Testing of Image Resolution Enhancement Techniques Using Bi-cubic Spatial Domain Interpolation

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Abstract. The technique for increasing digital image resolution from low-resolution image to high-resolution image based on digital image processing is called the super-resolution technique. In this paper, a super-resolution technique is presented using a two-dimensional bi-cubic interpolation method in the spatial domain. The order of the super resolution method applied is as follows: (1) selecting ten images as samples, (2) decrease the sample image resolution to one-fourth of the original resolution by deleting three quarters of the pixel number, (3) increasing the image resolution of a quarter of the part becomes like the initial resolution using bi-cubic interpolation for three quarters of the additional new pixels, (4) testing this bi-cubic interpolated image with the same pixel-sized initial image, (5) using parameters: average value, minimum value, maximum value and standard deviation value as a comparison parameter between bi-cubic interpolated images and the same pixel-sized initial image. The results obtained from the super-resolution technique using spatial bi-cubic interpolation are: (1) The average error value of the bi-cubic interpolation method in image objects in this study is between 4% to 10% or still quite low, (2) Bi-cubic interpolation methods can work well on square pixel-sized images (m = n) compared to non-square pixel-sized images, (3) Bi-cubic interpolation turns out to produce an array of image pixel values that mirror symmetry against the main diagonal lines of the image before being interpolated.

1. Introduction
The application of digital image processing has been very broad and covers various fields of human life. Ranging from the fields of photography, the field of security, the medical field to the field of space [1 - 3]. One of the things that are needed for example in the field of security and space is how to get high-resolution digital images from low-resolution images. Low-resolution images are obtained due to limited capacity and camera facilities. Meanwhile for analysis needs, for example by police and space scientists, high-resolution images are needed. The technique for obtaining high-resolution images from low-resolution images is called the super-resolution technique. Super-resolution technique is a technique to get image resolution by processing it on the image itself. Super-resolution techniques can be a restoration, reconstruction, or continuous image recovery process from samples of images [4].

High-resolution images are needed for various image-based fields of analysis. High-resolution images contain more information contained in them. In the process of increasing image resolution, many methods can be used. Some methods that can be used include the nearest neighbour, bi-cubic interpolation, cubic spline interpolation, maximum loneliness, maximum posteriori. The super-resolution method developed by the researchers mostly uses quite complex methods, such as the use of wavelets [5], simultaneous registration and reconstruction [6], frame fusion techniques [7], non-linear mapping [8], pixel weighting [9] and others.
In this study, the super-resolution method used is quite simple, because it is only based on the results of interpolating pixel values for new pixels resulting from the addition of pixels to increase image resolution. With this fairly simple method, it is hoped that super-resolution images will be obtained with quality that is close enough to the quality of super-resolution images with these complex methods. In this paper, we use the method of increasing image resolution in the spatial domain using bi-cubic interpolation. The bi-cubic interpolation used is two-dimensional bi-cubic interpolation for the entire pixel image whose resolution will be increased.

2. Method

2.1. Image Object

In this study, ten color image objects (RGB images) with various sizes of pixels are used. The ten color images are shown in Figure 1 below:

![Research object image](image)

**Figure 1.** Research object image: a. Yellow.jpg; b. Red.jpg; c. Laut.jpg; d. Hijau.jpg; e. Pink.jpg; f. Orange.jpg; g. Baby.jpg; h. Imp.jpg; i. Daun.jpg; j. Kapal.jpg

The size of the ten-pixel numbers of the RGB images is presented in Table 1. In Table 1 shows that of the ten images, there are a number of pixel-sized image of the 5 squares (m = n), ie images: Hijau.jpg, Orange.jpg, Baby.jpg, Imp.jpg, Kapal.jpg and 5 other images that are not square in size. This non-square image is divided into an image with the size of m (number of rows of pixels) smaller than n (number of pixel columns), ie images: Yellow.jpg, Red.jpg, Pink.jpg, Daun.jpg and image with size m is greater than n, ie image: Laut.jpg.

| Image Name  | Size     |
|-------------|----------|
| Yellow.jpg  | 225, 255, 3 |
| Red.jpg     | 255, 300, 3 |
| Laut.jpg    | 300, 255, 3 |
| Hijau.jpg   | 300, 300, 3 |
| Pink.jpg    | 150, 200, 3 |
| Orange.jpg  | 525, 525, 3 |
| Baby.jpg    | 200, 200, 3 |
| Imp.jpg     | 255, 255, 3 |
| Daun.jpg    | 525, 700, 3 |
| Kapal.jpg   | 400, 400, 3 |
2.2. Research Flow Chart

The order of work steps in this study is presented in the form of a flow diagram in Figure 1. Broadly speaking, the research flow diagram consists of 4 main steps, ie: forming an original matrix of image A, forming a matrix reduction B, forming a matrix resulting from interpolation of bi-cubic C, and form an accuracy matrix D.

![Flow Chart](image)

**Figure 2.** Research flow chart

The original matrix of image A is a matrix obtained from the direct reading of image pixels. Reduction matrix B is matrix A matrix reduction which measures the number of pixels m x n x 3 into a B matrix measuring ½m x ½n x 3. The B matrix formation process is done by removing even-numbered rows and even-numbered columns on matrix A as shown in Figure 3. The interpolation matrix C is a pixel-sized matrix of m x n x 3 obtained from the results of two-dimensional bi-cubic interpolation on matrix B. The process of forming C matrix is done by adding a series of pixels placed as even numbers and columns new rows the new even-numbered column in matrix B as shown in Figure 3.

![Interpolation Process](image)

**Figure 3.** Schema of the reduction and interpolation process
D accuracy matrix is a matrix obtained from the difference between C interpolation matrices to the original matrix A. The D matrix states the difference in the values of each pixel from bi-cubic interpolation to the original matrix for all pixels in the image which is m x n x 3. From the values on the element, This D matrix element can then be calculated statistically the average value, minimum value, maximum value, and standard deviation value as a comparison parameter between the bi-cubic interpolated image and the original image.

2.3. Bi-cubic Interpolation Method

Interpolation (resampling) is a method to get the value of the data you want to search for and not contained in the observation data from several data that have been obtained from observations. There are various interpolation methods, such as linear interpolation (first degree), squared interpolation (second degree), cubic interpolation (three degrees), and others. Bi-cubic interpolation is a cubic interpolation (three degrees) to interpolate data in two dimensions.

In digital image processing, interpolation can be applied to obtain images with a higher resolution in the original image. Bi-cubic interpolation results in finer image enlargement at the edges rather than biliary interpolation (two-dimensional linear interpolation). Bi-cubic interpolation uses 4x4 neighbouring pixels as a data source forming interpolation. The bi-cubic interpolation function \( P(x, y) \) can be stated as follows [7]:

\[
P(x, y) = \frac{1}{16} \sum_{i=0}^{3} \sum_{j=0}^{3} a_{ij} u(s_x)u(s_y)
\]

(1)

Where \( u(s) \) is a one-dimensional cubic interpolation function with the following equation:

\[
u(s) = \begin{cases} 
\frac{3}{2}s^3 - \frac{5}{2}s^2 + 1 & \text{for } 0 \leq |s| \leq 1 \\
-\frac{1}{2}s^3 + \frac{5}{2}s^2 - 4s + 2 & \text{for } 1 \leq |s| < 2 \\
0 & \text{for } 2 < |s|
\end{cases}
\]

(2)

Wheres is the distance between pixels that are interpolated with neighbouring pixels.

3. Results and Discussion

3.1. Research Results

The fourth value of the analysis variable, namely the average value (µ), the minimum value (Min), the maximum value (Max) and the standard deviation value (σ) for each image are shown in Table 2.

| Image Name  | µ     | Min | Max | σ      |
|------------|-------|-----|-----|--------|
| Yellow.jpg | 10.9773 | 0   | 221 | 24,3051|
| Red.jpg    | 11.3689 | 0   | 195 | 26,4784|
| Laut.jpg   | 13.0656 | 0   | 114 | 26,8827|
| Hijau.jpg  | 16.6118 | 0   | 234 | 31,0509|
| Pink.jpg   | 15.7511 | 0   | 232 | 35,0783|
| Orange.jpg | 17.7367 | 0   | 205 | 35,0820|
| Baby.jpg   | 18.7511 | 0   | 217 | 36,1780|
| Imp.jpg    | 16.1993 | 0   | 227 | 41,9467|
| Daun.jpg   | 19.0165 | 0   | 251 | 43,1915|
| Kapal.jpg  | 25.2071 | 0   | 231 | 45,6477|
3.2 Analysis of Variable Accuracy

3.2.1 Average value

In this study, the mean is the average value of the difference in the value of the results of the interpolation of the original value (D matrix element) for the entire pixel that is raised in the process of increasing image resolution.

\[
\mu = \frac{1}{m \times n} \sum_{i=1}^{m} \sum_{j=1}^{n} (x_{ij} - D_{ij})
\]

By:

\[
\mu = \text{mean or average value for each RGB of the matrix D}
\]

\[
x_{ij} = \text{matrix D element i-row j-column for each RGB matrix}
\]

\[
D_{ij} = \text{difference value of the interpolation value to the original value for the pixel in i-row and j-column}
\]

\[
m = \text{number of pixel lines from the image}
\]

\[
n = \text{number of pixel columns of the image}
\]

The average value of the difference between the results of the interpolation of the original is also done for each image D matrix, namely the D matrix for red (\(\mu_R\)), green (\(\mu_G\)) and blue (\(\mu_B\)). So that the average value for all images is:

\[
\mu = \frac{\mu_R + \mu_G + \mu_B}{3}
\]

The average value variable (\(\mu\)) states the average of the difference in the value of the results interpolated with the original value. The small \(\mu\) value indicates that the interpolation results are good enough. Conversely, the large \(\mu\) value states that the results of the interpolation are not good enough. Based on the data in Table 2, the average value of the ten image objects ranges from 10 to 25. If the average value of this error is compared with a maximum pixel value of 255, then the value of this error is at a percentage of 4% to 10%. This means that the error value of the bi-cubic interpolation method is still quite low. Average error value is indeed quite low, but this variable is not the only variable for assessing image quality. The quality of the interpolated images can be evaluated directly visually.

3.2.2 Minimum and Maximum Value

In this study, the minimum value is the smallest value of the difference in the value of the results of interpolation to the original value for the entire pixel that is raised in the process of increasing image resolution. Conversely, the maximum value is the greatest value of the difference in the value of the interpolation of the original value for the entire pixel that is raised in the process of increasing image resolution.

The minimum value (Min) and maximum (Max) is the smallest value and the greatest of the difference in the value of the results of the interpolation of the original value. These two variables only provide information about two extreme values, the difference between the results of the interpolation of the original value. Ideally, both of these variables must be zero, meaning that bi-cubic interpolation gives perfect results. Minimum and maximum values that are not ideal do not mean that the results of bi-cubic interpolation are not good. This is because the minimum and maximum variables are only auxiliary variables, not the main variables. The data in Table 2 shows that the minimum value reaches the ideal value (i.e. zero) for all images. Meanwhile, the maximum value varies from the greatest value close to the peak value (i.e 255) in Leaf images, jpg to the smallest approaching the half peak value (127) in the Sea image, jpg. This means that an error in bi-cubic interpolation can change a pixel that should be black (pixel value 0) to white (pixel value 255).
3.2.3 Standard Deviation

Standard deviation or standard deviation is one of the statistical techniques used to explain the homogeneity of data groups. Standard deviation is also defined as the variation in the data distribution. The smaller the distribution value means the data is getting the same. Conversely, the greater the distribution value, the more varied the data. The standard deviation is calculated as the root of the average square of the difference in the data to the mean.

\[ \sigma = \left( \frac{4}{3mn} \sum_{i=0}^{n} \sum_{j=0}^{m} (x_{ij} - \mu)^2 \right)^{1/2} \]  

By:

\( \sigma \) = standard deviation for each RGB matrix  
\( m \) = number of pixel lines from the image  
\( n \) = number of pixel columns of the image  
\( x_{ij} \) = matrix D element \( i \)-row \( j \)-column for each RGB matrix  
\( \mu \) = mean or average value for each RGB matrix

The overall standard image deviation in this study is expressed as the average value of the standard deviation for red (\( \sigma_R \)), green (\( \sigma_G \)) and blue (\( \sigma_B \)). So that the average value for all images is:

\[ \sigma = \frac{\sigma_R + \sigma_G + \sigma_B}{3} \]  

Standard deviation or standard deviation states the homogeneity of the data group. The smaller the standard deviation value, the more homogeneous the data group is. The data in Table 2 shows that the standard deviation value varies from 24 to 36. The results were pretty good interpolation will generate a standard deviation value which is quite small (homogeneous). Just like the minimum and maximum value variables, the standard deviation value variable is also not the main variable. This variable is an auxiliary variable for the main variable average value which describes how much the difference in the accuracy of the interpolated value of the original value of each pixel in the image.

3.3 Discussion

In contrast to the super-resolution method that has been developed by a number of researchers which tend to be quite complex [5-9], the super-resolution method used in this study is quite simple. This method is only based on the results of interpolating pixel values for new pixels resulting from the addition of pixels to increase image resolution.

The quality of interpolated images can be evaluated directly visually. An example is in Figure 4, two sample images are shown for different cases. The first image is the Yellow.jpg image which is a non-square image and the second image is the image of Daun.jpg which is square. In Figure 4, you can see the results of bi-cubic interpolation in Yellow.jpg images that are not square images resulting in dark areas (black) on the right side of the image. Whereas the results of bi-cubic interpolation in the Daun.jpg image which is square have no dark areas (black) in the interpolated image. This means that the bi-cubic interpolation method can work well on square pixel-sized images, compared to not square pixel-sized images.
In Figure 4 it also shows that the bi-cubic interpolated images, namely Yellow.jpg and Daun.jpg imagery turned out to be mirror symmetry images of the main diagonal lines of the image before being interpolated (i.e. reduction images). This kind of thing also occurs in all the images that are the object of this research, both square and non-square.

An important result obtained from the application of the bicubic interpolation method in increasing image resolution in this study is the relationship between the quality of the interpolation results and the pixel size of the image before interpolation. Most likely the cause of the bi-cubic interpolation method that only gives good results on square pixel-sized images is in the form of bi-cubic function formulas that are equivalent between the x and y variables. In this regard, there needs to be further research to improve and modify the shape of the bi-cubic function formula that no longer should be equal between the variables x and y variables. Modification of bi-cubic function formula form which is not equal between variable x and variable y is expected to be able to work well on square and non-square images.

4. Conclusion
The average error value of the bi-cubic interpolation method in the image objects in this study is between 4% to 10% or still quite low. Although the average error value is quite low, this variable is not the only variable to assess image quality. The quality of interpolated images can be evaluated directly visually and the results are obtained that the bi-cubic interpolation method can work well on square pixel-sized images (m = n) compared to non-square pixel-sized images. Bi-cubic interpolation turns out to produce an array of image pixel values that mirror symmetry against the main diagonal lines of the image before being interpolated.

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Revision Notes:
1. Write more about research gap, state of the art, and the comparison of another related research
   
   Has been revised:
   - Research gap: existing super-resolution methods are complex enough so that it needs to develop simpler methods.
   - State of the art: the super-resolution method with the bi-cubic interpolation method is quite simple
   - The comparison of other related research: the super-resolution method used in this study is a fairly simple process when compared with the methods used by other researchers.

2. The resolution is too low, so it is unreadable flow chart
   
   Has been revised: Flowcharts are made with a higher resolution so that they can be read

3. Typo: bikubik
Has been revised: Bikubik becomes bi-cubic

4. Typo: neighboring
   Has been revised: neighboring becomes neighbouring

5. What evaluation measure that you used in this study, how you counting the accuracy of the image?
   Has been revised: A description of the accuracy variable was added before the discussion

6. Explaining the differences of image resize with this result? The result is very bad, please compare with another methods, and make a synthesis from your result
   Has been revised: It has been added to the paper that the probable cause is the bi-cubic function used in the study is equivalent between the x variable and the y variable. There is no research on this and we will study it in the next research.

7. Write without bullet and numbering
   Has been revised: It has been written without bullet and numbering

8. How you get this number of error?, Your said that it is quite low, but did you know that the result of image isn’t good enough
   Has been revised: It has been added to the paper that the average error value is indeed quite low, but this variable is not the only variable for assessing image quality. The quality of interpolated images can be evaluated directly visually and has been written in the second and third points of the conclusion

9. The references are too few for international publication, please adding more up to date primary references
   Has been revised: References from the latest international papers have been added