APPLICATION OF RESOLUTION ENHANCEMENT ALGORITHM TO CLOSE-RANGE SURFACE MODELLING

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ABSTRACT

The enhancement of digital images is a research topic which is being reported with increasing frequency in image and signal processing journals. The applications in which these algorithms are being used include medical imaging, industrial applications and for the conversion of video images to high-definition television (HDTV) format.

The purpose of this paper is to present the results of a practical close-range application of an algorithm used to enhance the resolution of digital images. Several images of low resolution were combined to form a higher resolution image. The technique involved using a combination of area-based matching to register the images with respect to one another and a rigorous mathematical model to form the new image. Digital terrain models were generated over a test object using both raw digital images and those enhanced by the algorithm. The resulting surface models were compared for three dimensional accuracy. The experimentation had to take many factors into consideration, including control points, illumination and texture of the object surface to optimise the results from the image matching.

Further discussion is presented on the future research directions for refining this algorithm, including alternative matching algorithms and the incorporation of additional parameters into the enhancement model.

1. INTRODUCTION

Digital photogrammetry can be a fast, efficient and cost effective method of obtaining three dimensional information, depending on the requirements of the application to which it is being applied. The automation in digital photogrammetry reduces the amount of manual labour required from the traditional stereo-plotter operator. Digital photogrammetry will not fully replace traditional photogrammetry due to the many limitations which have not yet been overcome. More likely, the two technologies will be integrated to take advantage of the best points of each. This integration will continue until digital methods can provide sufficient accuracy at a reasonable cost.

The limitations to digital photogrammetry include the need to store large amounts of digital data, insufficient or overly expensive computing power, the expense of acquiring images at sufficient resolution, and insufficient accuracy for the requirements of the application. Many of these hurdles have been overcome with modern technology, but still require further improvements before traditional photogrammetric methods will be completely superseded (Saleh, 1996).

Imagery for digital photogrammetric applications can be acquired in several ways, including from digital still cameras and analog video cameras in combination with a frame grabber. The accuracy achievable in an application is related to the resolution of the digital imagery used. The lower the resolution of the imagery, the lower the level of accuracy attainable. Depending on the requirements of the application, the resolution also affects the visual quality of the results and the precision of classifications made from the imagery. This limitation has been noted by several researchers, including Motala, 1997; Uffenkamp, 1993; Wong and Obaidat, 1994, and is the subject of investigation by the authors of this paper.

Scanning images from film is an alternative method of digital image acquisition, with unique considerations and limitations, such as film distortions, scanner distortions and processing time from film to digital form. Scanning is regularly used in applications such as mapping from aerial photography. Despite many improvements in scanning technology, the quality of scanned images does not yet equal the quality of aerial photographs (Kölbl and Bach, 1996).

Many applications, particularly close-range, require the speed and on-line capabilities of analog video cameras, or the portability and flexibility of digital still cameras. However, digital cameras with high resolution sensors are expensive and inaccessible to many users. Often, a lower resolution camera is used rather than one which would produce the best results for the application. Thus the accuracy achievable is also reduced.

1.1 Scope of Research

After noting the limitations of digital photogrammetry which are imposed by insufficient resolution in the imagery, it was concluded that an inexpensive method of attaining high resolution imagery was required. An algorithm was developed to use several low resolution images captured by an inexpensive digital camera. These images were combined to produce a higher resolution image. The algorithm was based on a model of a static scene with a dynamic or portable camera, thus allowing small shifts between each of the low resolution images. This provides the basis of the solution of the algorithm presented.

This paper firstly presents methods of resolution enhancement of digital imagery as reported by other researchers. There are an increasing number of hardware and software solutions becoming available to enhance image resolution.

The resolution enhancement algorithm developed by the authors is described and applied to a close-range application. Digital photogrammetry was used to create a digital terrain model (DTM) of a test object using original digital images and images enhanced by the algorithm. The accuracy of each DTM was analysed and compared. Over 200,000 points from each DTM were used in the comparison to deduce if the enhancement of the resolution of the digital images had increased the accuracy of the determined surface models. Factors of the experimentation which were taken into consideration included control points, illumination, image enhancement and DTM creation. A description of future research directions is also presented.

2. RESOLUTION ENHANCEMENT OF DIGITAL IMAGES

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). The difference between enhancement and restoration is that restoration is a means of modifying the image so it becomes how it appeared originally. Enhancement is trying to improve the original image to give better visualization (Weeks, 1996), or accuracy in classifications or measurements.

The enhancement being investigated in this paper is that of determining higher resolution images. Hardware and software solutions are the two main ways this enhancement can be achieved. Hardware techniques include increasing the size and number of pixels of 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.

2.1 Hardware Techniques

There have been many investigations into medium and high resolution cameras which are commercially available and, as previously mentioned, relatively expensive. Kochi (*et al.*, 1995) reported the development of a measurement system using a high resolution camera with sensor dimensions of 4096 x 4096 pixels. The system is modular, including image acquisition, measurement and calibration software. Peipe (1995) presented an investigation on the Kodak DCS460, which is a digital still camera with a 3000 x 2000 pixel sensor. The camera was found to be suitable for off-line single sensor applications and the relative accuracy achievable was in the order of 1/180,000.

Some hardware techniques have modified cameras to produce high resolution digital images. Godding and Woytowicz (1995) described a system of providing a digital back for a Rollei film camera, with a sensor resolution of 2048 x 2048 pixels, which could achieve relative accuracies of 1/150,000.

Lenz and Lenz (1993) used a method based on the accurate movement of the CCD array at a sub-pixel level and described this method of resolution enhancement as micro-scanning. Also discussed was a method termed macro-scanning, which involved mosaicking patches of digital imagery thus producing a large 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 (*ibid*, p59). The CCD chip is actually moved inside the camera left-to-right and up-and-down by increments as small as 3μm to capture multiple images of an object. These are integrated to give a higher resolution image, but the cost of adding the electronic drive system to move the array is very high (approximately US$30,000).

A relatively new invention is in the Pixera Pro camera (Reis, 1997), which 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. This is used to create an image with an apparent resolution four times greater than the resolution of the sensor.

2.2 Software Solutions

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 was 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. A least squares solution was employed, involving singular value decomposition analysis. The limit in the final resolution was determined by a combination of the noise level in the measurements and in their overlap.

A notable point raised by Long (*ibid*) 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 modelled in resolution enhancement techniques to ensure the enhanced image has not suffered any noticeable degradation in accuracy.

Wiman (1993) presented a method where a scanner was used to acquire several images of an aerial photograph at known sub-pixel translations from the first image. Equations linking the images were set up with the unknowns being the values of the pixels of a combined, higher resolution image. The grey values of the pixels in the high resolution image were determined using a pseudo-inverse method as the equation system was under-determined. Wiman did not pursue the experimentation after initial results were inconclusive as the system of equations he developed could not be accurately solved. He suggested further investigation was necessary before definite conclusions could be drawn.

The image processing approach to resolution enhancement is often based on interpolation techniques. Schultz and Stevenson (1996) presented a Bayesian interpolation method which used 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 could directly affect the quality of the enhancement algorithm. 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.

A method which has taken into account the blurring in images due to non-zero aperture time was presented by Patti (*et al.*, 1997). This method included de-interlacing video images and removing acquisition degradations and consisted of three basic components, being motion compensation, interpolation and the removal of blur and noise. The algorithm increased the image resolution by a factor of two.

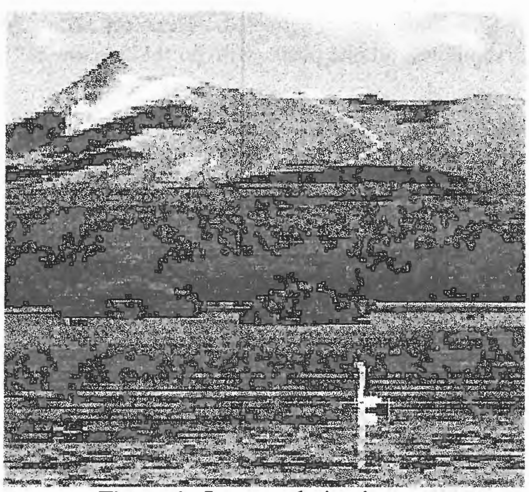

Figure 1. Low resolution image.

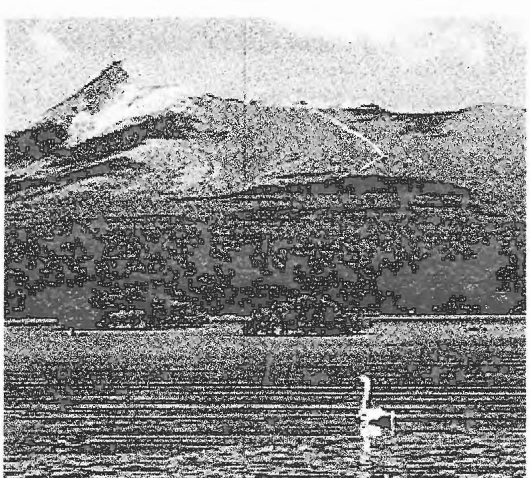

Figure 2. High resolution image.

3. RESOLUTION ENHANCEMENT ALGORITHM

The algorithm developed by the authors (for full details, see Fryer and McIntosh, 1997), combines multiple low resolution digital images of a static scene to produce a high resolution image. The method determines the shifts between the low resolution images using least squares area-based matching.

It is important to ensure that the shifts are determined as precisely as possible. To take into account any distortions or variations which may occur in the images, a method was developed where the shifts between images were determined at intervals over the image. This approach was similarly followed by Althof (*et al.*, 1997).

The model uses the knowledge that the scene has not changed, however there will be slight differences between the images due to the small shifts in camera position at the time of acquisition. A least squares system of equations is developed, where the pixel values of the original images form the observations, and the values of the pixels in the higher resolution image are the unknowns.

An important point to note is that the relationship between the fine pixels and the original low resolution pixels is not simple nor direct, and therefore cannot be solved by simple interpolation.

To illustrate the concept of this algorithm, an example is shown using test data, where low resolution images have been generated from a scanned higher resolution image. By doing this, the higher resolution image is already known and can be compared to the result determined using the algorithm. Figure 1 shows one of the four low resolution images which were used to determine the higher resolution image, shown in Figure 2. The pixel size of the low resolution image is 1.5 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. Four low resolution images with known relative shifts were generated to be used as input data. The images were 200 x 320 pixels and were enhanced by a ratio of 1.5, giving a higher resolution image of 300 x 480 pixels. Although the shifts between the images were known, the images were enhanced using the shifts determined by the matching algorithm, thus showing the accuracy of the matching. The RMS of the difference between the true shifts and those found by image matching was 0.018 pixels. The precision of these matches was determined from the variance-covariance matrix of the area-based least squares matching solution. For this example, the average standard deviation of the matches was 0.004 pixels, which indicates high precision due to the large window size used in the matching.

The higher resolution pixels are the unknowns in the system of equations. The standard deviation of these unknowns can be found from the variance-covariance matrix, and was on average 0.23 grey values for this data set. The areas of overlap in the image provides another indication of the quality of the enhancement, with the average standard deviation of the overlap values being 0.09 grey values. As the higher resolution image is already known, a comparison can be made between the 'true' image and the determined image. The RMS of the difference between these two images was found to be 0.65 grey values.

The processing time taken was 6 hours and 44 minutes to solve for 144,000 unknowns, using a Pentium-100 PC and software designed to produce results for the analysis of the precision of the enhancement. A faster method can be used when precision analysis information is not required. Using the faster method, the processing time is reduced to 40 minutes. The differences in methods is further described in the Section 4.

4. EXPERIMENTATION

An experiment was devised to test the effect of the enhancement algorithm on the accuracy of three dimensional surface models (or DTMs) of a test object. The DTMs were created by digital photogrammetry using raw and enhanced images and the results compared.

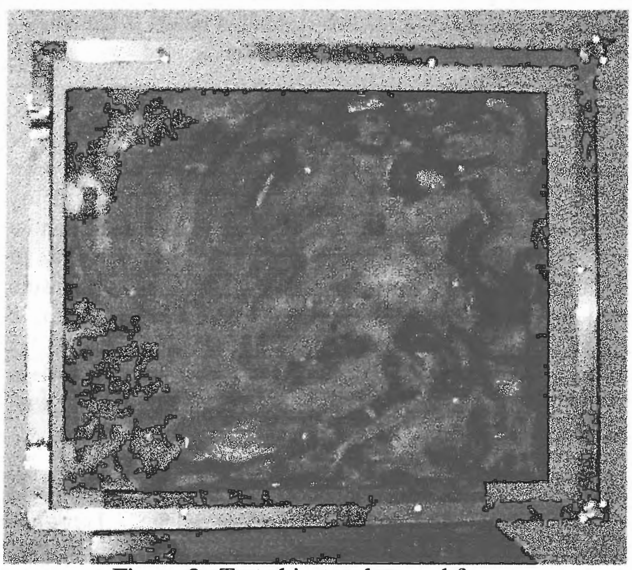

Figure 3. Test object and control frame.

The test object is shown above in Figure 3, with dimensions of approximately 600 x 500 mm. A planar surface was used to constrain the factors affecting the results from the experimentation. The contrast of the colours on the surface of the object was important to ensure the results of the image matching were precise, as the matching algorithm being used produced the best results with images of varying levels of grey. Matching algorithms suited to highly contrasted images (*ie* near to black and white) are being investigated.

The control frame which was used is also shown in Figure 3. The control points were retro-reflective targets on a sturdy metal frame, which had been coordinated previously by a fellow researcher. As the control frame was separate from the test object, care was taken to ensure no movement occurred between acquisition of images.

A diffused flash was used during image acquisition to best utilise the properties of the retro-reflective targets. A balance had to be found between the bare flash and diffuse lighting. The bare flash would saturate areas of the image, producing large white areas while over-illuminating the rest of the object, whereas the diffuse light did not take advantage of the retro-reflective properties of the targets.

The digital still camera used to acquire the imagery was a Logitech Fotoman, which had a CCD sensor with 768 x 512 pixels. For the calibration information of this camera, see McIntosh (1996). The camera had an in-built flash and on-board image storage, both of which were utilised in the experimentation.

The aim of this experiment was to use digital photogrammetric methods to determine a DTM of the test object using low resolution images and enhanced resolution images. Therefore, the imagery needed to be convergent. The set-up of the camera stations was with an object distance of 1.8m and a base of 0.6m. An adjustable tripod was used to mount the camera in position at the two camera stations. At each station, six images were acquired, with each image slightly shifted (less than 3mm) in the X and Y directions, while keeping the axis of the camera parallel to the initial Z direction, as illustrated in Figure 4. Therefore all six image centres should lie on one plane, with no rotation around the Z axis.

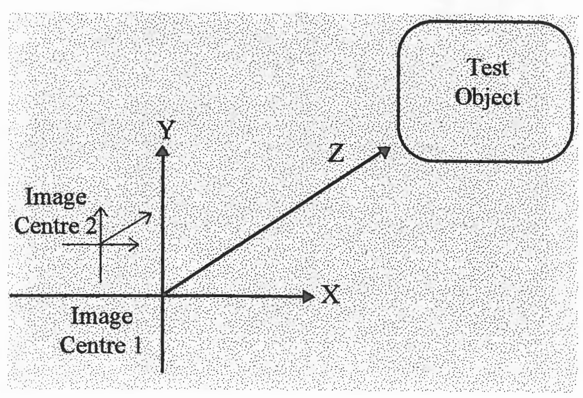

Figure 4. Relative shifts of image centres.

To reduce computation time, the images were cropped to only show the necessary objects in the scene, such as the test object and the control frame. 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. The dimensions of the final low resolution images used was 332 x 392 pixels. The enhancement ratio for this experiment was 1.5, thus a image of 498 x 588 pixels was to be determined.

To solve for the higher resolution image as an entity, the enhancement program would be required to solve a system of equations with more than 290,000 unknowns, one for each pixel in the enhanced image. This would take an extremely long time and require a very large amount of processing capability and storage space in the computer being used. Therefore, to overcome these disadvantages, the enhancement program was modified to solve for the enhanced image in sections, with the user being able to specify the size of the section and the amount of overlap between sections. The overlapping pixels ensured continuity at the edges of sections.

Two programs have been developed to solve the system of equations in sections. The first, named *Enhance*, determines a solution by inverting the ATA matrix of the least squares observation equations system. The second program, *Sparse*, utilises techniques of sparse matrix storage to reduce the amount of computer memory required, and uses a faster solution method, being Gaussian elimination, which does not perform an inversion. The inversion of the ATA matrix gives precision information about the unknowns, however a good indication of the precision of the enhancement can also be found by comparing the overlapping values from adjacent sections.

Sparse is less robust than *Enhance*, as it has a lower tolerance to sections that are close to being singular. This situation can occur on the edges of the enhanced image where it is not covered by all the low resolution images due to the different shifts.

The program *Sparse* was used to process the experimental data sets for this research, due to the large size of the images. An indication of the precision of the enhancement was given by comparing the overlapping grey values from adjacent sections and is detailed in the Section 5.

The DTMs were created using a digital photogrammetric workstation called Virtuozo. Two separate projects were created which were virtually identical, being for the processing of the original images and for the enhanced images. All relevant parameters were kept the same to ensure that a direct comparison could be made between the two data sets.

The images were transferred to the workstation and converted to the system format for processing. The small scale of the project produced some problems while using the software package. To overcome these problems, the dimensions of the pixels were scaled up by a factor of 10, but this factor has been taken into account in the presented results.

The processing included setting up the projects with the appropriate parameters, including a calibration file for the camera, a file of the coordinates of the control points, setting the photo scale and the contour interval. The images were dealt with as stereo-pairs. No interior orientation was required as the camera was non-metric. The relative orientation was started with the operator manually pointing to several points to seed the automatic orientation process. The absolute orientation was then carried out by the operator adding in the control points with their correct point numbers. The program was then able to automatically process the absolute orientation.

Epipolar images were created of the area to be modelled. In both projects, the area was the maximum over the plate which could be covered without extending over the edge. These images were matched to determine the x-parallax, which is used in the determination of the DTM. The grid interval for the DTM creation was set at 1mm in object space, as was the contour interval. The DTM was created, thus allowing the contours to be generated.

Many output files were created during the processing, including the images of the contours and orthophoto and an ASCII file of the DTM. The ASCII file was reformatted to be used in a surface fitting program, where a plane was fitted to the DTM points. The results of this processing are detailed in the following section.

5. RESULTS

The quality of the results from the enhancement algorithm depends on the precision of the initial image matching which determines the shifts between the images. The internal precision of the matches was similar as that found in the example test data, with an average standard deviation of 0.003 pixels. 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 1.05 grey values for the Left data set and 2.62 grey values for the Right data set, showing the images did not have large differences in illumination levels.

Each data set was processed on a Pentium-100 PC, with processing time being approximately 7 hours to solve for 293,911 unknown values with no precision assessments. The average difference in the overlap values of adjacent sections in the solution was 0.26 grey values for the Left data set and 0.15 grey values for the Right data set, indicating a high level of integrity in the solution. The dimensions of the enhanced images were 589 x 499 pixels and were cropped to 580 x 492 pixels for processing in Virtuozo, compared to 392 x 332 pixels for the original low resolution images.

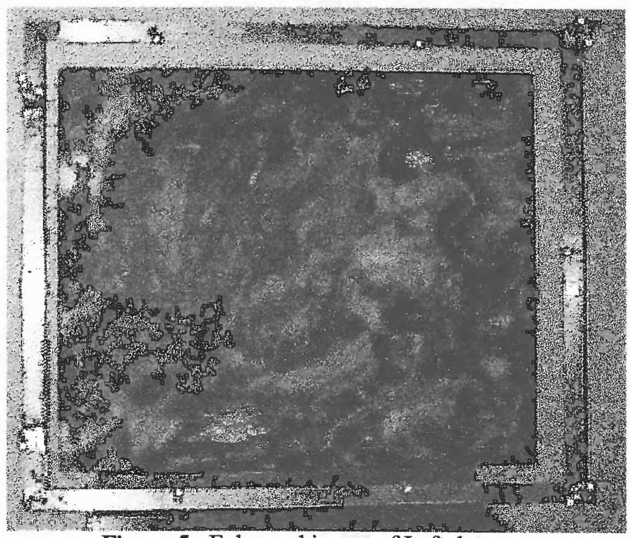

Figure 5. Enhanced image of Left data set.

Figure 5 shows the enhanced image from the Left data set. Degradations can be seen on the edges in the image, due to sharp changes in grey value. Investigation is continuing into overcoming this problem.

The digital photogrammetric workstation provides information on the quality of the orientations. The results of the relative orientation were similar for each data set. Ten control points were measured and an absolute orientation completed. The horizontal accuracy, as determined by a RMS value of the control points measurements, was 0.62 mm and 0.35 mm for the original data set and the enhanced data set respectively. The vertical accuracy was 0.24 mm for the original data set and 0.40 mm for the enhanced data set. Reliability percentages were given for the matching of the epipolar images, with the highest being 90% and 91% in the coarse and enhanced data sets respectively.

An ASCII file containing the DTM information was modified to be used in a surface fitting program. The information in this file includes: the starting x and y coordinates, the orientation, the grid spacing, the contour interval, the number of columns and rows in the array of Z values. The grids which were produced were 415 x 563 millimetres in the coarse data set and 447 x 547 millimetres in the enhanced data set. However, to make a direct comparison these were reduced to 400 x 520 in each case, allowing 208,000 points to be fitted to the planar surface.

Small sections of the surfaces created by Virtuozo have been plotted in a graphics software package and are shown in Figures 6 and 7, being the original data set and the enhanced data set respectively. These are in millimetres and show approximately the same area on the test object.

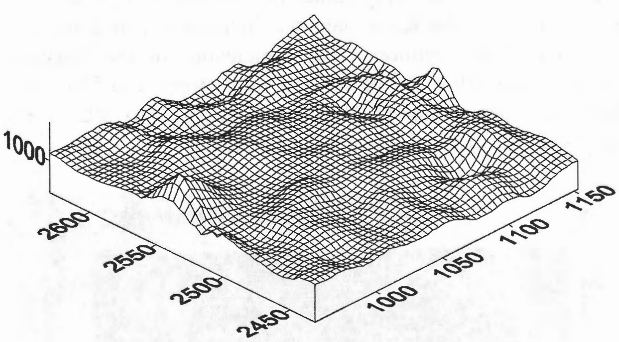

Figure 6. Surface plot from original images.

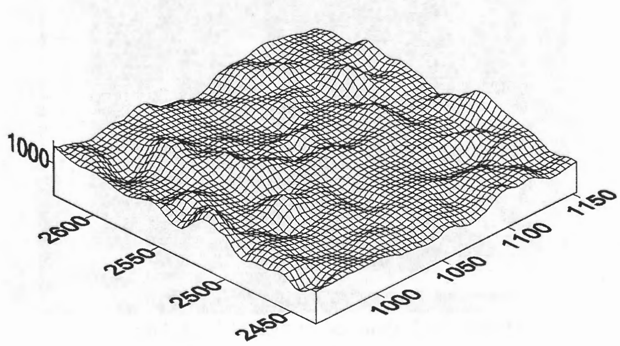

Figure 7. Surface plot from enhanced images.

The results from both data sets appear very similar when considered visually. However, when statistical analysis was undertaken, differences between the data sets were encountered. The surface generated from the original data sets had more variation, as shown in the Table 1.

Height Data	Original Data	Enhanced Data
Z minimum	973.5	982.3
Z maximum	1073.8	1024.7
Average	1001.6	1001.3

Table 1. Height information.

A surface fitting program was used to fit a plane to the DTMs. The enhanced data set produced the better result, having a RMS difference from the plane of 3.86, whereas the original data set had an RMS of 4.76. To check the repeatability of these results, the DTMs were generated with a different grid spacing and produced results within 0.1 of the stated RMS values. Therefore, it can be concluded that by using the resolution enhancement algorithm, the accuracy of a digital photogrammetric application can be improved by approximately 20%. Extensive testing of other geometric surfaces is being conducted to further prove the validity of the improvement in 3D accuracy of digital photogrammetric applications when higher resolution imagery is used.

6. DISCUSSION

At present, there are several constraints on the algorithm which must be overcome to ensure the generality and applicability of the enhancement procedure. Several issues which are being investigated are: the incorporation of additional parameters into the model, using alternative registration methods to accommodate different types of scenes, and modification for use with colour images.

The images which are used in the enhancement procedure are usually acquired using a scanner or digital still camera on a tripod, so that the images will not have any relative rotations. It is envisaged that the algorithm will be used to enhance images taken with either hand-held or mounted video cameras. Each represents a different situation with unique considerations. Hand-held cameras would be used with static scenes, for example, reverse engineering applications, determining as-constructed details of new buildings and recording architectural facades for heritage preservation. Mounted cameras would be utilised for dynamic scenes, such that objects would move within the video sequence with a stationary background, for example, scenes from security and surveillance cameras.

With hand-held cameras, the images may contain significant amounts of rotations or distortions, which will degrade the results of the algorithm in its present form. Parameters are being incorporated into the algorithm to overcome this constraint. The image registration technique used in the enhancement algorithm determines the amount of rotation between the images. When the rotation becomes significant, two methods can be used to minimize the effects, either by determining shifts at intervals over the images, as previously mentioned in Section 3, or including a rotation parameter into the determination of the observation equations, with the effectiveness of this solution being currently investigated.

Mounted cameras will required a different approach than that taken when using a hand-held camera, as the objects within the scene will require identification and tracking. Feature identification and matching will be employed to isolate the significant objects in the images and determine their relative motion. Resolution enhancement for images with independent object motion has been investigated by (Schultz and Stevenson, 1996), however interpolation techniques were used in that case and a different approach is being developed.

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. One method being considered was presented by Krupnik (1996), where several images are matched at the same time, instead of only two, and actual grey values are used to determine the shifts as an alternative to using the difference between grey values. The robustness of his solution was improved due to the increased ability to find a correct solution where previously the solution may have been weak.

At present, the resolution enhancement algorithm 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 information, it is proposed to enhance each of these images and then combine the result to produce a colour image with enhanced resolution.

7. CONCLUSION

The results of experimentation have been presented to show the improvement to three dimensional accuracy achieved by enhancing the resolution of the digital images used in the creation of DTMs. Further refinements to the presented algorithm are being undertaken to increase the improvement in accuracy achievable and to diversify the range of applications which could benefit from utilisation of the algorithm.

The resolution of digital image acquisition devices is constantly improving and becoming less expensive. As the presented algorithm is a device independent software solution to the limitations of low resolution imagery, it may be used to enhance all types and forms of digital imagery.

8. BIBLIOGRAPHY

Althof, R., Wind, M. and Dobbins, J., 1997. A rapid and automatic image registration algorithm with subpixel accuracy. IEEE Transactions on Medical Imaging, 16(3): 308-316.

Fryer, J. and McIntosh, K., 1997. Integration of low resolution digital images. In: S. El-Hakim (Editor), Videometrics V. SPIE, San Diego, California, USA, pp. 136-144.

Godding, R. and Woytowicz, D., 1995. A new digital high resolution recording system. In: E.P. Baltsavias (Editor), From Pixels to Sequences. ISPRS, Zurich, Switzerland, pp. 31-35.

Gonzalez, R. and Wintz, P., 1987. Digital image processing. Addison-Wesley Publishing Company, Sydney.

Jensen, K. and Anastassiou, D., 1995. Subpixel edge localization and the interpolation of still images. IEEE Transactions of Image Processing, 4(3): 285-295.

Kochi, N. et al., 1995. Development of a metric CCD camera and its application. In: E.P. Baltsavias (Editor), From Pixels to Sequences. ISPRS, Zurich, Switzerland, pp. 254-258.

Kölbl, O. and Bach, U., 1996. Tone reproduction of photographic scanners. PEARS, 62(6): 687-694.

Krupnik, A., 1996. Using theoretical intensitiy values as unknowns in multiple-patch least-squares matching. PEARS, 62(10): 1151-1155.

Lenz, R. and Lenz, U., 1993. New developments in high resolution image acquisition with CCD area sensors. In: A. Gruen and H. Kahmen (Editors), Optical 3D Measurement Techniques II. Wichmann, Zurich, pp. 53-62.

Long, D., Hardin, P. and Whiting, P., 1993. Resolution enhancement of spaceborne scatterometer data. IEEE Transactions on Geoscience and Remote Sensing, 31(3): 700-715.

McIntosh, K., 1996. A calibration procedure for CCD array cameras. In: K. Kraus (Editor), Spatial Information from Images. ISPRS, Vienna, Austria, pp. 138-143.

Motala, S., 1997. A camcorder-based rapid mapping system. Masters Thesis, University of Cape Town, Rondebosch, 100 pp.

Patti, A., Sezan, M.I. and Tekalp, A.M., 1997. Superresolution video reconstruction with arbitrary sampling lattices and nonzero aperture time. IEEE Transactions on Image Processing, 6(8): 1064-1076.

Peipe, J., 1995. Photogrammetric investigation of a 3000 x 2000 pixel high resolution still video camera. In: E.P. Baltsavias (Editor), From Pixels to Sequences. ISPRS, Zurich, Switzerland, pp. 36-39.

Reis, C., 1997. An imaging price / performance pacesetter: an inside look at Pixera. Advanced Imaging, 12(1): 26-30.

Saleh, R., 1996. Photogrammetry and the quest for digitization. PEARS, 62(6): 675-678.

Schultz, R. and Stevenson, R., 1996. Extraction of high-resolution frames from video sequences. IEEE Transactions on Image Processing, 5(6): 996-1011.

Uffenkamp, V., 1993. Conception of a digital turning and tilting camera. In: A. Gruen and H. Kahmen (Editors), Optical 3D Measurement Techniques II. Wichmann, Zurich, pp. 72-80.

Weeks, A., 1996. Fundamentals of electronic image processing. Imaging Science & Engineering. SPIE Optical Engineering Press, Washington, 570 pp.

Wiman, H., 1993. Improvement of digital image resolution by oversampling. 57, Department of Photogrammetry, Royal Institute of Technology, Stockholm.

Wong, K. and Obaidat, M., 1994. A knowledge-based system for stereovideo measurement. IAPRS, 30(5): 443-446.