ALGORITHM DEVELOPMENT FOR THE ENHANCEMENT OF PHOTOGRAMMETRIC DIGITAL IMAGES TO IMPROVE DEM GENERATION

John G. Fryer and Gabriel Scarmana.

Civil Surveying and Environmental Engineering
University of Newcastle, Australia.
Callaghan, new South Wales 2308
cejgf@cc.newcastle.edu.au

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ABSTRACT:

In digital photogrammetry applications such as digital elevation model generation (DEM), demanding highly detailed images, it is often not feasible or sometimes possible to acquire images of such high resolution by just using hardware (high precision optics and charged-coupled devices). Instead, image processing methods may be used to construct a high-resolution image from multiple, degraded, low-resolution images. This paper presents an algorithm which is device independent and can increase the spatial resolution of a sub-sampled, and thus aliased, image sequence. 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. In order to validate the algorithm's effectiveness as a photogrammetric tool, 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, DEMs were created using both the original images and images enhanced by the algorithm, and these indicated its potential use for photogrammetric surface modelling.

1. INTRODUCTION

Photogrammetry allows the determination of the size and shape of objects from measurements made on remotely sensed images. The advent of digital technology has produced opportunities for new and diverse applications of this discipline to be undertaken which were not feasible with traditional photogrammetric techniques. Automated generation of DEMs. (Digital Elevation Models) is one of such applications.

Digital photogrammetry is sometimes limited by the cost of acquiring digital imagery at appropriate resolutions. Low-resolution imagery is relatively inexpensive to acquire, but may not provide the accuracy required, especially in subsequent processing to derive DEMs.

This paper presents an algorithm which is *device independent* and can increase the spatial resolution of an undersampled, and thus aliased, image sequence. It is assumed that these low-resolution images are degraded, noisy, and displaced by sub-pixels shifts or translations with respect to a reference frame. Global translations between random frames in the sequence provide information that can be used to reduce some of the aliasing present in the frames. Translations vectors for each frame are estimated 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.

In order to validate the algorithm's effectiveness as a photogrammetric tool, 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, DEMs were created using both the original images and images enhanced by the algorithm. These indicated its potential use for photogrammetric surface modelling.

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 or 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.

The enhancement of the resolution of digital images via hardware solutions has been based on the accurate movement of the CCD array at a sub-pixel level. For example, the new CanoScan scanner D660U by Canon 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

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 undersampled infrared image sequence in which the frames are shifted by random motion of the 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 that 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 a robust but 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 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 previously unknown amounts. The magnitude of these translations and rotations are accurately determined using a least squares area based registration technique. This algorithm involves a number of computational difficulties due to the large sparse matrices and iterative computations required to define edge areas.

3. 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 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:
[1] Collect several left and right low-resolution images of the object; **[2]** Determine pixel offsets of each image from the first using least squares area-based image registration; **[3]** Form a set of observation equations by combining harmonic theory with the geometry of the enhancement and the grey levels of the low-resolution images; **[4]** Solve the system of observation equations and define the higher resolution pixels; **[5]** Display the resultant left and right higher resolution images; **[6]** Use the higher resolution images in a photogrammetric application and generate improved DEM.

4. IMAGE REGISTRATION

For a correct detection of the shifts or offsets, 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 useless, 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, 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 obtained. The average of all possible combinations of the sets of relative positions (i.e. centred in their first moment) defines a better estimate of such shifts or offsets.

5. GEOMETRIC FACTORS OF THE ENHANCEMENT

To describe the geometry of the enhancement the input images are referred to as the “coarse” images, and the higher resolution image will be referred to as the “fine” image. The enhancement does not create an image which is larger in area than the input images. The process creates an image with a larger number of smaller pixels over the same scene. Fig. 1 illustrates the relationship between the coarse (C) pixel size and the fine (F) pixel size.
To develop the geometric relationships between coarse and fine pixels, each pixel in the coarse images must be “mapped” onto the fine pixels coordinate system, thus determining which fine or unknown pixels are affected by each individual coarse pixel. For example in Fig. 1, the coarse pixel C2 covers the area bound by (0.5, 2) → (2, 3.5) in the fine pixel coordinate system.

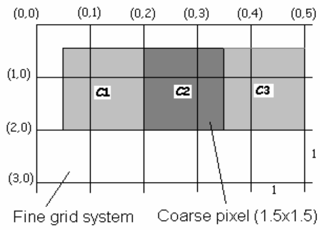


Fig. 1 - Coarse data mapped on the enhancement grid

These coordinates show the upper, lower, left and right bounds of the coarse pixel. Using these bounds, the proportion of the coarse pixel which affects each fine pixel can be found, such that in terms of grey-scale values:

$$C2 = [F(2,3) + 0.5*F(1,3)+ 0.5*F(2,4)+ 0.25*F(1,4)]*p^{-2}$$

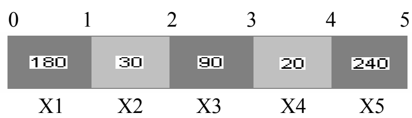
Where p is the enhancement ratio (p = Fine : Coarse) which in this case is 1.5 as deduced form Fig. 1. In this figure, a 3x6 fine pixel array of unknowns would require at least a system of 18 observation equations for a solution, thus requiring at least three 2x3 coarse images. To solve for a higher enhancement ratio, more coarse images are needed.

6. IMAGE RECONSTRUCTION AND HARMONICS

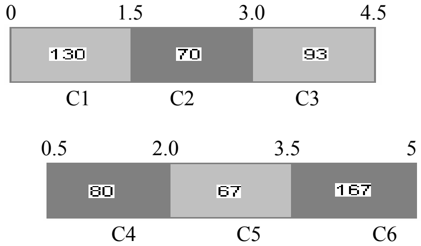
Since a given function P(x) is frequently represented by a series of discrete points (observations), the resulting Fourier polynomial depicts the points and the closeness of fit between the points, and therefore, the usefulness and accuracy of Fourier series will depend on the actual frequencies present 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) is completely periodic. The standard form for a Fourier series of period T is given by:

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

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



Let us now consider a situation whereby the coefficients a_i and b_i in P(x) can be found from the data of the two coarse images below.



The grey level value of 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 Equation 1 using coordinate positions 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	$0.5a_0 - 0.06a_1 + 0.83b_1 - 0.44a_2 + 0.07b_2$
70	$0.5a_0 - 0.81a_1 - 0.19b_1 + 0.31a_2 + 0.32b_2$
93	$0.5a_0 + 0.54a_1 - 0.63b_1 - 0.21a_2 - 0.39b_2$
80	$0.5a_0 - 0.44a_1 + 0.71b_1 - 0.06a_2 - 0.44b_2$
67	$0.5a_0 - 0.44a_1 - 0.71b_1 - 0.06a_2 + 0.44b_2$
167	$0.5a_0 + 0.77a_1 - 0.32b_1 + 0.40a_2 - 0.19b_2$

The solution of this set of simultaneous linear equations via least squares produces the desired coefficients a_i and b_i of the discrete Fourier polynomial P(x), 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 as established earlier in this section. 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.

7. PRECISION AND ACCURACY TESTS IN 2-D

An example of the effectiveness of this method can be seen in Fig. 2. Undersampling a properly sampled target image 68x80 of the *Koala* with random sub-pixel offsets, using cubic convolution, created a sequence of five synthetic images 38x44. The enhancement ratio is 1.8. By application of the algorithm using harmonic analysis and using the calculated offsets, the original target mage could be regenerated.

In addition, the performance of the registration algorithm was measured by comparing the known shifts with the estimated ones. These differences are depicted in Table 1 and show the accuracy of the image registration process.

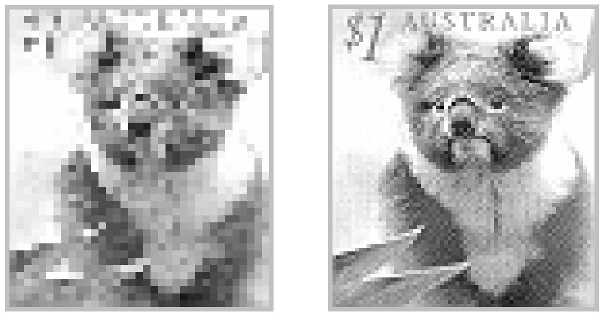


Fig. 2 – The Koala, coarse vs. regenerated image.

	TRUE OFFSETS		REGISTRATION	
images	x	y	x	y
A	0.000	0.000	0.000	0.000
B	0.500	0.500	0.471	0.476
C	0.250	0.750	0.199	0.800
D	1.000	0.000	1.022	0.003
E	0.750	0.750	0.698	0.731

Table 1 – True offsets and vs. computed offsets.

In a second experiment a picture of the lighthouse (Baxes, 1994) was repositioned and scanned on five occasions producing low-resolution images each of 20x25 pixels. The same photograph was rescanned at a higher resolution using an enhanced factor of 1.8, thus defining a 36x45 pixels image. The resulting enhanced image could then be compared with the rescanned. The standard error of the differences between the enhanced image and the rescanned image was +/-1.8 grey levels. Fig. 3 shows one of the coarse images of the lighthouse and the enhanced composite.

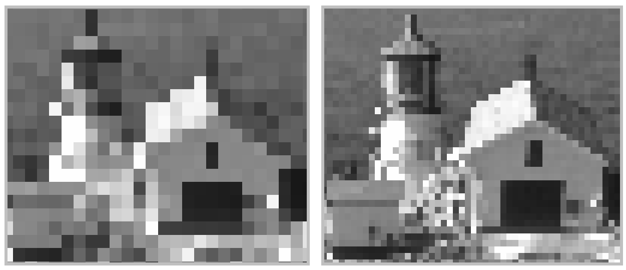


Fig. 3 - The lighthouse, enhanced image vs. coarse.

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 Fig. 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 (1-16) 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 precision of the results. Upon increasing the noise level from +/-1 to +/-5 grey levels the accuracy of the enhanced image deteriorated from an RMS=+/-3.3 to and RMS=+/-7.9 intensity values. Further, it could be shown that the accuracy of the enhanced image was improved as the number of coarse images increased.

8. 3-D APPLICATIONS OF THE ALGORITHM

An experiment was devised to test the effect of the enhancement algorithm on the accuracy of three-dimensional surface models 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 shown in Fig. 4 is a spherical surface referred to as the "globe", having an axis of approximately 600 mm, and was used to constraint the factors affecting the results from the experimentation. 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 eight 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 eight images was only 1.65 grey values for the left data set and 2.4 grey values for the right data set.

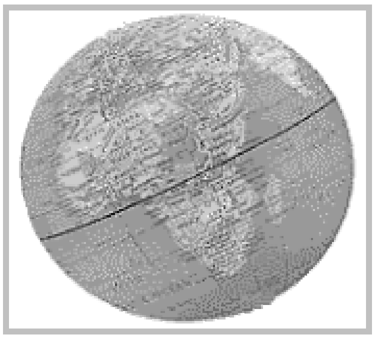


Fig. 4 – The globe

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 were first generated using these sets of high-resolution images.

All relevant setting parameters in Photomodeler were kept the same for a direct comparison between all the data sets. The required contrast on the surface and background of the test object was provided by the surface of the globe, which depicted a political map of the world, whereas the reference targets consisted of the details visible on the globe's surface (i.e. text, intersection of meridian and parallels etc.) which defined a random spread of target points over the spherical surface. A total number of 100 points was selected.

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 enhanced images over coarse images can be deduced.

	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 DEM

CONCLUSIONS

The algorithm herein described can be successfully used to improve the results attainable from digital photogrammetric applications. For many applications, DEMs produced from single left and right images in a stereo pair may not be sufficiently accurate whereas multiple images from the left and right locations could be combined by software to produce images with a greater number of pixels. Such development opens the possibilities for using either low cost digital still cameras or even analog or digital video cam-corders to obtain suitable imagery. The scope for the acceptance of digital photogrammetry is thereby widened. The notable findings from this experimentation include:

[1] 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 solve by simple interpolation methods; **[2]** The amount of noise in the low-resolution images proportionally affects the precision of the resultant enhanced image. However, the precision 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; **[3]** 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; **[4]** The least squares solution of the system of observations 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; **[5]** 3-D measurements were improved substantially, from +/-3.2mm to +/-1.7mm when using enhanced imagery in the case of the spherical surface described in section 8.

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