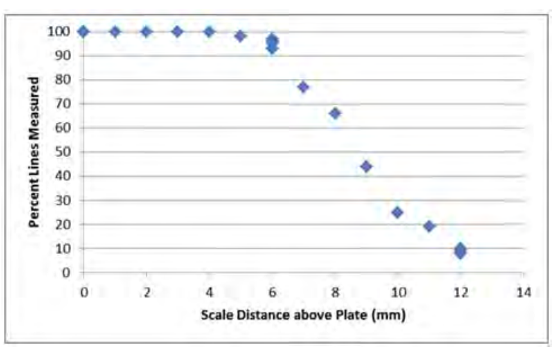

FIGURE 24. **PERPENDICULAR PERCENT OF LINES MEASURED AS A FUNCTION OF DISTANCE ABOVE GLASS PLATE.**

one pixel over the tested 216 mm width of the bed. Again, there seems to be no trend or periodicity as pronounced as those shown in Figures 17 and 19. The Kolmogorov-Smirnov test indicated the data in Figure 20 were from a normal distribution.

Variation Due to Height of Glass Scale

Figure 21 shows the parallel average measured distance between the 1 mm lines as a function of the glass scale's distance above the glass plate of the scanner. Note at 0, 6, and 12 mm heights, five repeated measurements were made to assess the repeatability at a given height. There is an obvious trend for the lines to be measured as smaller when farther away from the plate (about 4% over a height of 12 mm). This was expected since objects usually appear smaller as they move away from an imaging system and similar to the results of Korin, Larrainzar, and Ipina (2008). However, at about 4 mm above the plate, the criteria used failed to measure all one hundred 1 mm lines, as shown in Figure 22. This was expected since the images were becoming blurred. More complex criteria could have extended the height range of the measurement but for consistent comparison within the present paper, the criteria were not changed.

Similar results are shown in Figures 23 and 24 for the perpendicular data. However, there was more variability in the line distance measurements than exhibited by the parallel data. This was expected since the overall perpendicular data (Figure 19) had more variation than the overall parallel data (Figure 17).

Variation Due to Scanner Resolution

Figure 25 shows the perpendicular average measured distances between the 1 mm lines as a function of selected scanner resolutions. The glass scale was scanned five times at each selected resolution. Due to pixel sizes increasing with resolution, the pixel distances between lines were converted to millimeters for comparison purposes. Data are shown only for resolutions down to 300 pixels per inch. Very few lines were measureable at the 75 and 150 pixels per inch resolutions as indicated in Figure 26. To reduce scanning time under these conditions, one might choose 1200 pixels per inch since all lines were measured and since the mean and range were closer to the expected distance (1.000 mm) than at higher resolutions.

Similar results are shown in Figures 27 and 28 for the parallel data. Again, one might choose 1200 pixels per inch for the same reasons as stated for the perpendicular data. This suggests that higher scanner resolutions do not necessarily lead to more accurate and precise measurements. Furthermore, the optimum resolution for measurement may be lower than the highest resolution available even if time is not a constraint. Essentially, the resolution may have to be "tuned" to the geometry of the feature to be measured.

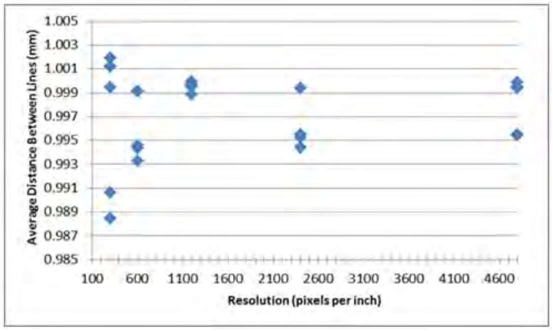

FIGURE 25. **PERPENDICULAR DISTANCES OF LINES MEASURED AS A FUNCTION OF SCANNER RESOLUTION.**

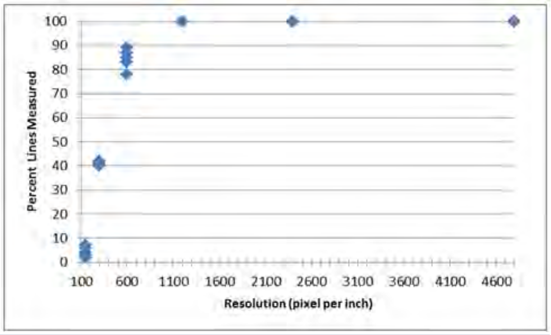

FIGURE 26. **PERPENDICULAR PERCENT OF LINES MEASURED AS A FUNCTION OF SCANNER RESOLUTION.**

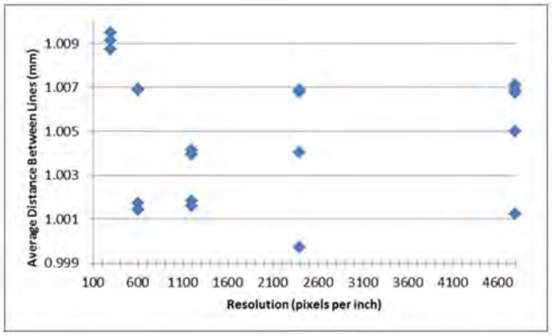

FIGURE 27. **PARALLEL DISTANCES OF LINES MEASURED AS A FUNCTION OF SCANNER RESOLUTION.**

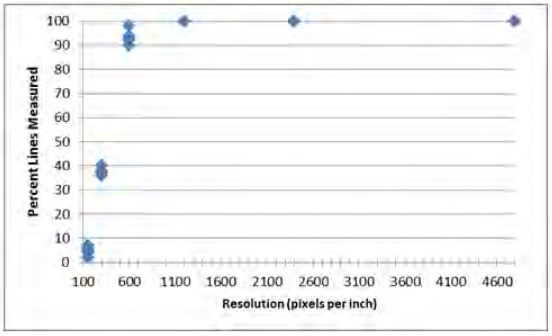

FIGURE 28. **PARALLEL PERCENT OF LINES MEASURED AS A FUNCTION OF SCANNER RESOLUTION.**

CONCLUSIONS

Flatbed scanners can be used to accurately measure the dimensions of a wide variety of objects. This research demonstrates the effect of an object's position relative to the scanner plate and the effect of scanning resolution on dimensional measurement. Some patterns in measurement variation emerged from studying the above effects.

At 4800 pixels per inch resolution, the average of all measured values of 1 mm lines was 189.18 pixels with a 3σ estimated standard error of the mean of $\pm$ 0.124 pixels. Since the expected value at 4800 pixels per inch is 188.976378 pixels, overall the measurement method of a 1 mm distance was accurate to within 0.1% of the known value. For distances parallel to the scan head, there was about a half percent gradual increase in the measured value of 1 mm from end-to-end of a 100 mm glass scale. The source of this variation is attributed to asymmetry of the scanner's optics. For distances perpendicular to the scan head, there was about a one percent periodic variation in the measured value of 1 mm that repeated about every 20 millimeters of the glass scale. One possible source of this variation is attributed to roundness deviations of the scanner's drive wheels as discussed in the "Introduction" and "Results and Discussion" sections of the present paper. The size of the measured lines generally decreased (about 4% over a height of 12 mm) as they were elevated above the scanner's plate and fewer lines were able to be measured because the images became increasingly blurred. The effect of scanning resolution was most surprising to the researchers. It was thought more accurate and precise measurements would follow higher scanning resolution. However, beyond 1200 pixels per inch, measurement of the 1 mm lines did not improve.

The present research was limited to only one scanner. Other different makes/models of desktop scanners should be compared to assess their particular effects on measurement variation. Although it is beyond the scope of the present paper, a gage capability study is being designed to assess the measurement variation due to the manufacturing process for various scanners. Also, a smaller index (used to move the scale around the scanner bed), might have revealed more localized patterns in the measurement variations. Note that only one location on the glass plate was used for both the resolution and height studies. Results might have been different for other locations of the glass plate.

Based on the results of this study, it is recommended that users consider scan direction and resolution to optimize the accuracy and precision of flatbed scanners for dimensional measurements. Also, users should be aware of the opportunity to measure features on objects that are away from the scanner's plate, provided that the decrease in image size is accommodated.

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APPENDIX

Bitmaps of the scanned images were opened and displayed to the operator using “ImageJ” software. The following macro (written in “ImageJ” software) was then used to guide the operator in acquiring the line profile across the scanned graduation lines on the glass rule:

```
makeLine(0+50, getHeight()/2, getWidth()-100, getHeight()/2, 20);
title = “WaitForUserDemo”;
msg = “How does it look?”;
  waitForUser(title, msg);
//setTool(“zoom”);
run(“In”);
run(“In”);
run(“In”);
run(“In”);
//setTool(“point”);
 title = “WaitForUserDemo”;
msg = “Adjust the profile line”;
  waitForUser(title, msg);
run(“Plot Profile”);
```

The output of the “Plot Profile” is a list of positions and corresponding gray values. The list was then copied by the operator into an “Excel” spreadsheet where the local minima gray values positions were identified from about 19,000 data pairs using the following format for a conditional statement:

=IF(AND(A265<=200, A263>A264, A264>A265, A265<A266, A266<A267), B265,0)

Where “200” is the threshold gray value and the “A” cells (A265, A266, etc.) are the gray values from the “Plot Profile” above described. When the above conditional statement is true, the position value in column B is placed in column C for the same corresponding row. When false, a zero is placed in column C. The Figure 1A shows an example of data that meets the above conditional statement (true):

	A	B	C	D	E	F
"	"	"	"			
"	"	"	"			
"	data pairs		minima			
"	gray value	position	positions			
262	178.4781	257	0			
263	167.7161	258	0			
264	162.6483	259	0			
265	162.4232	260	260	<== meets conditional statement		
266	165.9252	261	0			
267	177.0545	262	0			
268	185.1259	263	0			
"	"	"	"			

FIGURE 1A. **EXAMPLE OF DATA MEETING CRITERIA TO BE A GRADUATION LINE.**

Since there are 101 one millimeter graduation lines on the 100 millimeter glass rule, there will be 101 corresponding nonzero minima positions in column C among about 19,000 zeros. An “Excel” macro was written to find all the nonzero minima positions and copy them sequentially to a column on the worksheet. The difference between successive minima positions gives the distance between adjacent one millimeter graduation lines in units of pixels which, at a 4800 dpi scanning resolution, is about 188 pixels. The following is the “Excel” macro that was used to find, copy, and paste the nonzero minima positions:

```
Sub DelEmptyRow()
Range(“C3:C20036”).Select
   Selection.Copy
   Range(“D3”).Select
   Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Application.CutCopyMode = False
Rng = Selection.Rows.count
j = 0
ActiveCell.Offset(0, 0).Select
Application.ScreenUpdating = False
For i = 1 To Rng
If ActiveCell.Value > 0 Then
j = j + 1
Selection.Copy Destination:=Cells(j + 2, 4)
ActiveCell.Offset(1, 0).Select
Else
ActiveCell.Offset(1, 0).Select
End If
Next i
Application.ScreenUpdating = True
End Sub
```