Resolution Enhancement of Photogrammetric Digital Images

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Abstract

Photogrammetry is the science of extracting three-dimensional data from overlapping sets of images. To obtain the highest accuracy, it has always been essential to obtain high-resolution images. Many digital camera systems cannot provide resolution equivalent to their film counterparts and hence their use in photogrammetric applications has been restricted. This paper describes the implementation of an algorithm which is device independent and can combine several low resolution images into one single high resolution composite, that is, the same field of view is represented by more pixels and by more grey scale information. This algorithm is illustrated with applications which show its implementation using Fourier theory to model the grey-scale surface of the enhanced image.

1. Introduction

Photogrammetry allows the determination of the size and shape of objects from remotely sensed measurements made on 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. Digital image technology and digital photogrammetry find applications in a wide range of fields, including industrial measurements, archaeological, architectural, astronomical, medical, GIS updating, close range and aerial mapping as well as law enforcement forensics. Examples of these applications are regularly presented at conferences of the International Society for Photogrammetry and Remote Sensing, such as that held in Amsterdam in June, 2001.

Innovative applications of digital photogrammetry are being reported at an increasing rate. In particular, close range applications require the speed and on-line capabilities of analog CCD cameras, or the portability and flexibility of digital still cameras. While there exist many areas where digital photogrammetry can be efficiently used, its applications are often limited by the resolution of the imagery.

2. Why Enhance Resolution?

The main objective of digital photogrammetry is to obtain accurate spatial information about remotely sensed objects. Fundamental to this objective is the indisputable fact that the best results are always obtained from images with the highest resolution. In other words, the lower the resolution of the imagery, the lower the level of accuracy attainable. The resolution can also affect the visual quality of the results and the precision of classifications made from the imagery.

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 a DTM (Digital Terrain Model). Hence, the purpose of image enhancement is to improve the quality of a lower resolution image so that it becomes more suitable for an application than the original image [1]

3. Digital Image Resolution Enhancement

Developments into the enhancement of the resolution of digital images can be divided into two main streams: those using **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 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. Lenz and Lenz [6] attempted resolution enhancement by moving the CCD array in a regular pattern by very small amounts (approx. 3μm) between each image in a sequence of 25 images. This successful hardware solution to the problem added substantial costs to the camera. Other hardware-based solutions have been incorporated to some modern image capture devices but these are very specific, purpose-built devices. For example the new CanoScan

D660U by Canon utilizes a Variable Refraction Optical System (VAROS) that allow 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 1200*1200 optical image. Jahn and Reulke [3]) utilised an analogous approach in describing a staggered line of arrays in PushBroom sensors onboard aircrafts or satellites.

As far as the software techniques are concerned, Long [7] presented a method for generating enhanced resolution radar images of the earth's surface using spaceborne scatterometry. The method utilized the spatial overlap in scatterometer measurements made at different times. A notable aspect raised by Long was that noise in the refined image increased as the resolution was improved. This is a drawback that has to be precisely modelled in resolution enhancement techniques to ensure that the enhanced image has not suffered any noticeable degradation in accuracy.

Jensen and Antastassiou [4] presented a non-linear interpolation scheme for enhancing the resolution of digital still images by determining edges within the images to sub-pixel level.

Image processing methods are also designed to visually enhance images for specific applications by changing the values of the pixels in the image. While these methods improve the visual quality of the image they do not increase the resolution of the image. Some of these methods include edge enhancement, noise reduction, and blur removal [1].

Many enhancement algorithms also use interpolation methods to create a higher resolution image. In this case, a surface is fitted to the data of the low resolution images, where the shifts and rotations of these images relative to one another have been determined by least squares matching techniques. As the surface passes through all the data points it is then possible to interpolate it at specified points defined by a uniform and refined sampling grid using algorithms based on Nyquist Frequency Theory [8].

4. Interpolation techniques

There are three common methods for interpolating scattered data to a uniform refined grid: **nearest neighbour, bilinear interpolation, and cubic convolution**.

Nearest neighbour uses the digital value from the pixel in the original image which is nearest to the new pixel location in the corrected image. This is the most simple method and does not alter the original values. This method tends to result in a disjointed or blocky image appearance.

Bilinear interpolation takes a weighted average of four pixels in the original image nearest to the new pixel location.

Cubic convolution interpolation goes even further to calculate a distance weighted average of a block of sixteen pixels from the original image which surround the new output pixel location. As with bilinear interpolation, this method results in completely new pixel values. However, these two methods both produce images which have a much sharper appearance. The result of these techniques is shown in the simulated example below.

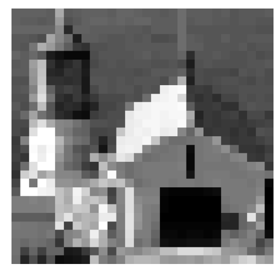


Figure 1 – Original image

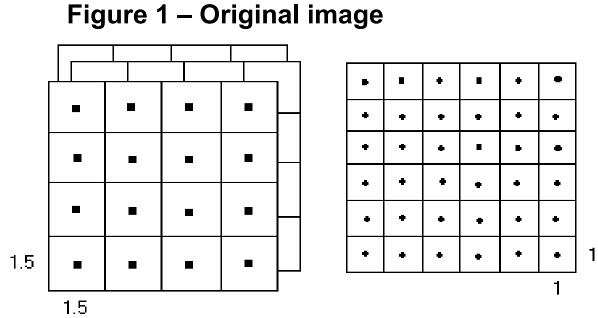


Figure 2 – Fine/coarse grid geometry

Sixteen images were manufactured from the original image shown in Figure 1. Each image was created by sampling the original image at uniformly spaced points starting from the sub-pixel shifts assigned to each coarse image. Three of the sixteen coarse images are shown in Figure 3. Figure 2 shows the geometry of the fine/coarse grid ratio (1/1.5) considered in this example.

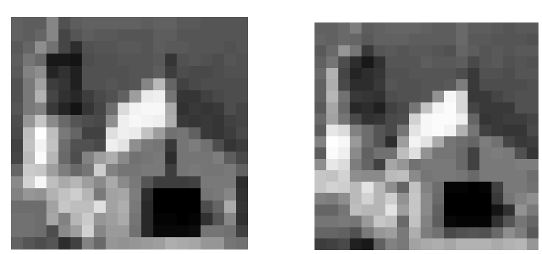


Figure 3 – Coarse images (1, 2 . . . 16)

The results of combining 8 of the above samples of coarse images using the above mentioned interpolation techniques are illustrated in Figure 4. The enhancement does not create an image which is larger in area than the input images; rather it creates an image with larger number of smaller pixels over the same area.

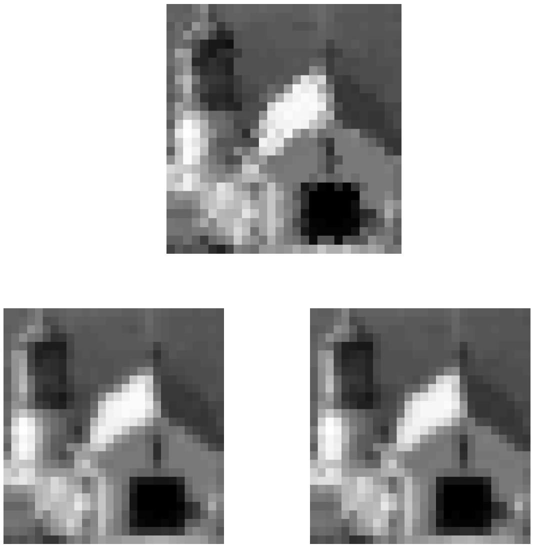


Figure 4 – Enhancement results by interpolation. From top to left and right: Nearest neighbour, Linear and Cubic

The accuracy of each interpolation technique is shown in Figure 5. This graph depicts the standard error of the differences between the interpolated images and the original, thus giving a result in terms of grey values. Using more than 8 coarse images *does not* improve the final resolution. In addition, the curves reveal how the cubic convolution method of interpolation produces the results closest to the original image in Figure 1.

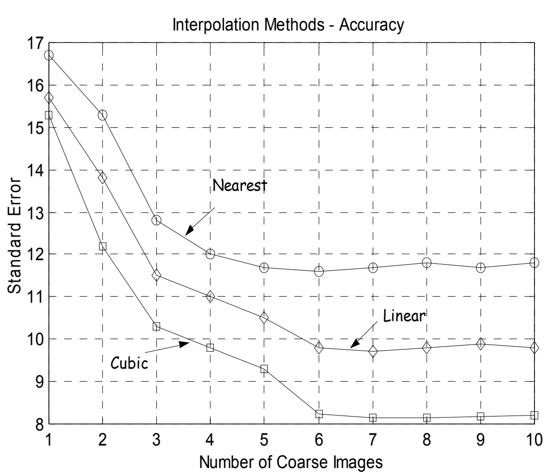


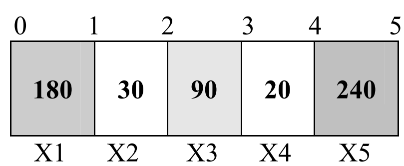
Figure 5. Accuracy measure of interpolation techniques.

5. A rigorous geometric algorithm

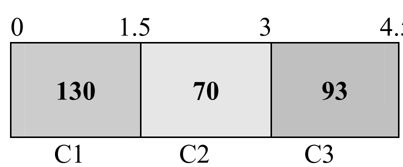
This section relates to the published work of Fryer and McIntosh [2], and briefly describes a rigorous geometric algorithm which uses several low-resolution images to produce one high resolution resultant image. The general steps of this algorithm are described below. This algorithm, combined with harmonic, or Fourier, theory together with the geometric configurations of the pixels in object space forms the foundations for a generalised surface model for digital images.

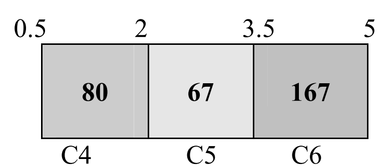
1. Collect several low-resolution images.
2. Determine pixel offsets of each image from the first using least squares area-based image matching.
3. Form a set of equations using the offsets as coefficients, the enhancement ratio and the grey levels from the low resolution images as observations.
4. Solve for higher resolution pixels.
5. Display the resultant higher resolution image.

The pixel offsets mentioned in point 2 above refer to finding the shifts and rotations between the low resolution images. Least squares matching techniques can overcome difficulties arising from radiometric differences in the images being matched and can achieve sub-pixel accuracies of approximately 0.1 pixels. A simplistic 1-D example of the methodology and the geometry involved in this algorithm is given below. Consider just 5 fine pixels from a line in the 'true' (or higher resolution) image we require:



TRUE pixels, that is, those we wish to find





COARSE pixels, such as those captured by a camera

Figure 6. Showing an Example of True and Coarse Pixels

The Xi values represent the unknown grey values of the high resolution pixels in a least squares solution. Consider the determination of these unknowns from two images referred to as coarse images, and let the enhancement ratio be 3/2 (*i.e.*, three fine pixels are equivalent in length to two coarse pixels). In this example, the left-most fine image coincides with the left-most coarse image. The second coarse image is shifted half a fine pixel. If the pixels in coarse image 1 are C1, C2 and C3 and the pixels in coarse image 2 are C4, C5 and C6, then consideration of the proportion of a fine pixel that a coarse pixel covers, and the enhancement ratio, provides the observation equations. The set of equations and their matrix representation ([C]=[A][X]) as well as the results of the solution via simultaneous equations using least squares methods ($[X]=[A^TA]^{-1} * [A^TC]$) are given below:

Observation equations	Ci
$C1 = (X1 + 1/2\ X2) * p^{-1}$	130
$C2 = (1/2\ X2 + X3) * p^{-1}$	70
$C3 = (X4 + 1/2\ X5) * p^{-1}$	93
$C4 = (1/2\ X1 + X2) * p^{-1}$	80
$C5 = (X3 + 1/2 X4) * p^{-1}$	67
$C6 = (1/2 X4 + X5) * p^{-1}$	167

A = Matrix of coefficients

1	0.5	0	0	0
0	0.5	1	0	0
0	0	0	1	0.5
0.5	1	0	0	0
0	0	1	0.5	0
0	0	0	0.5	1

$$[X]=[A^TA]^{-1} * [A^TC] = [180\ 30\ 90\ 20\ 240]$$

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, lens distortions and other phenomena which produce differences in real images have been excluded from the above example.

It should be pointed out that the relationship between the fine pixels and the coarse pixels is neither simple nor direct. Therefore, the fine pixels can only be solved by equations such as those set out above.

The 2-D case relates to similar geometric considerations. Figure 7 shows a simple case of a ratio 3/2, with the coordinates on the arrays illustrating the fine array coordinate system in row and columns.

To develop the observation equations, each pixel in the coarse images must be related to the fine pixel's coordinate system, thus determining which fine or unknown pixels are affected by each individual coarse pixel. For example in Figure 7, the upper left hand coarse pixel C(1,1), covers the area bound by (0,0) → (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:

$$\text{Coarse}(1,1) = [\text{Fine}(1,1) + 0.5*\text{Fine}(2,1) + 0.5*\text{Fine}(1,2) + 0.25*\text{Fine}(2,2)] * p^{-2}$$

Where Fine(1,1), Fine(2,1), Fine(1,2) and Fine(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.

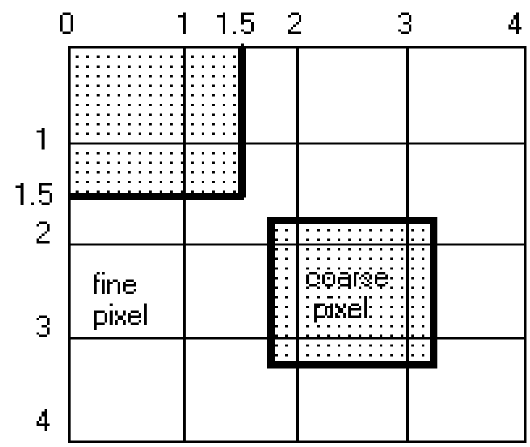


Figure 7 – Coarse pixel on the fine coordinate system

6. Fourier surface modelling for digital images

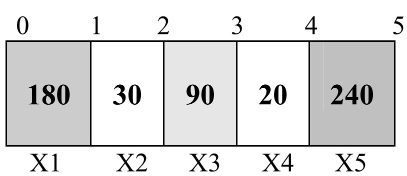
The algorithm described in this section forms the foundations for modelling digital images in terms of surfaces using Fourier theory. The precision of this development and the beneficial aspects of this transformation are described in the ensuing sections.

Fourier analysis is the process of fitting Fourier series by least squares to data and of calculating the various amplitudes and phase angles of the various waves. Since a given function P(x) is frequently represented by a series of discrete points (observations), the resulting Fourier series 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 most simple assumption and the one used here is that P(x) repeats itself completely, that is, it is completely periodic. An important aspect about Fourier series on periodic functions is that the first few terms often are a pretty good approximation to the whole function, not just the region around a specific point. For full details of the theory behind Fourier series the reader is referred to [5].

The standard form for a Fourier series of period T is given by

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

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 $\mathbf{a_0, a_1, b_1, a_2, b_2}$, . . . are the Fourier coefficients. There exist functions which can be evaluated numerically to acquire the Fourier coefficients for continuous functions, and can then be used to calculate the amplitudes and phase angles for each of the series components. However, for the purpose of this paper the determination of such coefficients is based on describing P(t) in terms of a number of discrete points (pixel grey values) separated by constant intervals. For example, the five grey levels used in the 1-D example developed in section 5 can be expressed as a generalized Fourier linear model in which the 'discrete' Fourier series includes five terms, that is, the number of the required fine pixels:



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

Let us now consider a situation whereby the coefficients of the above series can be found from the same data, assumptions and geometric considerations of the two coarse images described in section 5 where, for instance, the coarse pixel C1 was geometrically related to the fine pixels X1 and X2 by the expression C1=(X1+1/2X2)*2/3 etc. The same C1 can be also related to the P(x) above so 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, 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 equations via least squares produces the required coefficients a_i and b_i of the discrete Fourier expansion, which is then evaluated at the fine coordinate points x= 1, 2,…,5 in order to recover the grey values of the original fine pixels.

$$P(x) = 111.97 + 82.18 \cos wx + 46.80 \sin wx + 46.75 \cos 2wx + 61.62 \sin 2w$$
$$x = 1, 2, 3, 4, 5$$
$$[Xi] = [180\ 30\ 90\ 20\ 240]$$

The two dimensional case adheres to the same principles described earlier and uses the same geometric relationships between coarse and fine pixels established in section 5. Here, 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.

An example of the effectiveness of this method can be seen in Figure 8. This is the general 2-D case. Four of the coarse images of the lighthouse in Figure 3 have been combined to produce a higher resolution image. There are grey levels in the finer resolution image that are higher and others which are lower than in any of the four coarse images. By way of comparison note how the cubic convolution interpolation method (combination of 8 images) produces a blurred image with less contrast.

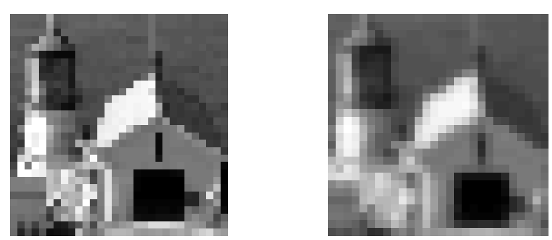


Figure 8 – Enhanced resolution image (Fourier) and interpolated image (cubic)

The Fourier approach combined with the algorithm of section 5 provides for a thorough and global surface representation of a digital image and has a valuable effect on the formation and solution of the observation equations. The Fourier surface model generates a function which incorporates the edges of the image and this is of importance when dealing with very large images requiring the sectioning of the fine pixel array in order to produce sub-images of a size which can be economically computed.

The method described is section 5 required sparse matrix storage techniques because the number of non-zero elements in the overall matrix of observation equations from the image enhancement was typically 2% of the total number of elements in the array. The present Fourier surface approach involves the successive adding of sine or cosine curves to model the surface shape and since sine or cosine can only range between 0 and 1, the system of equations will be more balanced and only a small portion of elements will be equal to zero.

7. Precision and accuracy tests

To assess the precision of the enhancement algorithm, a series of tests were carried out using the low resolution images of the lighthouse test image shown in Figure 3. These tests were simulated so that the true image was known prior to the enhancement. In this way, both the internal precision and the accuracy could be assessed. The tests were performed using an enhancement ratio of 1.5 with a varying number of images (from 2 to16) 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 the digital image from a typical camera system 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. There is a progressive, yet proportional, worsening of results as the noise in the images increases. Further it could be shown that the accuracy of the enhanced image was improved as the number of coarse images increased, although more than 8 images did not improve the final resolution.

8. Conclusion

The objective of this paper was to introduce the use of harmonic, or Fourier, analysis to a rigorous geometric algorithm for enhancing the resolution of photogrammetric digital images. Improving the accuracy of digital photogrammetry necessarily involves improvements in image resolution. A software solution, *which is device independent*, has been proposed. The application of the enhancement algorithm has been demonstrated in simulated tests using sets of low-resolution images whose relative positions with respect to one another are known. The notable finding from the experimentation included:

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

(ii). The amount of noise in the low-resolution images proportionally affects the precision of the resultant enhanced image. The results can be improved by using more than the minimum number of images required for the enhancement process.

(iii) Fourier surface modelling proved to be an efficient method for treating edge areas of the fine pixel array and the edges of sub-sections used to process large images.

(iv) Fourier surface models provided an alternative and more balanced system of observation equations as compared to the previously published rigorous method.

(v) Least squares image matching is the most crucial aspect of the process, as the coefficients for the resolution enhancement are based on the shifts which are determined by this technique.

Further work and investigation is required into this Fourier approach, especially with regard to: the use of polynomials or other suitable functions for surface representation of a digital image as compared to a Fourier approach; testing the Fourier surface model with real data and varying enhancement ratios; testing the Fourier surface method as a photogrammetric tool in a series of close range 3-D experiments; and, determining the effectiveness of the methods in the case of images containing sharp changes of grey levels.

9. References

[1] **Baxes, G.A**., 1994**,** Digital Image Processing, Principles and Applications. *John Wiley & Sons, Publishers.*

[2] **Fryer, J.G. and McIntosh, K.L.**, 2001, Enhancement of Image Resolution in Digital Photogrammetry, *Photogrammetric Engineering and Remote Sensing,* 67(6): 741-749

[3] **Jahn, H. and Reulke, R.,** 2000, Staggered Arrays in Push broom Cameras: Theory and Application. *International Archives of Photogrammetry and Remote Sensing*. Vol. XXXIII, PartB1, Amsterdam.

[4] **Jensen, K. and Anastassiou, D**., 1995, Sub-pixel Edge Localization and the Interpolation of Still Images. *IEEE Transactions of Image processing*, 4(3), 285-295.

[5] **Kendall, M. and Ord, K.,** 1990, Time Series, *third edition*, Oxford University Press.

[6] **Lenz, R. and Lenz, U.,** 1993, New developments in High Resolution Image Acquisition with CCD area sensors. *Optical 3-D Measurements Techniques II, Wichmann*, Zurich, 53-62.

[7] **Long, D., et al**, 1993. Resolution Enhancement of Spaceborne Scatterometer Data. IEEE Transactions on Geosciences and Remote Sensing, 31(3), 700-715.

[8] **Weeks, A.R.,** 1996, Fundamentals of Electronic Image Processing. *Spie Optical Engineering Press,* SPIE/IEE Series on Imaging Science & Engineering.