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IMPROVING DEM GENERATION BY ENHANCING THE RESOLUTION OF REMOTELY SENSED DIGITAL IMAGERY

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Abstract

In today's world of advanced technology where most remote sensing and photogrammetric data are recorded in digital format, virtually all image interpretation and analysis involves some element of digital processing. Digital image processing may involve numerous procedures including formatting and correcting of the data, digital enhancement to facilitate better visual interpretation, or even automated classification of targets and features entirely by computers. In order to process remotely sensed imagery digitally, the data must be recorded and available in a digital form.

This paper examines a rigorous image enhancement technique for estimating a high-resolution image, with reduced aliasing, from a sequence of undersampled frames. This algorithm is illustrated with applications which show its implementation using harmonic theory. The proposed method is of moderate computational complexity and has proved to be robust under noisy circumstances.

Although the quality and resolution of the sensor arrays used to capture digital data continue to evolve, it is important that any algorithm used to enhance resolution must be *device independent,* thus capable of using input from not only low-resolution images, but also from higher resolution devices. This will allow even the highest resolution images to be improved while ensuring the longevity and applicability of the algorithm.The method is further validated as a tool to generate improved Digital Elevation Models (DEMs). A series of 3-D tests using objects of known geometry were carried out using low-resolution images and images enhanced by the algorithm. Results indicate its potential use for 3-D surface modelling.

1 Introduction

Photogrammetry and remote sensing are sciences concerned with the acquisition of information from images. In photogrammetry the emphasis is placed on geometric information, while in remote sensing thematic information is more important.

The advent of digital imaging technology has produced opportunities for new and diverse applications of remote sensing and photogrammetery to be undertaken which were not feasible with traditional techniques. Automated generation of DEMs is one of such applications. DEMs may be combined with remote sensing data for a variety of purposes. DEMs may be useful in image classification, as effects due to terrain and slope variability can be corrected, potentially increasing the accuracy of the resultant classification.

Accurate DEMs are also useful for generating 3-D perspective views by draping remotely sensed imagery over the elevation data, enhancing visualization of the area imaged.

In applications that demand highly detailed images, it is often not feasible or sometimes possible to capture images of such high-resolution by just using hardware (i.e. high precision optics, CCD or CMOS). Instead, image processing methods may be needed to construct a high-resolution image from multiple, degraded, low-resolution images.

This work estimates an unaliased high-resolution image from an aliased image sequence of the same view. This is possible if there exists a sub-pixel motion between the acquired frames. Hence, each frame provides a unique view of the scene. Random global motions and rotations between frames in the sequence provide information that can be used to remove some of the aliasing present in the frames. Motion vectors for each frame are estimated from the image content via area-based image registration algorithms. The proposed method is illustrated with applications which show its implementation using harmonic theory to model the grey-scale surface of the enhanced image.

The technique is of moderate computational cost and has proved to be robust under noisy conditions while effective in the presence of sharp variations of intensity values within the image. Performance of the algorithm does degrade, as would be expected, with increasing noise and decreasing number of low-resolution input images. The resulting image quality is also comparable with that of existing methods.

In order to validate the algorithm's effectiveness as a tool for generating improved DEMs, it was used in a series of three-dimensional tests using images of objects of known geometry. Stereoscopy sets of left and right images were taken of these objects, and DEMs were subsequently created using both the original images and images enhanced by the algorithm. Quantitative error analysis of these results is shown.

2 Digital Image Resolution Enhancement

Developments into the enhancement of the resolution of digital images can be divided into two main streams, that is, hardware and software solutions. Hardware solutions may involve modifications to the cameras used for image acquisition while software solutions may relate to different aspects of image processing, including image registration, reconstruction, restoration, synthesis and image fusion amongst others.

The enhancement of the resolution of digital images via hardware solutions has been based on the accurate movement of the sensor array at a sub-pixel level. A basic example is the case of the new CanoScan scanner D660U by Canon, which utilizes a Variable Refraction Optical System (VAROS) that allows a 600 dpi sensor to achieve 1200 dpi resolution by shifting the 'vision' of the sensor by half a pixel to create a second view of the subject. The two views are then interlaced to create a 1200x1200 optical image.

Jahn and Reulke (2000) utilised an analogous approach in describing a staggered line of arrays in Push-Broom sensors onboard aircrafts or satellites. A staggered line array consists of two identical CCD lines with one shifted half a pixel with respect to the other. The 3.34 Mega Pixel CCD of the new GC-QX3U digital still camera from JVC allows for high quality pictures at resolutions up to 2032x1536. Pro-Still Technology offer several modes that improve picture resolution even further when photographing stationary subjects. The 6 Mega Pro-Still mode uses advanced pixel shifting to create an even higher resolution image equivalent to over 6 Mega pixels.

On the other hand, there have been several software approaches to the basic problem of high-resolution image recovery using multiple frames. Hendicks and Vliet (1999) presented and compared a number of systems for significantly improving the spatial resolution of an under-sampled infrared image sequence in which the frames are shifted by random motion of a digital camera. The amount of sub-pixel translation is extracted from the frames themselves using different registration techniques. Once the magnitudes of the translations are defined, the image can be sampled at more points than provided by the detector array. The camera motions (induced vibrations) of the above systems cause translations but no significant rotation of the acquired images, yielding a constant image shift over the entire image.

Hardie et al. (1997) devised an iterative algorithm that does not rely on knowing the registration parameters *a priori*. In this method, the registration parameters are iteratively updated along with the high-resolution image in a cyclic coordinate descent optimisation procedure. The iterative nature of this accurate method is time consuming and would be impractical for real-time hardware applications. Fryer and McIntosh (2001) implemented a rigorous geometric algorithm based on accurately combining several individual coordinate systems, each referenced to the layout of the pixels on the sensing array, but also each translated and rotated by unknown amounts which were then determined by least squares area based registration techniques. This algorithm involves a number of computational difficulties associated with large sparse matrices and iterative computations.

Other image processing methods are also designed to visually enhance images for specific applications by changing the values of the pixels in the image. While these methods improve the visual quality of the image they do not necessarily increase the resolution of the image. Some of these methods include edge enhancement, noise reduction, and blur removal (Baxes, 1994).

Many enhancement algorithms also use conventional interpolation methods to create a higher resolution image. In this case, a surface is fitted to the data produced by the low-resolution images, where the shifts of these images relative to one another have been determined using registration techniques. As the surface passes through all the scattered data points it is then possible to interpolate it at specified points defined by a uniform and refined sampling grid using interpolation algorithms based on the Nyquist frequency criterion (Watson, 1992).

3 Interpolation methods

There are three common methods for interpolating scattered data to a uniform refined grid:

- nearest neighbour
- bilinear interpolation
- cubic convolution.

The **Nearest neighbour** uses the digital value from the pixel in the original image which is nearest to the new pixel location in the corrected image. This is the most simple method and does not alter the original values, but may result in some pixel values being duplicated while others are lost. This method also tends to result in a disjointed or blocky image appearance. **Bilinear** interpolation takes a weighted average of four pixels in the original image nearest to the new pixel location. The averaging process alters the original pixel values and creates entirely new digital values in the output image. **Cubic convolution** interpolation goes even further to calculate a distance weighted average of a block of sixteen pixels from the original image which surround the new output pixel location. As with bilinear interpolation, this method results in completely new pixel values. However, these two methods both produce images which have a much sharper appearance and avoid the blocky appearance of the nearest neighbour method. The result of these techniques is shown in the simulated example below.

Sixteen images were manufactured from the original image of the lighthouse shown in Figure 2. Each image was created by sampling the original image at uniformly spaced points starting from the sub-pixel shifts assigned to each coarse image. One of the sixteen coarse images is shown in Figure 1. In this example, the geometry of the fine/coarse pixel is taken as 1.8, that is, one coarse pixel corresponds to an area 1.8 bigger than the area occupied by the fine pixel on the fine pixel's coordinate system.

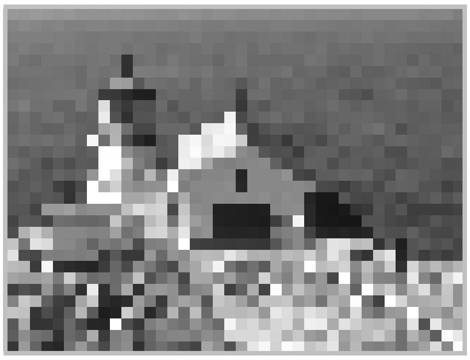


Figure 1 : Coarse

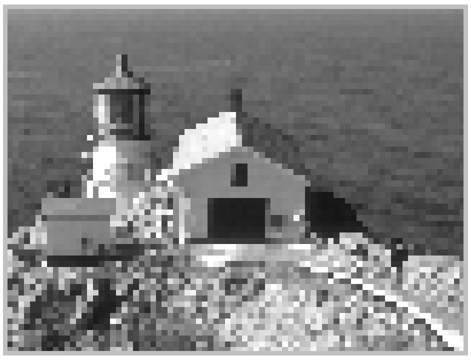


Figure 2 : Original

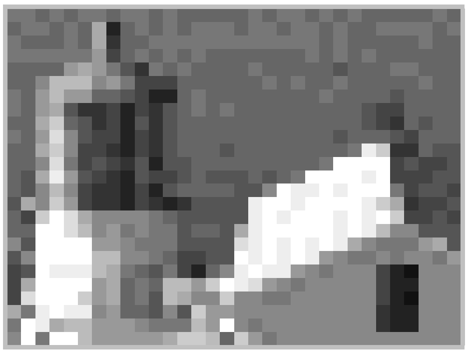


Figure 3(a) : One coarse image

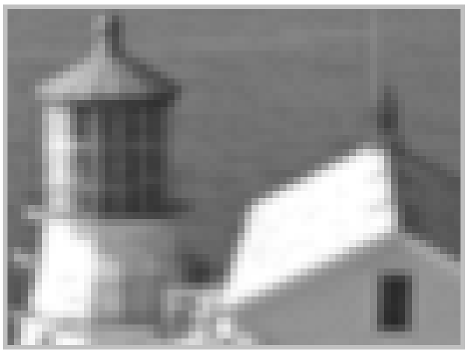


Figure 3(b) : Cubic interpolation

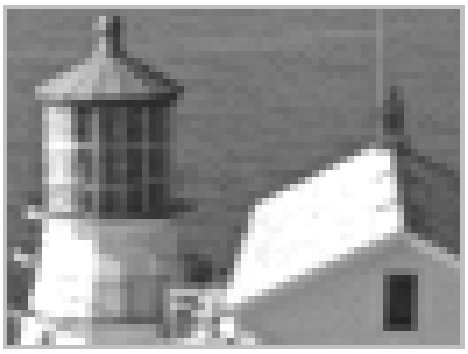


Figure 3(c) : Proposed technique

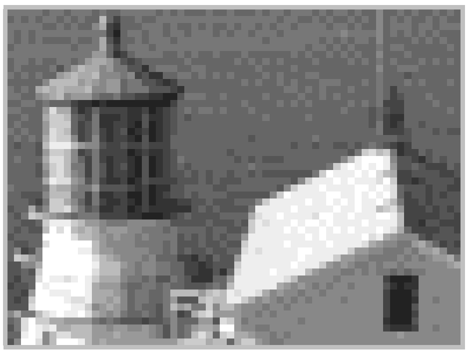


Figure 3(d) : Original Image

The result of combining 8 coarse images using cubic convolution as compared to the enhancement produced by the proposed enhancing algorithm is illustrated in Figure 3, (a) is a section of the coarse image given in Figure 1, (b) is the same section produced by cubic interpolation, whereas (c) shows the effect of applying the proposed enhancing technique which is then compared to the original image of the lighthouse (d). The enhancement does not create images which are larger in area than the input images; rather it creates an image with larger number of smaller pixels over the same area.

The standard error and correlation coefficients of the differences between the interpolated image and the original image were respectively +/-8.9 grey intensity values and 0.969 whereas using the proposed enhancement algorithm the values improved to +/- 3.87 intensity values and 0.997. By way of visual comparison, note also how the cubic convolution interpolation technique (combination of 8 images) produces a blurred image with less contrast. Adding more than 8 coarse images to the interpolation process would not improve substantially the final resolution.

When working with real data, the fine pixel coordinates are not known relative to the coarse images until all the required coarse images are matched and the relative shifts determined. The shifts between coarse images are computed by least squares area-based image registration. The matching process represents a crucial aspect for the implementation of the interpolation techniques described above as well as for the development of the rigorous methods for enhancing digital images described in the ensuing sections.

4 Image registration

The image registration technique herein implemented is used to match the grey scale intensity values of two digital images, while simultaneously detecting, and locating, any geometric differences that exists between the two images being matched. For the purpose of this paper such geometric differences relate to potential shifts and rotations between the frames being investigated.

Further, three basic assumptions are made: (i) the initial match position and orientation are not known before the registration process begins; (ii) the magnitude and extent of the differences that exist between the images, if any, are assumed to be unknown; and (iii) the technique is not an approximate registration procedure, but an accurate one. The registration process which is derived matches those intensity values identified as being common to both images, while simultaneously detecting and removing the intensity values which differ between models. The technique allows images to be registered without using any control points in the registration procedure.

In addition, for the correct detection of the shifts or offsets and rotations, the image must contain some features that make it possible to match two undersampled images. Very sharp edges and small details are most affected by aliasing, so they are not reliable to be used to estimate these shifts. Uniform areas are also of no use, since they are translation invariant. The best features are slow transitions between two grey values which are generally unaffected by aliasing.

Such portions of an image do not need to be detected, although their presence is very important for an accurate result. The method herein implemented for estimating the global shifts between two images relates to an area based matching technique. One strategy for area based matching is to adopt a least squares solution which can overcome difficulties arising from radiometric differences in the images being matched and can achieve sub-pixel accuracies of approximately 0.1 pixels.

The above method computes the shifts between two images at a time. However, in this application, what is required is the relative position of a sequence of images. By calculating the shifts with respect to a single reference image, all the relative image positions can be obtained. By repeating the procedure for another reference image, a second estimate for the relative positions can be made. By averaging all the possible combinations of the sets of relative positions (i.e. centred in their first moment) a better estimate of such shifts or offsets may be obtained.

5 A rigorous geometric algorithm

In the ensuing sections, the image enhancement approach by Fryer and McIntosh (2001) is re-examined and combined with harmonic, or Fourier, theory together with the geometric configurations of the pixels in object space so as to form a generalised surface model for digital images. The approach is expanded to validate its application for improving DEM generation. The various steps of this algorithm are given below:

- Collect several left and right low-resolution images of the object.
- Determine pixel offsets of each image from the first using least squares area-based image registration.
- Form a set of observation equations by combining harmonic theory with the geometry of the shifts, a selected enhancement ratio and the grey levels of the low-resolution images
- Solve for higher resolution pixels.
- Display the resultant left and right higher resolution image.
- Process the higher resolution images and improve DEM generation.

6 Geometric factors of the harmonic model

Each pixel within an image, represented visually as a square area, contains a single grey-scale value, representing the integrated average shade, or intensity value, of all the details in the area it covers. The grey-scale value of each pixel is derived from an eight-digit binary number representing a shade of grey from total black to total white in 256 gradations. The human eye can detect only about 32 different levels of grey, so the digital imaging and subsequent processing constitutes at least a fourfold improvement over visual processes.

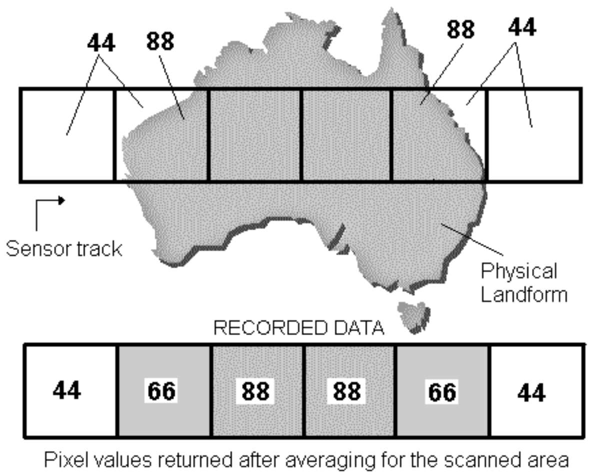


Figure 4 : Pixel integration of edge areas

In Figure 4, the recorded data represents a portion of one single line that a camera/scanner records as it passes over the object. As the diagram shows, an integration of values occurs where the edges of the darker object fall within the area of the camera's pixel definition. In the figure the camera records a value of 66 instead of either 88 or 44. In the recorded "coarse" data the sharp edges of the object are "lost" and the object may be unrecognisable.

However, the relationships between the values of the pixels contain more information about the original shape of the object than is visible to the eye. Because the specific variation of pixel values was originally derived from averaging of the values in the actual scene, with appropriate algorithms the original shape of the object can often be recovered. Such a procedure involves the original pixel and the values of immediately surrounding pixels.

In the technique herein proposed each pixel of the coarse images is examined one by one and are mapped onto a fine pixels coordinate system, thus defining which fine or unknown pixels are affected by each individual coarse pixel. In Figure 5, the upper left hand coarse pixel covers the area bound by (0.5, 0.5) - (2.0, 2.0) in the fine pixel coordinate system.

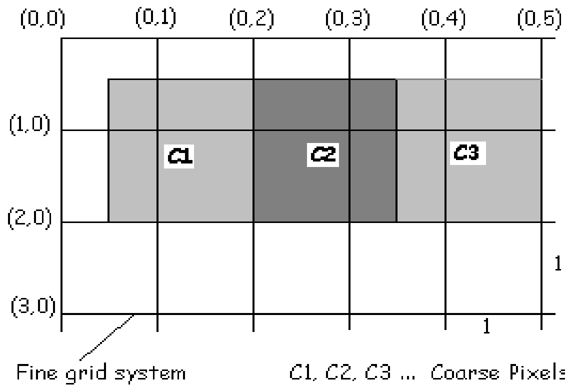


Figure 5 : Coarse data mapped on the enhancement grid

These coordinates show the upper, lower, left and right bounds of the coarse pixels (C). Using these bounds, the proportion of the coarse pixel which affects each fine pixel (F) can be found in terms of grey scale values:

$$C(1,1) = [0.25*F(1,1) + 0.5*F(2,1) + 0.5*F(1,2) + F(2,2)] * p^{-2} \qquad (1)$$

where p =1.5 is the enhancement ratio which determines the dimensions of the image in fine pixels with respect to the dimensions of the image in coarse pixels. The enhancement ratio is less than two, as required by the Nyquist criterion. The ratio is used as a factor which is applied to the coarse pixels to determine the boundary of each coarse pixel with respect to the fine pixel coordinate system. The fine pixel coordinate system defines the position of all the unknown fine pixels and is the system onto which the coarse images are mapped. Once the first coarse pixel is related to the fine coordinate system the process moves on to the next coarse data pixel.

7 Number of coarse images required

In Figure 5, a 3x5 fine pixel array of unknowns would require at least several 2x3 pixel array of coarse images to have enough information to fill one high resolution image. To solve for a higher enhancement ratio, that is, greater than 1.5 but less than 2, more coarse images would be needed. However, since we are dealing with noisy data, the required number of low resolution images will also depend on the distribution of the shifts, as well as on the signal to noise ratio. Nyquist sampling theorem states mathematically that in order to represent fully the spatial details of an original continuous tone image, the sample should occur at a rate at least twice as fast as the highest spatial frequency contained in it.

Thus, in order to capture an image's finest dark-to-light-to-dark detail, sampling must occur at a rate fast enough so that at least two samples fall upon the detail. This guarantees that both the dark and light portions of the detail are sampled, and hence preserved, in the resulting digital image.

In this definition, the sampling position is not taken into account. To mathematicians this is not new as for instance a polynomial of order n is completely defined by n+1 points, no matter how close together these points are. However, in mathematics data is never noisy so the position can indeed be of influence and therefore depending on the distribution of the samples we might need more than the minimum required frames to correctly reconstruct the high resolution image. Furthermore, limits to the resolution of the output image are set by the resolution of the lens system and the fill factor of the detector array.

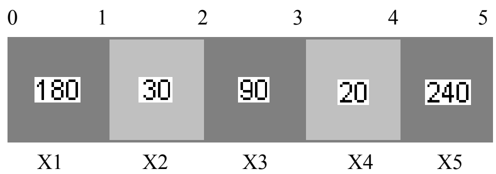
8 Image reconstruction and harmonic theory

The algorithm described in this section forms the foundations for modelling digital images in terms of surfaces using Fourier theory. The algorithm considers the image as a surface with the brighter the pixel, the higher it is considered on the image "surface". The precision of this development and the beneficial aspects of this harmonic transformation are described below.

Harmonic or Fourier analysis is the process of fitting Fourier series by least squares to data and of calculating the various amplitudes and phase angles of the various waves. Since a given function P(x) is frequently represented by a series of discrete points (observations), the resulting Fourier polynomial depicts the points and the closeness of fit between the points, and therefore, the usefulness and accuracy of Fourier series will depend on the actual frequencies present in P(x) and those calculable from the discrete points. However, if any interpretation is to be made from Fourier series, some assumptions have to be made about the function beyond the limits of the data. The simplest assumption and the one used here is that P(x) repeats itself completely, that is, it is completely periodic. The standard form for a Fourier series of period T is given by

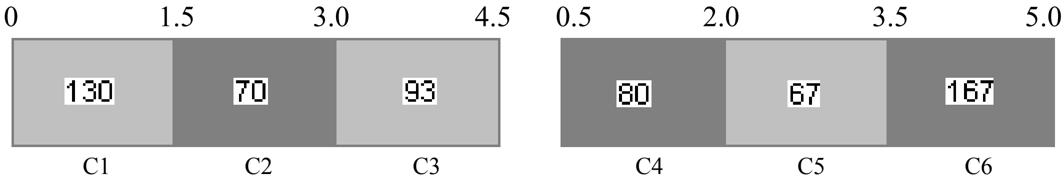
$$P(x) = \tfrac{1}{2} a_0 + a_1 \cos wx + b_1 \sin wx + a_2 \cos 2wx + b_2 \sin 2wx + \ldots \quad (2)$$

Where w is the angular frequency, w= 2π/T. In our case T, the period, represents the number of discrete points x = 1, 2,… , n. The constants a_0, a_1, b_1, a_2, b_2, … are the Fourier coefficients. In this paper the determination of such coefficients is based on describing P(x) in terms of a number of discrete points (pixel grey values) separated by constant intervals. For example, the five grey levels in the 1-D example below can be expressed as a generalized Fourier linear model in which the 'discrete' Fourier series includes five terms, that is, the number of the required fine pixels:



$$P(x) = 111.97 + 82.18 \cos(wx) + 46.80 \sin(wx) + 46.75 \cos(2wx) + 61.62 \sin(2wx) \quad (3)$$

Let us now consider a situation whereby the coefficients of the above series can be found from the data of the two coarse images depicted below.



COARSE pixels, such as those captured by a digital camera

The coarse pixel C1 can be geometrically related to the fine pixels X1 and X2 by the expression C1=(X1+1/2X2)*2/3. The same C1 can be also related to the Fourier polynomial P(x) in eq. 2 using their coordinate position such that C1=[P(1)+½P(2)]*2/3. P(x) is evaluated at x=1 and x=2 because these are the coordinates of the fine pixels X1 and X2 respectively. Thus, after evaluating and rearranging terms, the six equations associated to the six coarse pixels are:

130	$0.5a_0$-$0.06a_1$+0.83b1–0.44a2+0.07b2
70	$0.5a_0$-$0.81a_1$-0.19b1+0.31a2+0.32b2
93	$0.5a_0$+$0.54a_1$-0.63b1-0.21a2-0.39b2
80	$0.5a_0$-$0.44a_1$+0.71b1-0.06a2-0.44b2
67	$0.5a_0$-$0.44a_1$-0.71b1-0.06a2+0.44b2
167	$0.5a_0$+$0.77a_1$-0.32b1+0.40a2-0.19b2

The solution of this set of simultaneous equations via least squares produces the desired coefficients a_i and b_i of the discrete Fourier polynomial in (2), which is then evaluated at the fine coordinate points x = 1, 2,…,5 in order to recover, from the reconstructed signal, the original Xi grey values. The point of showing the pixels as adjacent is for descriptive purpose only. In reality the pixels are discrete, non-contiguous values. Other important considerations such as precision assessment, radiometric corrections parameters, lens distortions and other phenomena which produce differences in real images have been excluded from the above example.

The two dimensional case adheres to the same principles described earlier and uses the same geometric relationships between coarse and fine pixels established in section 6. In this case, the standard Fourier model would be a bivariate expansion (i.e. in x and y) representing a surface whose order depends on how many rows and columns exist in the image.

8 Precision and accuracy tests in two dimensions

To illustrate the concept of this enhancing method, an example is shown using test data, where low-resolution images have been generated from a scanned higher resolution image of the Kangaroo. By doing this, the higher resolution image is already known and can be compared to the result determined by the result determined by the proposed technique. Figure 6 shows one of the 5 low-resolution images which were used to determine the higher resolution composite shown in Figure 7. The pixel size of the low-resolution image is 1.8 times larger in each dimension than the higher resolution image, thus the images are of the same overall size but with different resolutions.

The initial image was acquired as a colour image and was modified to become a 256 grey scale image. Five low-resolution images with known relative shifts were generated to be used as input data. The images were 50x55 pixels and were enhanced by a ratio of 1.8 giving a higher resolution composite image of 90x100 pixels. Although the shifts between the images were known *a priori* in this test, the images were enhanced using the shifts determined by the matching algorithm, thus showing the accuracy of the matching. By way of example, the table below shows the differences between the known shifts and those calculated through the image registration

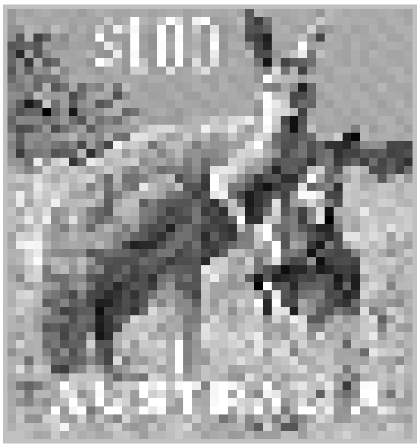


Figure 6 : Coarse image

Figure 7 : Enhanced image

	True offsets		**Registration**	
Images	x	y	x	y
A	0.000	0.000	0.000	0.000
B	0.500	0.500	0.481	0.466
C	0.250	0.750	0.195	0.800
D	1.000	0.000	1.020	0.004
E	0.750	0.750	0.694	0.701

Table 1 : "True" offsets vs. computed offsets

To further assess the precision of the enhancement algorithm, a series of tests were carried out using low-resolution images of the lighthouse test image as those shown in Figure 3. These tests were simulated so that the true image was known prior to the enhancement. In this way, both the internal precision and the accuracy of the enhancement could be assessed. The tests were performed using an enhancement ratio of 1.8 with a varying number of images (1-8) to which a range of levels of random noise had been added to the grey values of the coarse pixels.

It should be noted that there exists an amount of inherent noise in any digital image and these tests were to simulate that effect. There was a clear correspondence between the noise in the images and the accuracy of the results. There is a progressive, yet proportional, worsening of results as the noise in the images increases. Further it could be shown that the accuracy of the enhanced image was improved as the number of coarse images increased. By way of example, when the noise was added to the coarse images from +/-1 to +/-5 grey levels the accuracy of the enhanced image deteriorated from an RMS = +/-4.44 to an RMS = +/-9.7 grey intensity values.

9 Three-dimensional applications of the enhancing algorithm

An experiment was devised to test the effect of the enhancement algorithm on the accuracy of three-dimensional surface models (DEM) of a test object. The DEM were created by taking stereoscopic sets of left and right images, using coarse and enhanced images, and the result compared. The test object is shown in Figure 8. It was a spherical surface referred to as the geographic "globe", having an axis of approximately 600 mm.

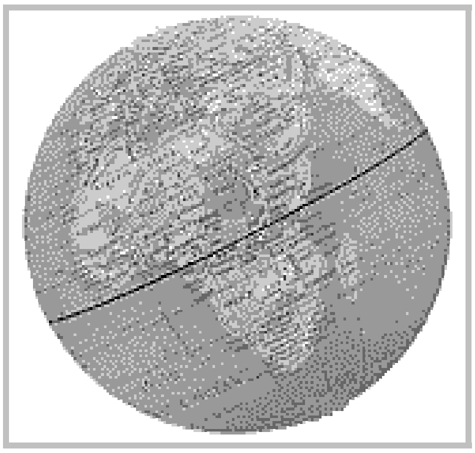


Figure 8 : The geographic globe

At each camera station (positioned at 1.2 metres from the globe and distanced 0.6 metres from one another) images of the globe were acquired with a conventional 35 mm film camera. The effects of lens distortion were minimised by ensuring the area of interest was in the centre of the image, where lens distortion is at a minimum. Eight low-resolution images were obtained by multiple scanning of the left and right images at 100 dpi using a conventional flat bed scanner. The images were cropped to be 180x180 pixels, and the enhancement was processed using a ratio of 1.8, thus producing an enhanced composite equal to 324x324. The average grey value was determined for each of the six images in the two data sets, and the images in each data set were adjusted to have the same mean value. The range of the mean value of the six images was only 1.55 grey values for the left data set and 2.43 grey values for the right data set.

The digital photogrammetric software known as Photomodeler Pro 4 by Eos Technologies was used to generate the DEM. The results for each DEM were analysed to allow for a comparison of the accuracy of the DEM generation between the enhanced and "true" images. "True" images were produced by scanning the original left and right images at an optical resolution of 600 dpi, which is the actual number of picture elements on the CCD of the scanner used in this experiment. A DEM of the test object was first generated using these sets of high-resolution images.

All relevant setting parameters in Photomodeler were kept the same to ensure that a direct comparison could be made between the data sets. The required contrast on the surface and background of the test was provided by the surface of the globe, which depicted a political map of the world, whereas the of reference targets consisted of the fine mapping details visible on the surface of the object (i.e., text, boundary lines between nations, intersection of meridians and parallels etc.), which defined a random spread of points over the spherical surface. A total of 150 points were considered in this exercise.

Marking and referencing the targets on the coarse and enhanced images of the globe with Photomodeler produced digital elevation models over the area of interest, which consisted of a section over Africa. The results of Table 2 are the standard errors and correlation coefficients of the differences between the DEM results obtained using the "true" images, the coarse images and the enhanced images. A substantial improvement using the enhanced images over the coarse images can be seen.

A key factor, which defined this improvement, was the accuracy of marking and referencing target points in the stereo pair. By way of comparison, Figure 9 shows an enlargement of typical target points on the enhanced image (i.e., intersection of parallels and meridians) and the same point on one of the coarse image and on the rescanned image.

	Correlation			**RMS mm**		
Coord.	x	y	z	x	y	z
Coarse	0.986	0.978	0.969	4.1	3.4	3.2
Enhan.	0.993	0.991	0.993	2.2	1.9	1.7

Table 2 – Correlation coefficients and RMS of DEMs

100 dpi approx. 180 dpi 600 dpi

Figure 9 : Enlargement of target points.

Conclusions

The objective of this paper was to introduce the use of harmonic, or Fourier, analysis to a rigorous geometric algorithm for enhancing the resolution of remotely sensed digital images, thus improving the accuracy of elevation models. A software solution, which is device independent, has been proposed. The application of the enhancement algorithm has been demonstrated in simulated tests using sets of low-resolution images whose relative positions with respect to one another are known. The notable findings from the experimentation include:

- The relationship between the fine pixels in the enhanced resolution image and the coarse ones in the original low-resolution pixels is neither simple nor direct, and therefore cannot be solved by simple interpolation methods.

- The amount of noise in the low-resolution images proportionally affects the precision of the resultant enhanced image. However, the precision an accuracy of the results can be improved by using more than the minimum required number of low resolution images in order to correctly reconstruct the high-resolution image.

- The image registration process can accurately determine the relative shifts between two images. However, second estimates of the shifts may be determined by changing and repeating the procedure using different reference frames.

- The least squares solution of the system of observations equations for the fine pixel determination can define both the external and internal precision of the results, which may not be the case with conventional interpolation techniques.

- Correlation coefficients and RMS results obtained from 3-D coordinates when using enhanced imagery improved by almost a factor of two as seen in the case of the globe in section 9.

Refinements to the proposed algorithm are being undertaken to increase the improvement in achievable accuracy and to diversify the range of applications which could benefit from utilising this device independent algorithm.

As image registration is an important component of the resolution enhancement algorithm, alternative registration methods are continuing to be considered for use in the algorithm. Moreover, the resolution enhancement technique herein presented is designed to process grey scale images, which is sufficient for many applications. However, the ability to use this algorithm with colour images would improve its applicability and generality. As colour images can be considered as three separate images containing red, green and blue components, it is proposed to enhance each of these channels and then fuse the results to produce a colour image with enhanced resolution.

The registration technique also determines the amount of rotation between the images when such rotation becomes significant. Further investigation is currently carried out to incorporate a rotation parameter when rotations become significant. Moreover, the possibility of merging data from different sensors, bringing the concept of multi-sensor data fusion may be added to the algorithm. Applications of multi-sensor as well as multi-resolution data integration generally require that the data be geometrically registered, either to each other or to a common coordinate system or map

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