Enhancement of Image Resolution in Digital Photogrammetry

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Abstract

In recent years, considerable developments have occurred in the field of digital photogrammetry. These have been due mainly to increases in computing power, the refinement of feature- and area-based image matching algorithms and the reduction in the cost of equipment capable of producing near real-time images in digital format. A major limitation to the widespread application of digital photogrammetry concerns the small format size of the CCD sensor itself and, consequently, the number of pixels on the sensor being limited in number. Much time and effort has been expended trying to improve coverage through hardware solutions such as producing imaging sensors with increased numbers of pixels. An alternative software solution is offered in this paper. An algorithm which combines several digital images, the photogrammetric technique of area-based image matching, and a rigorous mathematical solution to increase the effective number of pixels is described. The resolution of the final composite image is enhanced relative to its constituent images.

Introduction

Photogrammetry is a discipline which has derived benefit from the developments in digital technology. Methods and techniques are continually being devised to take advantage of emerging technologies, and new and diverse applications are being undertaken which were not feasible with traditional photogrammetric techniques.

The advancement of digital image technology and digital photogrammetry has been of benefit to applications in a wide range of fields, including industrial measurement, archaeological, architectural, astronomical, medical, GIS updating, close-range and aerial mapping, and forensic applications. Industrial measurement applications are diverse, ranging from the measurement of the surfaces of aircraft wings and wind turbine blades (Robson and Setan, 1996), the characteristics of train body surfaces (Kochi *et al.*, 1996) to reverse engineering from physical models (Petran and Krzystek, 1996). Medical applications use images not only from CCD cameras, but also from x-rays and other medical imaging sensors. Examples of such applications include the measurement of the changes to soft tissue after facial surgery (Gabel and Kakoschke, 1996) and the verification of the position of teeth during and after orthodontic treatments (Höflinger, 1996).

Virtual reality environments are being modeled from real scenes using digital photogrammetry and, coupled with data from laser scanning, are being used for industrial, medical, and training applications (El-Hakim *et al.*, 1996). Forensic imaging may involve the analysis of existing imagery such as old photographs which are digitized and then processed using image enhancement and recognition techniques to investigate crimes (Robertson, 1998).

New applications of digital photogrammetry are being reported at an increasing rate. Many applications, particularly close-range, require the speed and on-line capabilities of analog CCD cameras, or the portability and flexibility of digital still cameras. The main objective of digital photogrammetry remains the same as that of traditional film-based techniques: to obtain accurate spatial information about remotely sensed objects. Unfortunately, digital cameras with high numbers of pixels are expensive and inaccessible to many users. Often, a cheaper camera with a smaller format, and less pixels, will be used. If the same object area is captured, the resulting image may be at a lower than desirable resolution, compromising the eventual accuracy for the re-creation of the object. Areas where digital photogrammetry can be efficiently used are often limited by the resolution of the imagery. The resolution can also affect the visual quality of the results and the precision of classifications made from the imagery. This limitation has been noted by several researchers (for examples, see Uffenkamp (1993), Wong and Obaidat (1994) and Motala (1997)).

Review of Image Enhancement Literature

The objective of image enhancement is to produce an image which is more suitable for an application than the original image (Gonzalez and Wintz, 1987), thus improving the original image to give better visualization (Weeks, 1996) or increased accuracy in classifications or measurements.

Hardware and software solutions are the two ways this enhancement can be achieved. Hardware solutions to produce enhanced resolution include increasing the size of the sensor, increasing the number of pixels (photosites) on the sensor, decreasing the pixel size, and modifying a camera to move the sensor by known amounts. Software solutions include using one or more low resolution images to interpolate or solve for a higher resolution image when there are initially unknown amounts of shift between images.

Hardware Solutions

There have been many investigations into medium- and high-resolution cameras which are commercially available and, as previously mentioned, are relatively expensive (Bösemann *et al.*, 1990; Luhmann, 1990; Maas and Niederost, 1997). Peipe (1995) presented an investigation of the Kodak DCS460, which is a digital still camera with a 3000 by 2000-pixel sensor. The

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camera was found to be suitable for off-line single-sensor applications and the relative accuracy achievable was on the order of 1:180,000. Maas and Niederost (1997) described CCD sensors as very accurate devices, but noted that there was an inherent lack of stability in the lenses, camera bodies, and mounts of digital cameras because they are not produced for photogrammetric applications. This instability can degrade the absolute accuracy of measurements made from images acquired using digital cameras.

Investigations into hardware techniques which have modified cameras to produce high-resolution digital images are much fewer in number. Godding and Woytowicz (1995) described a system of providing a digital back for a Rollei film camera, with a sensor resolution of 2048 by 2048 pixels, which could achieve relative accuracies of 1:150,000.

Lenz and Lenz (1993) described a method based on the accurate movement of the CCD array at a sub-pixel level and referred to this method of resolution enhancement as micro-scanning. Micro-scanning is the process of acquiring a number of partial images, which are shifted in two dimensions by fractions of a pixel. Another method described was referred to as macro-scanning, which involved mosaicking patches of digital imagery, thus producing a larger digital image at the same resolution as the original images. These methods can be combined and used simultaneously, which occurs in the ProgRes 3000 camera (Lenz and Lenz, 1993, p. 59). The CCD chip is actually moved inside the camera left-to-right and up-and-down by increments as small as 3 μm to capture multiple images of a static object. These are integrated to give a higher resolution image, but the cost of adding the electronic drive system to move the array is high.

Uffenkamp (1993) developed a high-resolution scanning camera using a motorised tilting and turning device, with the aim of providing a robust, fast, and accurate image acquisition device. The notion behind the development was that the resolution of a digital camera could be increased if static objects were recorded sequentially with partial images at known relative positions to one other. The images were recorded at several stations. The accuracy achieved in the presented test case was on the order of 1:60,000 of the size of the object relative to the object distance.

The Pixera Pro camera (Reis, 1997) uses a magneto-optical effect found in special glass to achieve accurate shifts in the direction of light rays through the lens system, such that the scene can be positioned onto four different areas of the sensor. Each of the four horizontal and vertical movements is either a half or a single pixel in magnitude, to an accuracy of 0.25 to 0.35 μm. This is used to create an image with an apparent resolution four times greater than the resolution of the sensor.

Software Techniques for the Enhancement of Image Resolution

There have been several approaches to the problem of image enhancement which utilise software to process the imagery after acquisition. Jensen and Anastassiou (1995) presented a non-linear interpolation scheme for enhancing the resolution of digital still images by determining edges within the images to sub-pixel level. This method is very specific in the type of images it can be used to enhance. Jensen intended this method to be used in conjunction with other methods of image resolution enhancement.

Long *et al.* (1993) presented a method for generating enhanced resolution radar images of the Earth's surface using spaceborne scatterometry. Although the data being enhanced were different from the usual images used in photogrammetry, the strategy is still applicable and noteworthy. The method was based on an image reconstruction technique which utilised the spatial overlap in scatterometer measurements made at different times. The limit to the final resolution was determined by a combination of the noise level in the observations and in their overlap. A notable point raised by Long *et al.* (1993), was that noise in the refined images increased as the resolution was improved. This is a problem which has to be closely monitored and precisely modeled in resolution enhancement techniques to ensure the enhanced image has not suffered any degradation in accuracy.

Wiman (1992) presented a method in which a scanner was used to acquire several images of an aerial photograph at known subpixel translations from the first image. Equations linking the images were set up with the unknowns representing the values of the pixels of a combined, higher resolution image. The unknowns were determined using a pseudo-inverse method of solution, because the system of equations was underdetermined. Wiman did not pursue the experimentation after initial results were inconclusive, because the system of equations which were developed could not be accurately solved.

Many resolution enhancement algorithms use interpolation to create a higher resolution image from either a single low-resolution frame or multiple frames. This can be noted in several methods previously mentioned, and also in the work presented by Gavin and Jennison (1997), which used a Bayesian interpolation approach. There are several common methods of image interpolation, including nearest-neighbor interpolation, bilinear interpolation (Schalkoff, 1989), pixel replication, and cubic convolution (or curve fitting) interpolation (Rabbani, 1995).

Schultz and Stevenson (1996) presented a Bayesian interpolation method which utilised both the spatial and temporal information in a sequence of video images. Motion estimates were used to determine the pixel displacements between frames, and it was noted that the quality of those shifts would directly affect the quality of the enhancement. With only a single frame, this problem is ill-posed; however, with several images a unique solution can be found. This algorithm incorporates independent object motion within the video sequence and gives a better estimate of the higher resolution image than do single frame interpolation methods, provided the object motion had subpixel shifts. The most critical aspect of the algorithm was the accurate estimation of motion.

A method which has taken into account the blurring in images due to non-zero aperture time was presented by Patti *et al.* (1997). The technique was developed to utilize the ability of new frame grabbers to acquire multiple images; therefore, multiple frames could be used to overcome the limitations of low-resolution imagery. This method included de-interlacing video images and removing acquisition degradations. It consisted of three basic components: motion compensation, interpolation, and the removal of blur and noise. Motion compensation was used to map pixels from all low-resolution frames to a common reference frame and interpolation was used to map the information onto a high-resolution grid. An experiment was performed using digital camera equipment to acquire six 130- by 147-pixel low-resolution images. The algorithm increased the image resolution by a factor of two.

Other image processing methods are 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 images, they do not increase the resolution of the images. Some of these methods include edge enhancement, noise reduction, and blur removal. For examples of these methods, see Gonzalez and Wintz (1987), Schalkoff (1989), Pandit and Joshi (1994), Weeks (1996), Aldave-Matar and Ley-Koo (1996), and Atkinson and Curran (1997).

Summary of Enhancement Techniques

The hardware and software techniques discussed above involve many different aspects of image processing, including image registration and image fusion. It is important to acknowledge the diverse approaches and methodologies which have

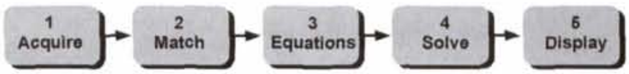

Figure 1. Schematic flowchart of an algorithm to enhance image resolution.

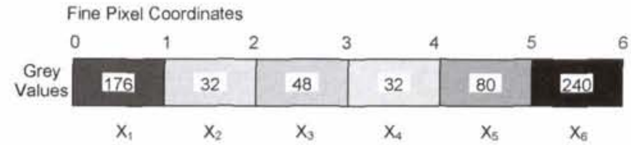

Figure 2. A section of a higher resolution or known "true" image.

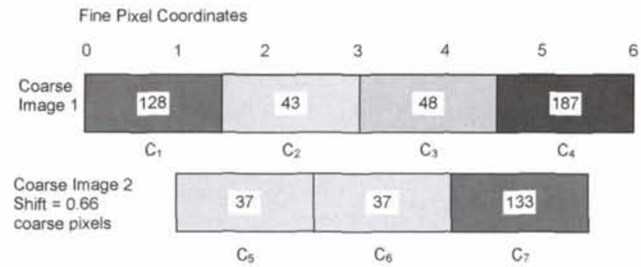

Figure 3. Two coarse (low-resolution) images of Figure 2.

been developed for a range of tasks in image processing. The approaches to resolution enhancement included modifications to the cameras used for image acquisition, and software methods which processed or interpolated lower resolution images to create images of higher resolution.

The resolution of digital images has a direct effect on the quality of photogrammetric results, so, because the format size of the sensing arrays in digital cameras continues to increase, it is important that any software algorithm developed to enhance resolution must be *device independent*. This will allow even the high-resolution images from sensors with large format areas and with many photosites to be improved and will ensure the longevity and applicability of the algorithm. The image enhancement procedure described in this paper produces a higher resolution image from several overlapping, and slightly offset, images of lower resolution.

Algorithm Development

Figure 1 shows the general steps which must be undertaken during the resolution enhancement process. The method determines the shifts and rotations between the low-resolution images using least-squares area-based matching. The enhancement factor can be up to but not equal to two, due to a limiting factor which has been derived from sampling theory and is known as the Nyquist frequency (Russ, 1995). The steps in the algorithm are as follows:

- Collect several low-resolution images. Select an enhancement ratio (range 1.1 to 1.9). This determines the size of the higher resolution pixels and depends on the number of coarse images available.
- Determine pixel offsets of each image from the first using least-squares area-based image matching.
- Form sets of equations using the offsets as coefficients, the enhancement ratio, and the grey levels from the low resolution images as observations.
- Solve for higher resolution pixels.
- Display the resultant higher resolution image.

Image Matching

Image matching is a fundamental component of the algorithm for the enhancement of low-resolution images. The shifts between images is a key component in the formulation of the equations relating coarse and fine pixels. There are two main methods of image matching: feature-based matching and area-based matching. Each method has its advantages and may be applied in different ways and in different situations.

Feature-based matching involves the detection of distinct features in an image, the description of these features in mathematical terms, and a decision as to whether two descriptions refer to the same element in the images being matched. Area-based matching involves finding the point of best correlation between corresponding windows in the images which are being matched. This method also determines the amount of translation and rotation between two images, is more accurate than feature-based matching, and is therefore better suited to photogrammetric applications requiring higher positional accuracy such as object reconstruction. However, feature-based matching is usually faster and more reliable and is more likely to find a match with poor *a priori* orientation values.

One strategy for area-based matching is to adopt a least-squares solution for the parameters involved in the matching process. Least-squares matching can overcome difficulties arising from radiometric differences in the images being matched and can achieve sub-pixel accuracies of approximately 0.1 pixel. Note that target centroiding accuracies to 0.01 pixels have been reported in industrial situations using high-contrast targets, a factor of 10 times better than is possible when using "natural" features.

The Algorithm in One Dimension

A one-dimensional case is detailed below to show the fundamentals of the algorithm, before two-dimensional data sets are considered, as the complexity of the two-dimensional situation is significantly greater than that found in the one-dimensional case.

Consider just six pixels from a line in the "true" (or higher resolution) image we wish to find: (see Figure 2). The X_i values in Figure 2 represent the unknown grey-scale values of the high-resolution pixels which will be found from a least-squares solution. Consider the determination of these unknowns from two coarse images. Let the coarse:fine ratio be three:two (i.e., three fine pixels are equivalent in length to two coarse pixels) (see Figure 3). Coarse image 2 was found by shifting the starting point of the sampling, thus producing the coarse pixels C_5, C_6, and C_7. Note that the grey values in the coarse images are not as high nor as low as those grey values of the finer resolution pixels. In this simple example, let the left-most fine image coincide with the left-most coarse image. The fine pixel coordinates are determined relative to the coarse images by area-based matching which calculates the relative shifts between the coarse images (see Figure 1).

The unit length of a fine pixel is determined by the enhancement ratio chosen. For this example, the enhancement ratio is denoted as ρ and is equal to 3:2. Each coarse pixel may be related to several fine pixels. The proportion of a coarse pixel which influences the grey level of a fine pixel is the factor used in the coefficient matrix in the observations equations. In this manner, an observation equation can be found for each coarse pixel. The pixels in Coarse Image 1 are represented as

C_1, C_2, C_3, and C_4 and the pixels in Coarse Image 2 are represented as C_5, C_6, and C_7 for the purposes of this example. Consideration of the proportion of the fine pixel that the coarse pixel covers and the enhancement ratio provides observations equations as follows:

$$\begin{aligned} C_1 &= (X_1 + 1/2\, X_2) * \rho^{-1} \\ C_2 &= (1/2\, X_2 + X_3) * \rho^{-1} \\ C_3 &= (X_4 + 1/2\, X_5) * \rho^{-1} \\ C_4 &= (1/2\, X_5 + X_6) * \rho^{-1} \\ C_5 &= (X_2 + 1/2\, X_3) * \rho^{-1} \\ C_6 &= (1/2\, X_3 + X_4) * \rho^{-1} \\ C_7 &= (X_5 + 1/2\, X_6) * \rho^{-1} \end{aligned} \tag{1}$$

These observation equations are then solved using least squares. The system may be represented as

$$\mathbf{C} = \mathbf{A}\,\mathbf{X} \tag{2}$$

where **C** contains the grey levels of the coarse pixels, **X** are the required grey levels of the fine resolution pixels, and **A** is the matrix of the coefficients. In this case,

$$\mathbf{A} = \rho^{-1} \begin{bmatrix} 1 & 1/2 & 0 & 0 & 0 & 0 \\ 0 & 1/2 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1/2 & 0 \\ 0 & 0 & 0 & 0 & 1/2 & 1 \\ 0 & 1 & 1/2 & 0 & 0 & 0 \\ 0 & 0 & 1/2 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1/2 \end{bmatrix}$$

$$\text{and } \mathbf{C} = \begin{bmatrix} 128 \\ 43 \\ 48 \\ 187 \\ 37 \\ 37 \\ 133 \end{bmatrix} \tag{3}$$

The solution to this set of equations is

$$\mathbf{X} = [\mathbf{A}^T\mathbf{A}]^{-1} * \mathbf{A}^T\mathbf{C} = [176, 32, 48, 32, 80, 240]. \tag{4}$$

Several obvious assumptions have been made at this point, such as all the pixels being adjacent. In reality, the values of the grey levels of the pixels are discrete and non-contiguous. Showing them as adjacent is for descriptive purposes only. Other important considerations, such as precision assessment, radiometric correction parameters, lens distortions, and other phenomena, which produce differences in real images, have been excluded here, but may be included in a refined mathematical model.

It should be emphasized that the relationship between the fine pixels and the coarse pixels is *not simple nor direct*, and is *not capable of simple interpolation*. The values of the fine pixels can only be solved for by the equations set out above. It is not possible to solve for each fine pixel by using their size relative to that of the coarse pixels, i.e.,

$$X_1 = 2/3\, C_1 = \rho^{-1}\, C_1 \tag{5}$$

will not produce the correct result.

Figure 4. Coarse and fine images in the fine coordinate system.

Other sets of one-dimensional studies have been made, using a variety of synthetic data sources. The enhancement algorithm always produced an accurate solution for enhancement ratios of up to 1.9 (19 fine pixels : 10 coarse pixels). No solution could ever be reached at a ratio of 2.0, due to singularity of the observation equation ($\mathbf{A}^T\mathbf{A}$) matrix in the least-squares solution. The singularity is due to the number of *linearly independent* observations being less than the number of unknowns (that is, fine pixels) being determined in the system of equations.

The Two-Dimensional Situation

The two-dimensional case has many more considerations than are shown above. For example, the coefficients will be based on the average shift across an array of pixels, not a simple linear movement. The numbering system also becomes quite complicated in the setting up of the observation equations from multiple images.

The enhancement algorithm does not create an image which is larger in area than the input images; rather, it creates an image with a larger number of smaller-sized pixels over the same scene. Note that the coarse pixels may not be square and it is important to keep the aspect ratio of the original data. It is not necessary to know or provide the information on the pixel size, thus increasing the device independence of the enhancement algorithm. The coordinates of the centers of the coarse pixels can be used in the algorithm; thus, image formats with rectangular pixels can be analyzed.

The enhancement ratio, RATIO, determines the dimensions of the image in fine pixels (FINE) with respect to the dimensions of the image in coarse pixels (COARSE), such that

$$\text{RATIO} = \frac{\text{FINE}}{\text{COARSE}} \qquad \{=3/2 \text{ in Figure 2}\} \tag{6}$$

where the ratio must be less than two, as required by the Nyquist limiting factor. The ratio is used as a factor which is applied to the coarse pixels to determine the boundaries of all pixels with respect to the fine-pixel coordinate system. Figure 4 shows a simple case of a ratio equal to 3/2, with the coordinates on the arrays illustrating the fine-array coordinate system in rows and columns.

To develop the observation equations, each pixel in the coarse images must be related to the fine-pixel coordinate system, thus determining which fine or unknown pixels are affected by each individual coarse pixel. For the example in Figure 4, the upper left-hand coarse pixel C(1, 1) covers the area bounded by $(0, 0) \rightarrow (1.5, 1.5)$ in the fine-pixel coordinate system. 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

$$\begin{aligned} C(1,1) = \{&F(1,1) + 0.5^* F(2,1) + 0.5^* F(1,2) \\ &+ 0.25^* F(2,2)\}^* \text{RATIO}^{-2} \end{aligned} \tag{7}$$

Figure 5. Four coarse images (top row), the resolution enhanced composite AMANDA (lower left), and a simple averaged image (lower right).

where F(1,1), F(2,1), F(1,2), and F(2,2) are the unknown fine pixels. This process is completed for each coarse pixel to build up the matrix of coefficients in the observation equations, which can be solved using a least-squares method of solution.

In the case shown in Figure 4, there is a 3- by 3-pixel array of unknowns which requires several 2- by 2-pixel arrays of coarse images to find a solution. Each pixel in each coarse image would contribute a row to the **A** and **C** matrices of the system of equations; thus, the number of rows in the **A** matrix will equal the number of pixels in the coarse images multiplied by the number of images used. The number of pixels in the fine image determines the number of unknowns, which determines the length of the **X** vector and the number of columns in the **A** matrix. In the above example, to solve for the 3- by 3-pixel array requires an **X** vector with nine elements to be solved, requiring at least nine observations for a solution. Therefore, three coarse images would be required for this example. To solve for a higher enhancement ratio, more coarse images would be required.

An example of the effectiveness of this algorithm can be seen in Figure 5. This is the general two-dimensional case. The four coarse images of the young woman's face have been combined to produce the higher resolution image. There are grey levels in the finer resolution image which are higher, and others which are lower, than in any of the four coarse images.

Interpolation techniques may be used to produce an image with a higher resolution. An image was produced using one of the simplest methods, that of averaging the nearest pixels to produce the new grey value. The result of the interpolation has been shown in the lower right in Figure 5, with the high resolution image produced using the enhancement algorithm shown to its left. The difference in visual quality of the results can easily be distinguished. The averaged image does not contain the brightness nor darkness of the enhanced image, instead having a blurred appearance.

Precision Studies Using Synthetic Images

Figure 5 (lower left) shows the original image from which the AMANDA data set was manufactured. Figure 6 shows the result when random noise based on a standard error of ± 7 grey scale levels (maximum range 0 to 255) was added to the grey scale values in each of the coarse images. From this and several other tests, a correspondence between the noise in the input images and the precision of the result was observed. There was a progressive worsening of results as the noise in the images increased. It can be concluded that the algorithm is sensitive to noise in the input images.

Figure 6. Seven sigma noise.

Another series of precision tests used various levels of random noise and solved for the enhanced image across a range of enhancement ratios. These tests indicated that the accuracy of the enhancement was affected not only by the level of noise present in the images, but also by the enhancement ratio being applied. As the enhancement ratio increased, the accuracy of the enhancement was increasingly degraded, most significantly after a ratio of 1.6. Thus, it may be prudent to limit the ratio of enhancement to that of 1.6 or less, depending on the amount of noise present in the images.

A positive result of the testing of the AMANDA data set was the strong confidence which could be placed on the matching

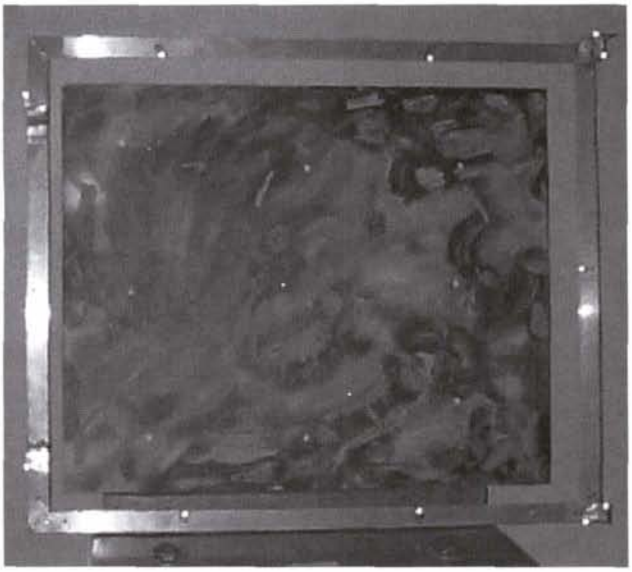

Figure 7. Test object and control frame for PLATE data set.

algorithm which determined the offsets between the synthetically generated coarse images. These relative shifts between images are used as coefficients in the observation matrix and it is important that they be accurately determined. Even with images severely degraded by noise, these shifts were determined to well within ±0.1 pixel.

Accuracy Tests with Real Data

The synthetically generated data sets provided an avenue for the testing of the performance of the resolution enhancement algorithm with respect to varying enhancement ratios, numbers of images, and noise in images under controlled conditions. To test the algorithm's effectiveness as a photogrammetric tool, it was used in a series of 3D tests using images of objects with known geometry, specifically, a flat plate and a cylinder.

Stereoscopic sets of left and right images were taken of these objects, and digital elevation models (DEMs) were created using both the original images and images enhanced by the algorithm. The proprietary digital photogrammetric software known as Virtuozo (Zhang, 1996) was used to generate the DEMs. The results for each DEM were analyzed to give a comparison of the accuracy of the DEM generation between the enhanced and original images. All relevant parameters in Virtuozo were kept the same to ensure that a direct comparison could be made between the two data sets. The grid interval for the DEM creation was set at 1 millimeter in object space.

PLATE Data Set

The test object for the PLATE data set, a flat plate with dimensions of approximately 600 by 500 millimeters, is shown in Figure 7. For any image matching algorithm to work effectively, there must be varying levels of grey on the object. The surface of the plate was coated with swirling painted colors to ensure that the image matching process was as effective as possible.

The control frame which was used is also shown in Figure 7. The control points were retro-reflective targets on a sturdy metal frame. A diffused flash was used during image acquisition to best utilize the properties of the retro-reflective targets while, at the same time, not over-illuminating the rest of the object and saturating areas of the sensor.

The camera used to acquire the imagery was a Logitech Fotoman, a common digital still camera, which has a CCD sensor

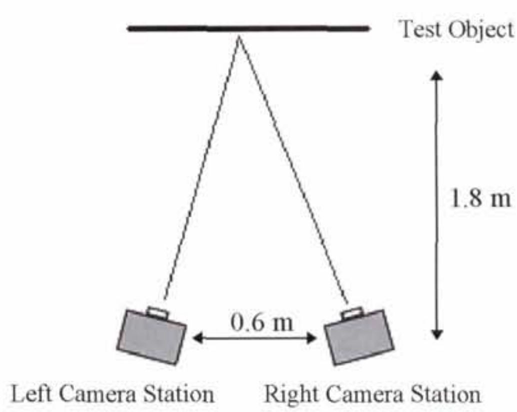

Figure 8. Plan view of experimental setup.

TABLE 1. HEIGHT DATA FROM DEM FOR PLATE DATA SET

Height Data	Original Data (Millimeters)	Enhanced Data (Millimeters)
Z minimum	1773.5	1782.3
Z maximum	1873.8	1824.7
Average	1801.6	1801.3
RMS diff. from plane	4.76	3.86

with 768 by 512 pixels. It must be emphasized that the individual size of the photosites is not a concern (they are approximately equal in size to those on a very expensive digital camera); rather, it is the relatively low total number of pixels per image which this algorithm addresses. For calibration information of this camera, see McIntosh (1996).

The set up of the camera stations included an object distance of 1.8 m and a base length of 0.6 m, slightly convergent as shown in Figure 8. At each camera station, six images were acquired, with each image center slightly shifted, by less than 3 millimeters, in a plane parallel to the object. The tripod allowed these adjustments to be made to the position of the camera without disturbing its orientation. Therefore, all six image centers would lie on one plane, with no rotation around the direction towards the object.

To reduce computation time, the images were cropped to show only the test object and the control frame. The effects of lens distortion were minimized by ensuring that the area of interest was in the center of the image, where lens distortion was at a minimum (McIntosh, 1996). The dimensions of the final low-resolution images used were 332 by 392 pixels. The enhancement ratio for these experiments was 1.5; thus, a fine image of 498 by 588 pixels was determined.

A comparison of 208,000 grid points (grid size 520 by 400) from each DEM was made to deduce if the enhancement of the resolution of the digital images had increased the accuracy of the determined surface models. Table 1 shows the result of fitting a planar surface of best fit to the DEMs. Note that the plane of the plate was surveyed as being 1800 mm away from the cameras. This value was averaged closely by each set of data, with the surface generated from the original data sets showing more variations compared to the enhanced data set, as indicated by the maximum and minimum Z values and the root-mean-square of the closeness of fit in Table 1.

A further experiment was conducted with the imagery for the PLATE. Using an interpolation method based on the nearest-neighbor principle, a stereopair was formed from the low-resolution images which contained exactly the same number of

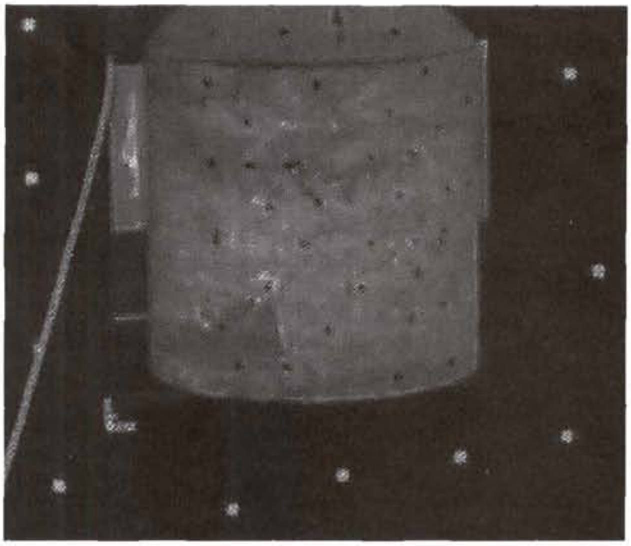

Figure 9. Enhanced image of CYLINDER data set.

pixels as those produced by the enhancement algorithm. A DEM was generated and was compared to the known surface, and the important finding was that the results were virtually identical to those of the original low-resolution images. Using interpolated imagery does not improve the accuracy of results. The interpolation process did not provide any new, *independent information which could improve the determination of the surface.* The extra data which interpolation provides is dependent on the original data from one image, whereas the enhancement algorithm provides new information by combining several of the original low-resolution images, thus producing independent information.

It can be concluded that, by using the resolution enhancement algorithm, the accuracy of this digital photogrammetric application has been improved by approximately 20 percent.

CYLINDER Data Set

Further testing of another geometric surface was conducted to validate the improvement in 3D accuracy of applications using digital photogrammetry when enhanced imagery has been utilized. A cylinder with a radius of 75 millimeters and a central axis length of 180 millimeters was manufactured and used as a test object, following the same procedure as described for the PLATE data set.

Significant experimentation was undertaken to optimize the environment for image acquisition. Contrast was required on the surface of the test object and was achieved by projecting a color satellite image from a slide projector, set up at close range. No overhead lighting was used and the flash of the digital camera was diffused so as to not wash out the projected pattern.

Images of the cylinder were acquired as stereo-pairs, with approximately the same configuration as for the previous experiment. The images were cropped to 246 by 288 pixels, and the enhancement was processed using a ratio of 1.5, with a resultant image shown as Figure 9.

Processing the coarse and enhanced images of the cylinder in Virtuozo produced digital elevation models (DEMs) over the area of interest. Using the entire area of the DEM available over the cylinder, the radius determined from the enhanced images was 74.3 millimeters, compared to 81.0 millimeters derived from the DEM using the coarse images (see Table 2).

The reduction in the value of the root-mean-square of the residuals from 7.15 mm using an original pair of images to 1.69 mm for an enhanced pair was outstanding. This conclusion again verified the validity of the enhancement algorithm, and indicated its potential for use for photogrammetric surface modeling.

Table 2. Results of Surface Fitting for CYLINDER Data Set

Cylinder Data	Original Data	Enhanced Data
Radius	81.0 mm	74.3 mm
RMS of Residuals from 75mm radius cylinder	7.15 mm	1.69 mm

Further Research

As a result of undertaking research into the algorithm for image resolution enhancement, several other issues and ideas which could be the subject of further research were revealed. These have not yet been fully investigated, but deserve consideration.

There are several constraints presently on the algorithm which must be overcome to ensure its generality and applicability to a wider range of operating environments. Issues which require further investigation include

- the incorporation of a rotation parameter into the matching procedure, thus lifting the requirement for all images to be tightly controlled with no angular movements;
- the addition of a scale parameter so that some images may be obtained at a different object distance;
- the incorporation of the structure of the array sensor into the algorithm, so as to account for the aperture size at each photosite;
- the utilization of alternative registration methods to accommodate scenes which do not have strictly defined edges or control points; and,
- the modification of the program for use with color images.

The algorithm as it is presently implemented has also assumed a stationary object with a camera or scanner which is moved slightly between frame capture. A logical extension is to review the effect of using stationary cameras for dynamic scenes.

Consider the first of these areas for future investigation, the matter of rotated images. There are at least three distinct methods of approaching this problem. The image matching algorithm could solve for a rotation angle between images. The mapping of the mesh of fine pixels over the low-resolution coarse pixels would immediately become more complex, because the contribution to each fine pixel from each coarse pixel must be calculated.

Alternatively, the rotation angle could be found by re-formulating the observation equations and making the rotation angle an unknown. A third solution to accommodate rotated images could be an image processing method, where pre-processing the rotated image would be performed to resample the image to a non-rotated coordinate system. Such a technique may introduce more uncertainty into the resolution enhancement model, because the grey values being used as observations would not be the original values. There is already an amount of imprecision in the original images due to noise in the image acquisition process, and resampling the images would increase this uncertainty. This example has been provided to indicate that even the simple suggestions for improvements require considerable further research.

Conclusion

Digital technology has been of great benefit to photogrammetry, with some of the most labor intensive aspects of the photogrammetric operator's role eliminated. To improve the accuracy of digital photogrammetry, it is axiomatic that image resolution must be improved. Hardware improvements in the form of increased sizes of CCD arrays are continuing to occur, but these larger arrays are expensive. Modification to digital cameras which move the sensor by pre-determined sub-pixel amounts have been developed but are also expensive to implement.

A software solution for image enhancement which *is device independent* has been proposed in this paper. It can improve image resolution by up to a linear factor of two, irrespective of the camera system which captured the multiple images. An important point is that the relationship between the fine pixels in the enhanced resolution image and the original low-resolution pixels is neither simple nor direct, and therefore cannot be solved for by simple interpolation.

The application of the enhancement algorithm has been demonstrated on images for visualization purposes, and on two geometric surfaces for photogrammetric measurements. The notable findings from the experimentation include

- the matching algorithm accurately determined the relative shifts between images of gradually varying grey values;
- the amount of noise in the low resolution images proportionally affects the precision of the resultant enhanced image;
- the enhancement ratio affected the quality of results, with degradations being especially noticeable when the applied ratio was higher than 1.6;
- the precision of the result can be improved by using more than the minimum number of coarse images required to find a solution; and
- 3D measurements were improved by approximately 20 percent when using enhanced imagery.

Further work and investigation is required into this area of research, especially with respect to such issues as enhancing color images and the case of stationary cameras and moving objects.

Future applications could include mapping architectural facades with a camcorder, security and surveillance applications, medical applications, and the enhancement of satellite imagery. This algorithm may be utilized for any application where a higher resolution is desired than has been achieved previously, as long as multiple images with sub-pixel shifts are available. Image acquisition devices which could be used include video recorders and digital video cameras. Applications for enhanced imagery suggested by Schultz and Stevenson (1996) include improved definition television (IDTV) and preprocessing for image or video analysis.

The experimentation described in this paper has shown that the algorithm can be successfully used to improve the results obtainable from digital photogrammetric applications. For many applications, DEMs produced from single left and right images in a stereopair may not be sufficiently accurate whereas multiple images from the left and right locations could be combined by software to produce images with up to four times the number of pixels. Such a development widens the scope for the acceptance of digital photogrammetry.

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