Transforming digital images by rotation and evaluating the outcome based on spatial frequency response analysis[1]

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In the practice of mass digitisation, positioning the objects perfectly on a capturing device all the time is often impossible.[2] Such errors can be fixed by repeating the scanning process after placing the object in a more precise manner or by altering the digital file. Altering the image digitally during the data processing stage by rotating the resulting image has a negative impact on its quality. The aim of the study was to analyse the extent of quality loss occurring as a result of applying a rotation to the resulting image file and to determine the correct methodology to follow when adjusting digital images at the processing stage. A comparison of the rotation and sharpening algorithms offered by different software products is beyond the scope of this paper and requires further research. In general, it can be assumed that, regardless of the software used, rotating the digital image facilitates its further use and should be carried out under controlled conditions with the appropriate measurement references.[3] If the processed images meet the established quality criteria after being altered, the raw variants can be removed from the archive to keep only the corrected versions, which are optimised for further use. Knowing the level of quality loss resulting from rotation, a decision can be made whether it is acceptable and thus determine whether the long-term storage of raw images is needed, which has a direct impact on the overall cost of storing the results of ongoing digitisation projects.

The third edition of the FADGI standard released in May 2023 permits rotating the image[4] as part of the post-scan file processing, which is quite a revolutionary change compared to the outright prohibition in previous versions, along with the requirement to place the scanned object on the device with a tolerance of ±1°.[5] This change constitutes a step in the

1 Spatial frequency response (SFR) is a parameter used to describe the quality of reproduction, as are parameters such as optical transfer function (OTF) and modulation transfer function (MTF) (editor's note).

2 This is particularly true for the mass digitisation of graphic files using flatbed scanners. If the lines of text on a scanned page are askew, even though they should be parallel to one of the edges of the digital reproduction, such as a reproduction is deemed unfit for use and needs to be corrected.

3 The term 'references' pertains to dedicated test targets (editor's note).

4 *Technical Guidelines for Digitizing Cultural Heritage Materials: Third Edition*, Federal Agencies Digital Guidelines Initiative, 2023, www.digitizationguidelines.gov/guidelines/FADGI Technical Guidelines for Digitizing Cultural Heritage Materials_3rd Edition_05092023.pdf (accessed 30 Nov. 2023), p. 18.

5 *Technical Guidelines for Digitizing Cultural Heritage Materials: Creation of Raster Image Files*, Federal Agencies Digital Guidelines Initiative, 2016, www.digitizationguidelines.gov/guidelines/FADGI Federal Agencies Digital Guidelines Initiative-2016 Final_rev1.pdf (accessed 30 Nov. 2023), p. 29.

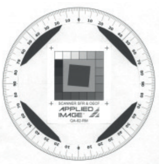
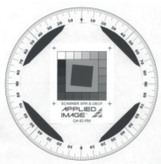
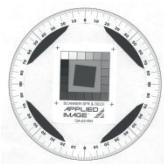
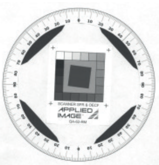
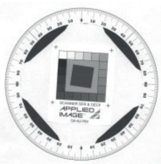
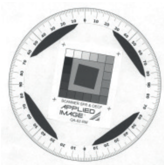
right direction; however, adding the quality control step for processed images increases the overall workload.

Preparing the test materials

The analysis requires a specialised test target and an imaging device, such as a flatbed scanner. The described analysis employed the QA-62 test target, while the test images were acquired using a Plustek OpticBook 4800 scanner. This device is not very accurate, but in the case of images with a resolution of 300 ppi[6] it enables achieving a sampling efficiency of 100% and a maximum amplitude of the frequency response of 1, which is sufficient to measure the effects of rotation and sharpening steps.

The test targets used in the analysis were scanned in several orientations with different angles of rotation ranging from 0° to 20°. The analysis covers images in which the delt.ae measuring tool[7] was able to recognise the target, which limited the maximum rotation angle to 3.5° and resulted in a set of five images with the following rotation angles: 0°, 0.2°, 1.32°, 2.38° and 3.5°. The sample was supplemented with one additional image, which was initially discarded, characterised by a rotation angle of 9.65° to be used for measuring the impact of the rotation. This resulted in a set of six test images.

Table 1. Test images

0°	0.2°	1.32°
		
2.38°	**3.5°**	**9.65°**
		

The test target was rotated on the glass bed of the scanner manually, by referencing a protractor reading, which made the rotation angle interval different between the samples; however, this slight deviation does not

6 The ppi (pixels per inch) value specifies the number of pixels (the smallest elements that make up a digital image) reflecting each inch (25.4 mm) of the length of the imaged object.

7 The delt.ae manual specifies a target rotation tolerance of ±2°, deltae.picturae.com/wiki?title=DeltaE:Input (accessed 30 Nov. 2023). The manual suggests that exceeding these values may result in erroneous test results. The results obtained in the course of the analysis show that the error for images with a rotation angle exceeding the prescribed limit does not seem to differ significantly from the results of images conforming to the limit. Presumably the software tolerance is greater than the manual suggests.

negatively affect the assessment of the methodology. Due to the fact that in the process of digitisation, the objects may be placed on the device with a rotation angle exceeding 2°, the author opted to use the range of 0-9.65°, which should be representative of most cases. The processing was carried out using the XnView 2.51 software, in particular the available tools enabling image rotation correction, image resizing tool using bicubic interpolation (Mitchell filter) for upsampling and downsampling, as well as the edge enhancement filter used to sharpen the image.

The QA-62 target

Image parameters were measured using the QA-62 target, which is used to analyse the spatial frequency response of digital images. The measurement methodology for these targets was described in the ISO 12233:2023: *Photography – Electronic still picture imaging – Resolution and spatial frequency responses* standard.[8] The key parameters in the context of the analysis include resolution in pixels per inch (ppi), sampling efficiency expressed as a percentage, SFR50, SFR10 and the maximum amplitude of the frequency response, expressed in real numbers.[9] All sample images used in the analysis were prepared in greyscale, in order to remove any colour information due to the fact that the colour aspects of the image are outside the scope of the study and are not relevant to the conclusions presented in this paper.[10]

Test target measurement before rotating

The test images were loaded into the delt.ae tool. The measurement results are presented in Table 2.

Table 2. Measurement results for raw images

Rotation angle	PPI	SEFF	SFR50	SFR10	MaxSFR
0°	299.4	100%	0.3	0.63	1
0.2°	299.4	100%	0.3	0.61	1
1.32°	299.3	100%	0.3	0.61	1
2.38°	299.4	100%	0.3	0.62	1
3.5°	299.4	100%	0.3	0.6	1
9.65°	–	–	–	–	–

8 ISO 12233:2023: *Photography – Electronic still picture imaging – Resolution and spatial frequency responses*; www.iso.org/obp/ui#iso:std:iso:12233:ed-4:v1:en (accessed 30 Nov. 2023).

9 For more on these parameters, see the FADGI standard, *Technical Guidelines for Digitizing Cultural Heritage Materials: Third Edition. Federal Agencies Digital Guidelines Initiative*, 2023; www.digitizationguidelines.gov/guidelines/FADGI Technical Guidelines for Digitizing Cultural Heritage Materials_3rd Edition_05092023.pdf (accessed 30 Nov. 2023), p. 15.

10 In spite of the fact that the QA-62 target enables such testing.

In the image rotated by 9.65°, the test target was not recognised by the software. The other images had no significant differences as far as the measurement results are concerned. In all the images that were successfully analysed, the obtained values were very good. They can be used as a benchmark for further processing analysis.

Test target measurement after rotating

The first processing comprised transforming the image by rotating it by the specified angle corresponding to the rotation deviation from the vertical axis. The resulting processed images contain a representation of the test target in the correct position. The processed images were loaded into the delt.ae tool, the measurement results are shown in Table 3.

Table 3. Measurement results for rotated images without double upsampling

Rotation angle	PPI	SEFF	SFR50	SFR10	MaxSFR
0°	299.4	100%	0.3	0.63	1
0.2°	299.4	99%	0.24	0.51	1
1.32°	299.4	88%	0.22	0.44	1
2.38°	299.4	87%	0.22	0.44	1
3.5°	299.4	88%	0.22	0.44	1
9.65°	299.4	89%	0.22	0.44	1

The reduction in sampling efficiency and the decrease in the values of the SFR50 and SFR10 parameters after exceeding a rotation angle between 0.2° and 1.32° are clearly visible as a result of performing just the rotation without upsampling the image first. The values of the maximum amplitude of the frequency response remain consistent and do not exceed 1 in any case.

Test target measurement after enhanced rotation

The enhanced rotation method comprises of upsampling the image by factor of two,[11] then performing a rotation and downsampling by halving

11 For the purposes of this analysis, the author used the upsampling factor of 2; however, the method may be used with other upsampling factors as well. The factor of 2 is the easiest to use, since it facilitates calculating the downsampling factor used to restore the image to its original size, 0.5 in this case. When rotating large images, magnification factors lower than 2 (for example 1.5) can be used due to the less requirements for computing power and memory. For the same reason, factors greater than 2 may prove difficult to use while having little impact on the results. Factors lower than 1.5 may cause additional distortions during other processing steps. When using this method, the author recommends using magnification factors between 1.5 and 2, with 2 being the optimal value.

the dimensions of the image to bring it back to the original resolution. The images processed in that way were loaded into the delt.ae tool, the measurement results are shown in Table 4.

Table 4. Measurement results of rotated images initially magnified by 200%

Rotation angle	PPI	SEFF	SFR50	SFR10	MaxSFR
0°	299.4	85%	0.22	0.43	1
0.2°	299.4	78%	0.21	0.39	1
1.32°	299.4	79%	0.21	0.39	1
2.38°	299.4	79%	0.21	0.4	1
3.5°	299.4	79%	0.21	0.39	1
9.65°	299.4	79%	0.21	0.39	1

A decrease in the value of sampling efficiency and the SFR10 parameter[12] can be observed in comparison to the unrotated image, which has undergone upsampling and downsampling. At the same time, the author found that upsampling the image before rotation and then downsampling it back to the original size eliminates the differences between all the rotated images. No major differences were found as far as other parameters are concerned.

Impact of rotation on resolution measurement

None of the transformations carried out as part of the analysis significantly affected the resolution measurement result. It can thus be surmised that performing the rotation and interpolation does not affect the resolution measurement. This is true only while upsampling and downsampling the image to the original size. Interpolating the image and leaving it in the upsampled state will result in increased resolution resulting from the upsampling factor. Since this has a negative impact on the other parameters, determining the actual resolution of an image is a more complex task than basing the measurement result on this parameter alone. This issue remains beyond the scope of the analysis presented in this paper and requires a separate study.

12 According to the FADGI standard, these parameters are essentially the same, which is confirmed by the results obtained, as the proportions of these parameters are similar. Minor differences may result from expressing the value of the sampling efficiency as a percentage, which may cause inaccuracies due to rounding; *Technical Guidelines for Digitizing Cultural Heritage Materials: Third Edition*, Federal Agencies Digital Guidelines Initiative, 2023; www.digitizationguidelines.gov/guidelines/FADGI Technical Guidelines for Digitizing Cultural Heritage Materials_3rd Edition_05092023.pdf, p. 15.

Losses due to the rotation

After comparing the measurement results of images rotated without earlier upsampling step (Table 3) with results for rotated images after earlier upsampling by factor of 2 (Table 4), it can be concluded that the sampling efficiency losses are greater for images rotated after earlier upsampling; however, the results of the measurements are not all that important when applying a rotation. Visual inspection makes it possible to see the changes in the image caused by the rotation, which affect its overall quality.

Table 5. Lower right-hand section of the QA-62 target of rotated images without earlier upsampling (sharpened to facilitate observation of distortions, v=100)

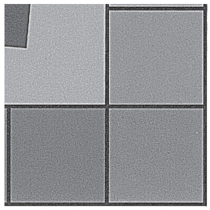
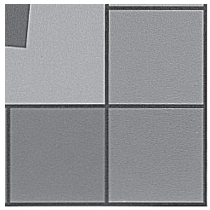
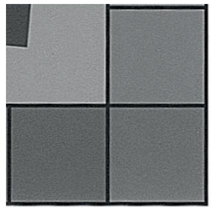
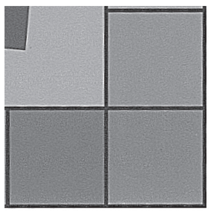
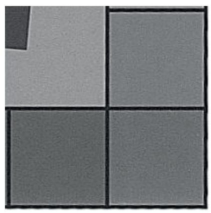
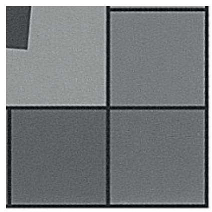
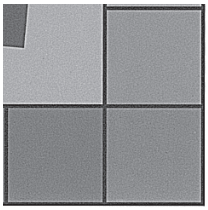
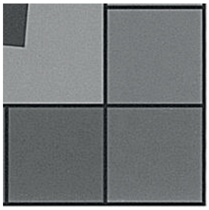
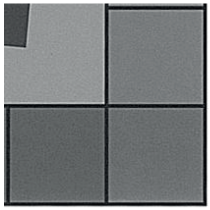
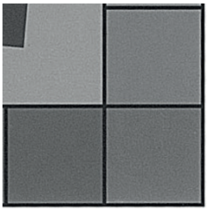
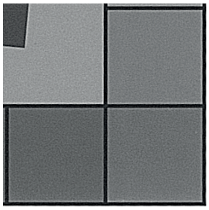
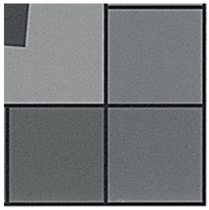
0°	**0.2°**	**1.32°**
		
2.38°	**3.5°**	**9.65°**
		

Table 5 includes examples of the effect of rotation on noise behaviour. Visible areas of increased and decreased noise sharpness can be seen, resulting in a distortion resembling a moiré effect. The use of an enhanced rotation reduces the occurrence of this effect and produces less discrepancies between images rotated at different angles.[13] The results of the enhanced rotation are presented in Table 6.

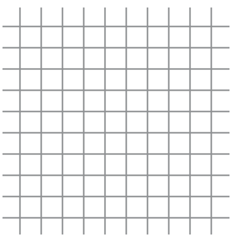
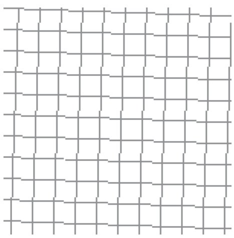
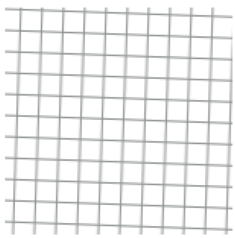
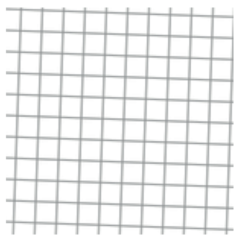
13 This is important in the digitisation process, since its objective is to achieve similar results for each reproduction of a multi-page document, and arbitrary inaccuracies resulting from the different placement of objects on the scanning devices, as well as the design of the objects themselves, mean that the angle of rotation is determined individually for each image.

Table 6. Lower right-hand section of the QA-62 target of rotated images with earlier magnification (sharpened to facilitate the observation of distortions, v=100)

0°	0.2°	1.32°
		
2.38°	**3.5°**	**9.65°**
		

The observed visual discrepancies seem to correspond to the results obtained in the analysis (Tables 3 and 4). It can thus be assumed that interpolating the image before rotation produces more uniform results when processing a batch of images. To better illustrate the results of an enhanced rotation, the same method was used for an artificially-created test image.

Table 7. Example of rotation based on an artificial test image

Input image	2° rotation without smoothing	2° rotation without initial upsampling	2° rotation with initial interpolation (2x)
			

The simulation the results of which are presented in Table 7 makes it possible to determine the impact of the rotation on the features of the processed image. It can be concluded that the focus on quality by first interpolating the image by upsampling before its rotation by a factor of 2 is the right direction. By means of this method, an image can be obtained that is geometrically more consistent compared to when smoothing is not applied. The resulting image is also more uniform in terms of sharpness compared to when interpolation is not used. As a side effect, the overall image sharpness is reduced.

Correcting defects by sharpening the image

The primary aim is to improve the image analysis results by sharpening the image so as to increase the sampling efficiency while not exceeding a value of 1 for the maximum frequency response amplitude. In order to determine the optimal parameters for the corrections, a sharpening of the test images with rotation angles of 0.2° and 1.32° was performed, using the sharpening factors (v) between 80 and 98 with an interval of 2.

Table 8. Measurement results for sharpened images with a 0.2° rotation angle, within the range of v=80 to 98

v	PPI	SEFF	SFR50	SFR10	MaxSFR
80	299.5	91%	0.27	0.45	1
82	299.5	92%	0.29	0.46	1
84	299.5	93%	0.3	0.46	1
86	299.5	94%	0.31	0.47	1
88	299.5	96%	0.32	0.48	1
90	299.5	97%	0.33	0.57	1
92	299.5	98%	0.34	0.58	1.01
94	299.5	99%	0.36	0.61	1.08
96	299.5	99%	0.38	0.63	1.25
98	299.5	100%	0.41	0.67	1.6

Table 9. Measurement results for sharpened images with a 1.32° rotation angle, within the range of v=80 to 98

v	PPI	SEFF	SFR50	SFR10	MaxSFR
80	299.3	90%	0.28	0.45	1
82	299.3	91%	0.29	0.45	1
84	299.3	92%	0.3	0.46	1
86	299.3	93%	0.3	0.46	1
88	299.3	94%	0.32	0.47	1
90	299.3	95%	0.33	0.48	1
92	299.3	97%	0.34	0.49	1.01
94	299.3	98%	0.36	0.5	1.1
96	299.4	100%	0.41	0.52	1.61
98	299.4	100%	0.41	0.52	1.61

The results of both tests indicate that the sharpening factor of v=90 is the optimal value for the processing filter used. In the case of higher values being used, the maximum frequency response amplitude exceeded 1, resulting in an oversharpened image.

Conclusions

The enhanced rotation is always a lossy process; however, once the corrections are applied, it is possible to partially fix the losses. Based on the results of this analysis, the level of lossiness of this transformation can be determined.

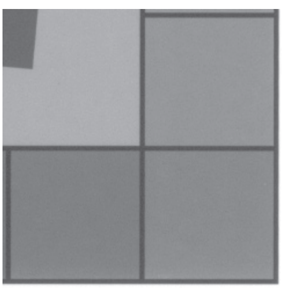
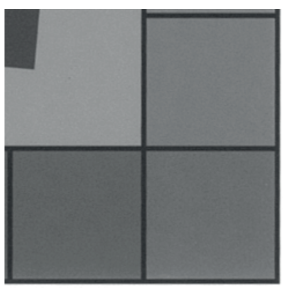
Table 10. Comparison of measurement results of raw images, rotated and uninterpolated images, as well as optimally rotated images with a rotation angle of 0.2° and 1.32°

	PPI	SEFF	SFR50	SFR10	MaxSFR
0°, v=0	299.4	100%	0.3	0.63	1
0.2°, v=0	299.4	99%	0.24	0.51	1
0.2°, UsP, v=90	299.5	97%	0.33	0.57	1
1.32°, v=0	299.4	88%	0.22	0.44	1
1.32°, UsP, v=90	299.3	95%	0.33	0.48	1

The summary presented in Table 10 shows that no significant differences were observed in terms of resolution measurements. Losses in terms of sampling efficiency for images transformed using the enhanced method range from 3% to 5%. For the SFR50 parameter, a deviation of 0.03 was observed in both cases, which corresponds to 10%, and for the SFR10 parameter, a deviation of 0.06 for the angle of 0.20° and 0.15 for the angle of 1.32° were observed, which corresponds to the range of 10% to 30%. The results for images rotated without interpolation were also included for comparison.

The images processed in this manner may not reach the quality level of raw images; however, these values are acceptable from the point of view of the digitization process, as the corrections applied by using the above-mentioned method result in obtaining straightened images that can be used for further processing.

Table 11. Example of a raw image rotated by 1.32° after interpolation with a upsampling factor of 2 and sharpening with a value of v=90

0°, v=0	1.32°, v=90
	

The example presented in Table 11 shows the side effects of the transformation. The processing parameters can be experimentally adjusted to reduce these effects on a case-by-case basis; however, achieving a higher degree of accuracy while balancing all measured criteria may prove difficult. For most practical applications, the presented method is sufficient for obtaining adequate results with an acceptable level of losses stemming from the processing.

The choice of the optimal image in the context of the method presented in this paper was made on the basis of the measurement results. If the visual inspection of the images processed using the optimal method presented in the paper confirms that the image is oversharpened in spite of obtaining the best analysis results, a lower filtering factor can be used to strike a better balance between the analysis results and the visual aspects of the image.

The enhanced transformation requires more computing power and memory, but enables obtaining more uniform outcomes. Given the current state of technology in this area, this can be seen as an acceptable cost.

The analysis was carried out on 300 ppi images and was intended to show the validity of the correction method applied. For images with a different resolution, the relations of the results obtained may be different, but the directions of the changes should remain the same. This matter requires further study. The presented analysis took advantage of a single filter included in a specific software suite. Various processing filters may work in different ways, which is why it is necessary to determine the correct values of sharpening factors for each tool used. The results of the analyses show that each sharpening filter might have a set of parameters that results in an improvement in the measurement results of the processed image. The parameters for each filter should be determined on a case-by-case basis.

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ISO 12233:2023: *Photography – Electronic still picture imaging – Resolution and spatial frequency responses*, www.iso.org/obp/ui#iso:std:iso:12233:ed-4:v1:en.

LIST OF ILLUSTRATIONS

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The study was carried out within the framework of the author's individual work.

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