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A FRAMEWORK FOR DIGITAL SURVEY FROM AERIAL PHOTOGRAPHS

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ABSTRACT

Despite the potential offered by modern computer technology to the labour-intensive work of 'Aerial Archaeology', few applications have been published. Where developments have been made, they have tended to be carried out in a somewhat haphazard manner, thereby compounding problems with data standards and consistency, which are essential issues as we move towards a national archaeological database. This paper provides an introduction to digital aerial archaeology, and describes the Aerial Archaeology System (AAS) - a computer package proposed as an integral component of the archaeologist's geographical information system (GIS) toolset, which assists the discovery, mapping, and classification of archaeological sites.

INTRODUCTION

The archaeological interpretation of aerial photography is often used for preliminary survey, which is a traditional discovery-oriented remote sensing application. It is also used for inventory-level recording of large areas as well as mapping and topographic analysis of smaller areas, prior to excavation (Ebert & Lyons 1983; Palmer 1989, 1991; Hingley 1991; Darvill 1996). Aalen makes a particularly compelling argument for the use of aerial photographs as an inventory tool when he points out that "other than the incomplete and seriously outdated large scale Ordnance Survey maps, we have no detailed account of our landscape" (Aalen 1985, p.22). For many regions there are archives of photographs available, though there is no coherent national archive available for consultation by archaeologists. Primarily due to the labour intensive nature of the work, few of the available photographs have been fully utilised for archaeological purposes.

For aerial photography to have value as a wide-area archaeological discovery and interpretation tool, objective means of making sense of observations are required, even at a level as basic as determining which observations are likely to reflect archaeological material and which are likely to reflect small-scale geomorphological processes (Ralston & Shepherd 1983; Palmer 1989). For these purposes, a number of classification schemes for archaeological sites have been proposed. Crawford's pioneering work in the 1920s classified sites in terms of the nature of the

evidence: for example, sites may be evident as crop marks, soil marks, or may be upstanding. Other schemes have attempted to classify archaeological features in terms of their morphology or other aspects: for example, enclosures can be classified in terms of their shape, number of banks and ditches, entrances, association with other features, topographical contexts, and so on (Barrett 1980; Edis *et al.* 1989; Whimster 1989; Stout 1991; Redfern 1997).

While computerised databases and Geographical Information Systems (GIS) are now being used to assist the collation of archaeological information at a regional and national level, the production and classification of this information has continued to be highly subjective. This is particularly troublesome for wide-area databases since these are invariably based on the work of many different archaeologists. Classification schemes such as *MORPH*, developed by the Royal Commission on the Historical Monuments of England (RCHME), certainly impose standardised description and classification, and provide centralised data access (Edis *et al.* 1989): however, they still suffer from a lack of objectivity. It has been shown that groups of archaeologists working with *MORPH*, when independently presented with aerial images of archaeological monuments, are likely to produce widely disparate interpretations (Horne & MacLeod 1991).

COMPUTER ASSISTED ARCHAEOLOGICAL INTERPRETATION OF AERIAL PHOTOGRAPHS

The computer software technologies of digital image processing, photogrammetry, and pattern recognition have the potential to improve the efficiency and objectivity of archaeological interpretation of aerial photographs, and some developments have been made to this end. The applications of these technologies to 'aerial archaeology' fall naturally into three categories:

- monument detection and mapping;
- geometric rectification and topographic modelling;
- cultural landscape analysis.

Image enhancement is a category of image processing techniques which allow the interactive adjustment and re-mapping of contrast or colour reproduction, thereby overcoming the limitations of the human ability to perceive subtle changes in tone or colour. Image enhancement techniques, which can be thought of as very flexible and efficient digital equivalents to traditional dark room re-processing, have been demonstrated as a useful technology for assisting the manual study of low contrast archaeological material in aerial photographs (e.g. Scollar *et al.* 1990; Booth *et al.* 1993; Forte 1993). However, only recently have attempts been made to go beyond this simple level of providing 'dark room' image *improvement* functionality, and to apply automatic scene *understanding* techniques in order to automate the process of monument discovery and mapping from aerial photos (Lemmens *et al.* 1993; Redfern 1997).

Computers have been used for a number of years to assist in the generation of plans of archaeological sites - particularly crop mark and soil mark sites - from oblique aerial photographs (Scollar 1975; Palmer 1977; Haigh *et al.* 1983; Herzog & Scollar 1989). The number-crunching ability of computers is of undoubted use in the automation of this image-to-map transformation task. A related application of aerial photography is topographic photogrammetry, whereby stereo pairs of photos are used to generate topographic models of the imaged landscape. Traditionally, topographic photogrammetry has operated on

the premise of physical projection and measurement of images viewed in stereo with the aid of precise optical-mechanical equipment. This equipment is typically very expensive and highly technical, and therefore not generally available to archaeologists. More recently, 'softcopy' approaches have become available, which produce digital elevation models (DEM). Softcopy photogrammetry applies mathematical models rather than physical projections, and is carried out entirely on a computer.

With the recent advent of geographical information systems (GIS), computers have assumed an important role in the analysis of cultural landscapes. Unlike the previous two categories of techniques for computerised aerial archaeology, which use data derived purely from aerial imagery, GIS-based analyses normally also involve higher-level archaeological information and other environmental data. Computers can also be used for pattern recognition (classification), which has some potential for assisting the interpretation of complex archaeological data, such as measurements collected from aerial photographs (Redfern *et al.* 1998).

THE AERIAL ARCHAEOLOGY SYSTEM

While developments have been made in each of the areas described in the previous section, they have not previously been integrated into a coherent framework. Such a framework would assist the efficiency of applying the various techniques, by allowing them to be seamlessly applied to objects from a common database. Perhaps more importantly, an integrated set of computerised tools would improve the standardisation and consistency of data, which is an increasingly important issue as we move towards a national archaeological database.

The Aerial Archaeology System (AAS) is a prototype software package which provides, in an integrated manner, many of the computerised techniques available for aerial archaeology. It was developed as part of the author's doctoral research at NUI, Galway (Redfern 1998a). During the development of the AAS, a number of improvements were also made to the techniques themselves. The AAS is designed to be deployed at an early stage in a hierarchical survey strategy: it attempts to

efficiently extract as much information as is possible from vertical aerial photographs, and

feeds its data directly into a GIS for subsequent analysis and survey planning.

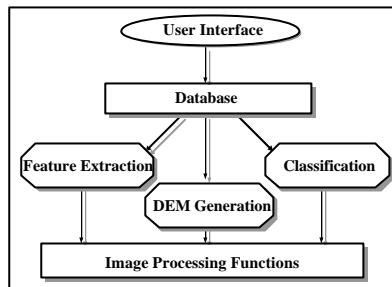


Fig. 1: Architecture of the Aerial Archaeology System.

Figure 1 provides a schematic of the relationships between the various components of the AAS. The user interface provides a Windows connection to the database management system; direct access to the lower level image processing functions is also provided. The database layer integrates the technical functions and keeps track of the various data products and their interconnections. The three primary data-generating and analysing sub-systems (feature extraction, DEM generation, and classification) all draw on a common set of low level image processing and photogrammetric functions, which carry out the bulk of the intensive analytical work.

The main features of the AAS are:

- Calculation of scale, location, and orientation of photographs from user-supplied control points measured from Ordnance Survey maps;
- Assisted discovery and accurate tracing of curvilinear archaeological features in the photographs;

- Automatic morphological measurement of these features, and calculation of their location in the user's co-ordinate system;
- Creation of Digital Elevation Models (DEMs) of monuments and their immediate localities through analysis of overlapping stereo pairs of photographs (Redfern *et al.* 1999);
- Automated classification of monuments, to assist initial interpretation of new monuments as they are discovered (Redfern *et al.* 1998);
- Integrated database management of all primary and derived data in the system;
- Import and export of data products in common GIS formats.

All of the commonly used functions of the software are provided directly from the main application window, which is built around the two main data products of the system: photographs and monuments. The main window of the AAS (shown in figure 2) provides a data-oriented view of the system.

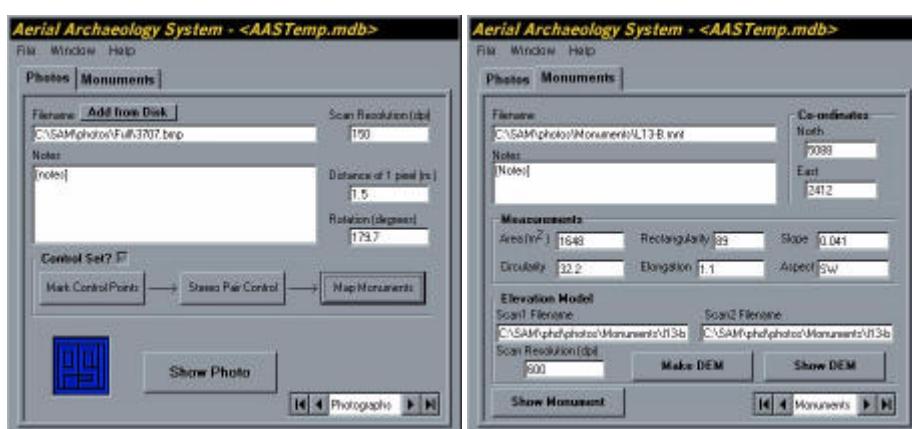


Fig. 2: The Main Window (Left: Photos Tab; Right: Monuments Tab).



Fig. 3: The Photograph Display and Manipulation Window. A variety of low-level image processing functions can be directly applied to a photograph, to assist its initial archaeological evaluation. The right mouse button is used to drag the photograph around in the window, in order to work with areas not in view. Enhanced or manipulated photographs can be saved as new image files.

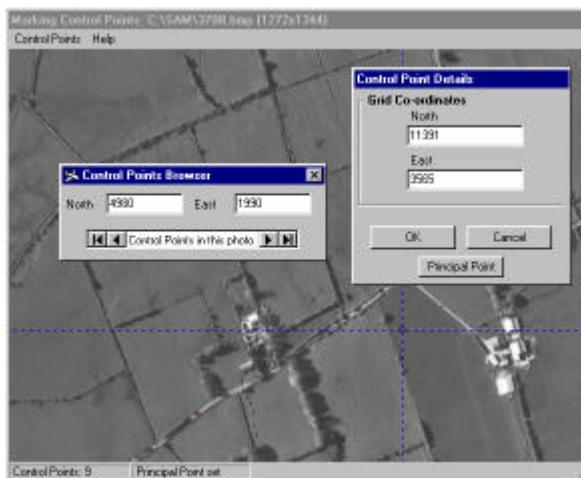


Fig. 4: Marking control points on a photograph. The user clicks on each spot on the photograph, and then types the North and East co-ordinates of this point, which have been derived from a map or other source. The dotted lines converge on the principal point of the photograph, which is also an essential piece of information required by the system.

Work on the two primary data products (photographs and monuments) is separated through the use of labelled tabs. The buttons provided on the two tabs provide the key functionality of the system, while additional support tasks can be initiated from the three menu items (File, Window, and Help). Navigation through the records in the AAS database is facilitated by standard Windows Data Access controls at the bottom right of the window.

Working with Photographs in the AAS

From the main window (figure 2), the *Show Photo* button displays the current photograph in a separate window, in which various low-level image processing functions can be applied directly, for early photographic analysis and to search for areas of interest (see figure 3).

The primary work on each photograph follows 3 steps, each of which is initiated by a click on a button in the main application window:

1. *Mark Control Points.* This button displays the photograph and allows the user to define 2-dimensional control points and the photo's principal point (figure 4). On return from this window, the scale and orientation of the photograph are worked out automatically.
2. *Stereo Pair Control.* For any 2 photos that share at least 3 control points, the user identifies their conjugate principal points, which simply means identifying the location of photograph A's principal point in photograph B, and *vice versa*. The system then calculates the distance flown by the plane between the 2 exposures (i.e. the *airbase*), and the rotation required to apply to each photograph to make their horizontal axes correspond to the flight path of the plane between the 2 exposures.

This information is required for the DEM generation system, which is described in a later section of this paper (Digital Elevation Model Generation).

3. *Map Monuments.* This button is used to initiate the computer-assisted identification and mapping of monuments. As each monument is mapped, a variety of morphological measurements are automatically carried out. The process is further described in the next section of the paper.

MONUMENT DISCOVERY AND MAPPING

Digital image processing has been used successfully for a number of years for assisting the discovery of monuments in aerial photographs. The most widely used class of technique involves manipulating the contrast of all or part of a photograph, in order to maximise the visual distinction of the features in it. The contrast of a greyscale image can be defined by its distribution of grey levels. If this distribution is concentrated near a certain level, then contrast is low and visual interpretation is difficult, since the human eye is poor at differentiating between similar tones. If a wide range of levels is represented, then contrast is high. Grey-scale manipulations are generally visualised in terms of their effect on the greyscale histogram, which is a histogram of the frequencies of each of the grey levels.

Contrast stretching spaces out (some of) the image's greyscale values so that they are further apart, thereby making them more easily distinguishable. Figure 5 shows the greyscale histogram of an image with poor contrast, while figures 6, 7, and 8 show various contrast enhancements and their effects on the image's greyscale histogram.

The uniform expansion pictured in figure 6 is called the linear stretch: subtle variations in tone become more accentuated, light values become lighter and dark values become darker. The linear stretch assigns as many grey levels to rarely occurring values as it does to frequently occurring ones. This is improved with a histogram-equalised stretch (figure 7). Here, image values are assigned to new values on the basis of their frequency of occurrence: more display values (and hence more

radiometric detail) are assigned to the frequently occurring portions of the histogram. The aim is to maximise the overall contrast: a uniform (i.e. flat) distribution is produced. In practice, perfect histogram equalisation is unlikely - this is clearly illustrated in figure 7, where a perfectly flat histogram has not been attained. It has been suggested that the best visual interpretation for general archaeological purposes is possible with images whose greyscale histograms approach the normal distribution, spread out over the reproduction range of the output device, with two standard deviations over the entire range of greys (Scollar *et al.* 1990).

Special analyses can be made by stretching a particular range of image values over the entire range, while disregarding the other image values. Figure 8 depicts one possible special stretch, which has been used to investigate the features which fall within the main central peak of the original low contrast image's histogram.

The AAS provides interactive local-area histogram effects as an integral part of the image analysis and site discovery process. Two examples of small areas of photographs containing areas of potential interest, which have been contrast enhanced, are shown in figure 9.

Recently, attempts have been made to automate the process of discovering monuments in aerial photographs (Lemmens *et al.* 1993; Redfern 1997). The goal is to be able to process archives of aerial photographs without the need for human assistance. Although visually obvious, high contrast and well preserved archaeological sites have been successfully detected automatically, no system has yet achieved much success with low contrast, damaged sites - which are those which are likely to be previously unknown. It is not only the low contrast of monuments that poses difficulty for a computer, but also the presence of high contrast modern features, such as walls and roads. This problem is termed 'clutter' in the image processing literature. The incredible skill of the human brain to interpret difficult images and filter out clutter is currently unrivalled by computer software: figure 10 illustrates a typical attempt to automatically detect monuments in an aerial image.

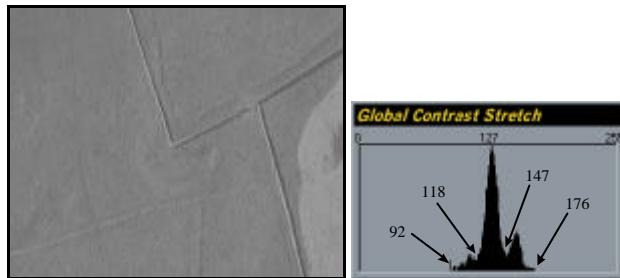


Fig. 5: An image with poor contrast and its greyscale histogram. Each pixel (dot) in the image has a greyscale (brightness) value in the range [0 - 255]. In this image, all radiometric detail is concentrated towards mid greytones with brightness values between 92 and 176. The archaeological feature at the centre of the image is barely, if at all, perceptible.

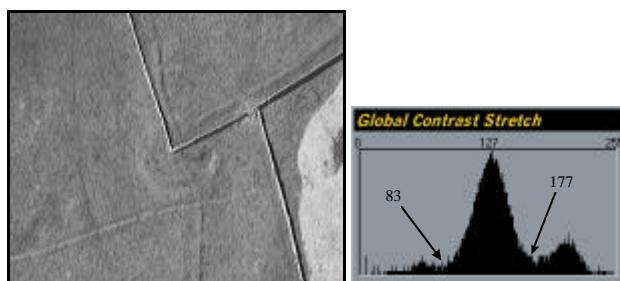


Fig. 6: The original image following a linear stretch, and its new greyscale histogram. The entire greyscale range [0-255] is now represented; however the bulk of the data still fall within a relatively narrow range [83-177].

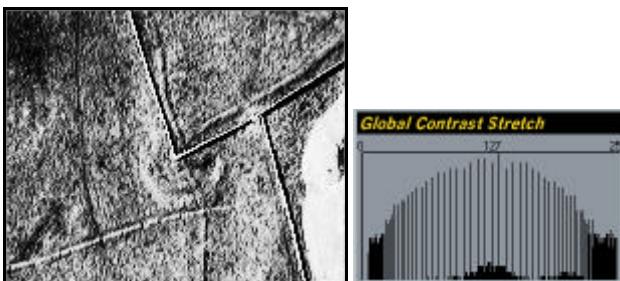


Fig. 7: The original image and its greyscale histogram following a histogram-equalised stretch. This stretch has attempted to maximise overall contrast.

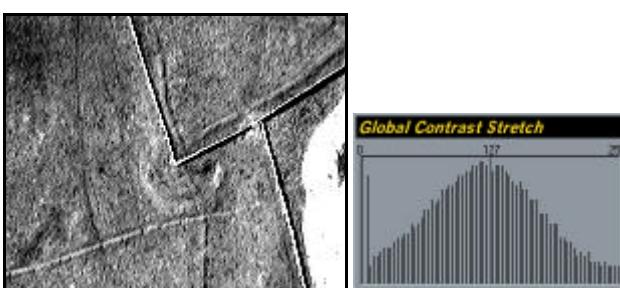


Fig. 8: The original image and its greyscale histogram following a special stretch, which has stretched the central peak [118-147] over the entire range [0-255]. The contrast of the central archaeological feature has been maximised, while outlying dark and bright values have been sent to black (value 0) and white (value 255), respectively.

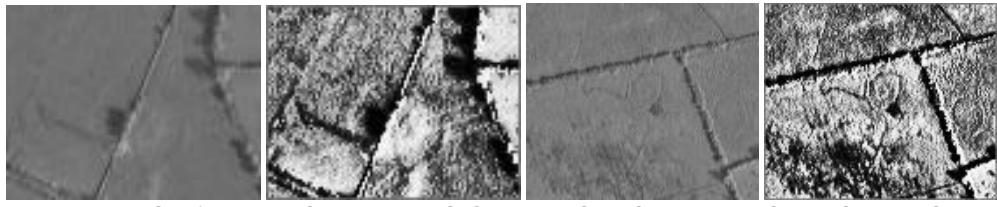


Fig. 9: Two examples of contrast enhancement, applied interactively in the AAS. In each case, the original image is displayed beside its contrast enhanced version.

The approach taken by the AAS involves the user and the computer collaborating: the user, with the help of contrast enhancement, identifies monuments; the computer then objectively and automatically traces the outline of the monuments. It does this by identifying and aggregating many small arcs from circles with varying radii and centre points. The steps outlined below are carried out in this procedure, which is described in more detail in (Redfern *et al.* 1998):

1. An approximate area (rectangle) containing the shape is identified by the user. It is assumed that a small region around the centre of this area contains all candidate arc centres, and that their potential radii fall within 25% and 50% of the length of the longer side of the rectangle.
2. For each candidate centre and radius, 50 discrete 7.2° arcs around the circle are tested.
3. At each point on the circumference of each arc, a greyscale value is calculated¹. A value is also calculated at the same point in the same arc *with a radius of 1 unit less*.
4. The difference between these yields a truly *directional* edge strength outwards from the centre of the arc². These strengths are summed over 12 points on each arc.
5. The 4 best arcs (those with the highest sum of edge strengths) between all tested circles at each of the 50 arc positions are used to build the final shape - i.e. 200 arcs in total, with varying radii and centre points.
6. Any outlying arcs whose radii are significantly above or below their local average are discarded.
7. The shape is drawn using a weighted moving average of radius and centre position, which smoothes the arcs into a coherent shape and approximates at weak areas where there is little or no evidence of edges³. Arc strength (sum of edge strengths) is used as the weighting factor, so arcs with good evidence affect the shape more (figure 11).

The key points of this approach that allow it to deal with the difficulties of the task, are:

- The directional edge detection, accurate to the sub-pixel level, maximises the available contrast;
- The arc averaging aspect of the technique deals elegantly with damaged and occluded monuments;
- The greatly reduced and geometrically constrained (arc-based) search regions minimise the effect of clutter.

The AAS technique for mapping monuments has been scientifically tested and proven to be more successful than other image processing techniques, when applied to this task (Redfern 1999).

Working with Monuments in the AAS

The procedure for mapping monuments in the AAS begins with a study of the photograph, and the interactive use of histogram equalisation to assist the identification of low contrast features (see figure 12). The area containing a monument is identified by the user, and the computer traces its circumference. This tracing can be touched up by the user

¹ Since the points on the arc will not fall neatly on the image pixels, interpolation is used to calculate these values.

² Searching for *edges* in an image is the first step in many digital image processing tasks. Abrupt changes in brightness normally imply edges of objects, and the aim is to automatically recognise objects in the scene, which are normally characterised by their edges.

³ The human mind is very good at visual interpretation, filling in the gaps in objects and ignoring unimportant information. The task of recognising objects from their edges is however very difficult to program a computer to do. The motivation for automating this process is twofold: it reduces the subjectivity inherent in recording, which is important for large archaeological databases; and, it requires far less effort from the user.

where required. The automatic shape extraction and manual touch-up (if required) only takes a few seconds and is almost fully automated, which means that the extracted shape is as objective as possible. A number of accurate and objective measurements of size and shape are automatically derived from the extracted monument, and its location in the user's co-

ordinate system is calculated. The 4 measurements currently made are: circularity, rectangularity, elongation, and total area. Since the monuments cover only very small areas in their overall photographs, the distortion of their shapes due to variations in elevation are negligible (Wong 1980).

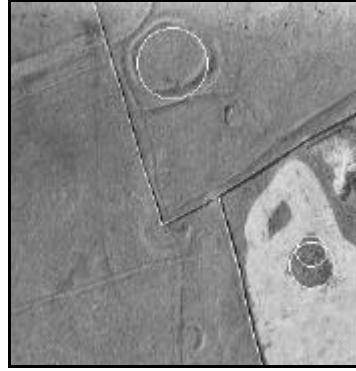


Fig. 10: An attempt at automatic monument detection. The computer has successfully detected the well preserved ringfort, though has also erroneously interpreted the high-contrast shape in another field as two monuments. The low contrast monument at the centre of the image (which was used as an example in figures 5-8) has not been detected at all.

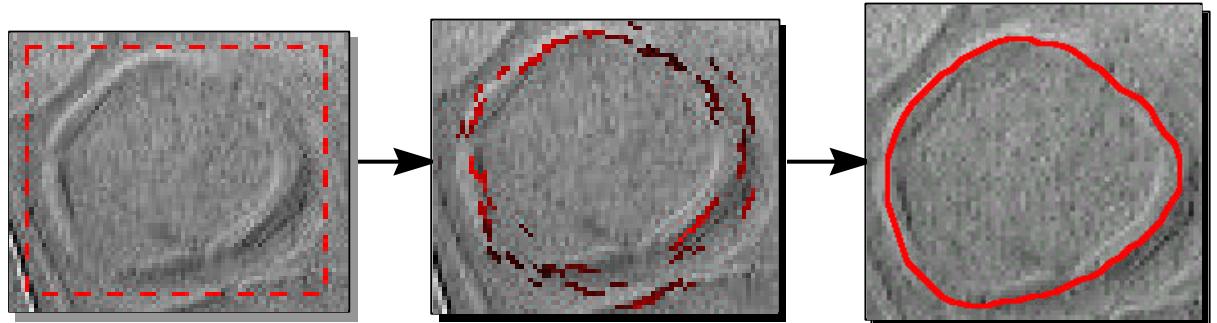


Fig. 11: Monument tracing. An area containing the feature of interest is identified. The computer then extracts arcs of varying strength, centre, and radius, rejects outliers, and smoothes the remaining arcs together using weighted moving averages into a coherent shape which is approximated at weak areas.

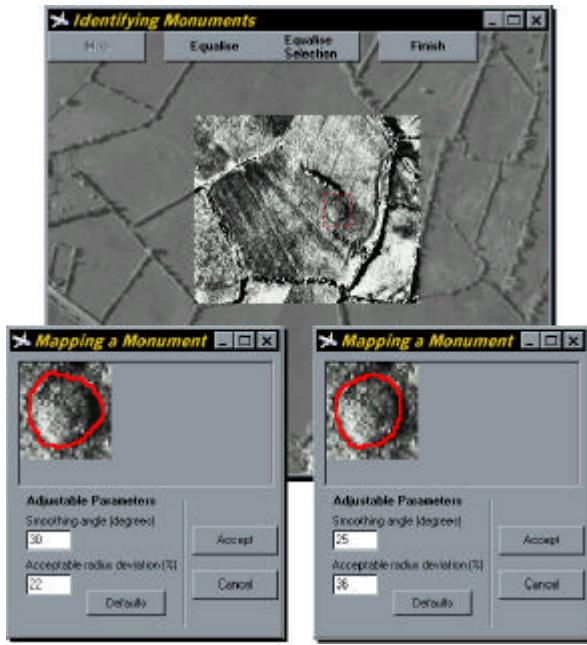


Fig. 12: The AAS monument mapping procedure. The user studies the photograph and makes use of local or global histogram equalisation, which attempts to maximise the overall contrast, and therefore visual interpretability, of the image. He/she then identifies the approximate area containing a monument, and the computer presents a suggested tracing of that monument (lower left). The user can “touch up” the suggested shape by modifying arcs with mouse clicks or adjusting parameters (lower right). The entire process takes a few seconds.

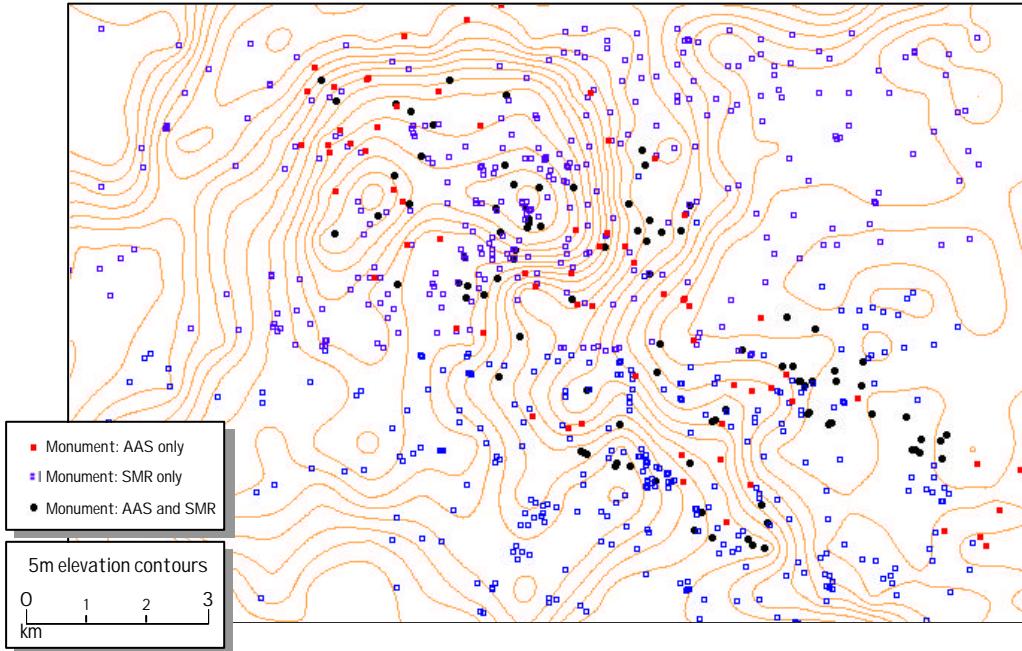


Fig. 13: Topographic map of the core Rathcroghan area, showing the archaeological monuments (a) discovered using the AAS but not in the SMR database, (b) in the SMR database but not visible in the aerial photographs, and (c) represented in both the AAS and SMR databases.

The Discovery of Previously Unrecorded Monuments using the AAS

In order to test the ability of the AAS to discover new monuments, a survey was carried out at Rathcroghan, Co. Roscommon (see Waddell 1988 for a discussion of this

archaeological complex). The Sites and Monuments Record (SMR) for the region was cross-referenced with the results of the AAS survey. In order to determine which of the AAS-mapped monuments represented previously undiscovered monuments, the distance between each AAS-identified monument and each monument of relevant type in the SMR database was calculated⁴. The nearest monument extracted from the photographs, if any, within a 50m radius of each SMR monument was assumed to be the same monument⁵. The remaining monuments, which numbered some 69 out of the total of about 800, were considered to be newly discovered. Clearly without field survey, it must be assumed that some of these features discovered by the AAS are not of archaeological origin.

DIGITAL ELEVATION MODEL GENERATION

Digital elevation models (DEMs) are valuable data products for archaeologists studying individual monuments, as well as the topographic contexts of wider archaeological landscapes. In addition to their use for visual site analysis, DEMs allow a variety of useful calculations, involving for example viewshed analyses, and calculations of slope, aspect (facing), and volume. The AAS makes use of a monument's local slope and aspect as part of its classification system (discussed in the next section). Small-area DEMs, for example those of

⁴ Monuments considered relevant were those classified as ringforts, any types of enclosure, or any types of mound or barrow, since these are the types of monuments dealt with by the AAS.

⁵ Clearly it was necessary to take into account the fact that the spatial accuracy of both the SMR and the AAS data was imperfect, when determining corresponding monuments in the two databases. An analysis of the distance between AAS monuments and their nearest SMR monument showed 50m to be a suitably high distance to choose: the majority of AAS monuments were within 10m of an SMR monument, very few were between 10m and 40m from an SMR monument, while none were between 40m and 50m of one. It was also found that there was a strict one-to-one correspondence between AAS and SMR monuments, i.e. AAS monuments were found to be close to *one and only one* SMR monument.

individual monuments, are also useful as base maps for geophysical or other subsequent survey.

Professional photogrammetry equipment, capable of generating DEMs from stereo pairs of overlapping vertical aerial photographs, has existed for a number of years. However, its cost and technical complexity has effectively made it unavailable to archaeologists. The two DEM generation approaches commonly taken by archaeologists have been: interpolation from contour maps, and ground survey using equipment such as electronic distance measure (EDM) devices (Haigh 1993). The former of these techniques is both labour intensive and inaccurate, while the latter is extremely labour intensive, though very accurate. Photogrammetry, by comparison, allows good accuracy while being highly labour efficient.

The AAS generates DEMs of small regions around individual monuments. It does not process the entire overlap between photographs because low-frequency distortions render these larger DEMs inaccurate. Severe distortions towards the edges of photographs also mean that monuments cannot be modelled if either image is close to the edge of its photograph (see Redfern *et al.* 1999 for an in-depth discussion of this component of the AAS).

Creating DEMs in the AAS

In order to generate a DEM of a monument and its vicinity, the AAS user manually identifies 3 or more corresponding points between the 2 images, which are displayed side by side (figure 14). They then click on the *Make DEM* button, and have the opportunity of adjusting parameters in the DEM generation process, as this is occasionally necessary when working with difficult images.

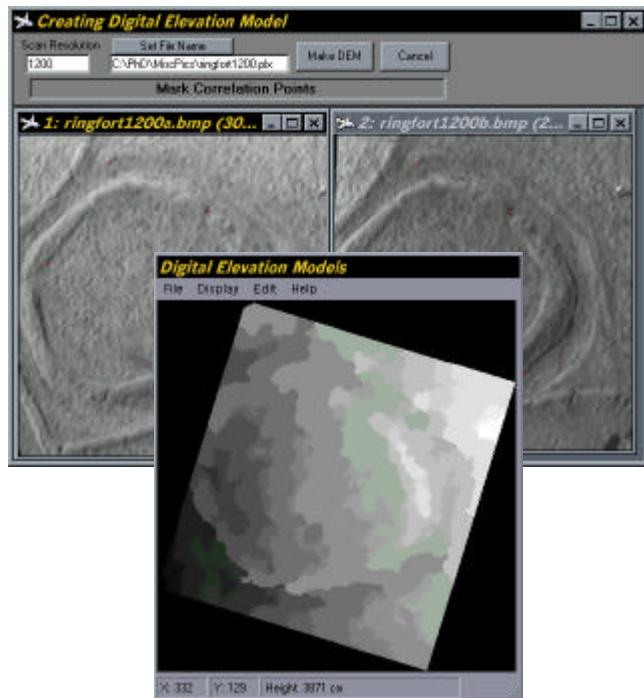


Fig. 14: Digital Elevation Modelling in the AAS. The stereo images are displayed, and the user identifies a few corresponding points. The software then produces a DEM. This 90,000 pixel example took about 10 minutes on a Pentium 166. The artificial “double-contour” effect is a result of scanning beyond the resolution of the photograph.

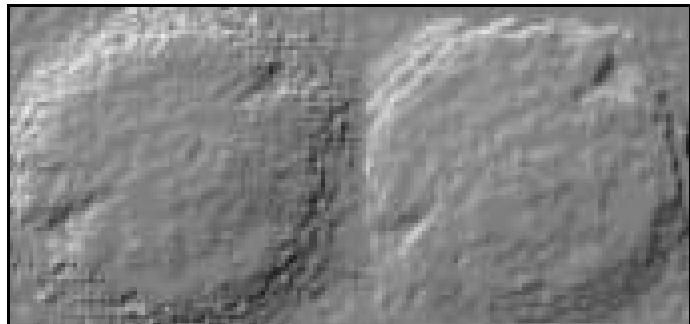


Fig. 15: DEMs of Rathcroghan mound, (left) generated by several weeks of ground survey, and (right) through use of the AAS.

Verification of the Accuracy of the Technique

A number of DEMs of monuments were generated by the AAS, and tested against Electronic Distance Measure (EDM)-derived DEMs of the same monuments. The monuments chosen represented a range of upstanding earthwork types, and their images also exhibited a range of textures and contrasts. Figure 15 provides one example, in which DEMs of Rathcroghan mound, Co. Roscommon, are presented. In this example, Pearson's correlation coefficient was calculated on a line-by-line (horizontal transect) basis, between the two DEMs. The average coefficient for these lines was 0.96. The heights

of corresponding pixels in these DEMs were plotted against each other, and the slope of the regression line was calculated to be 0.92. For this 7m. monument, this could lead to a systematic error of 56 cm. (8%) when estimating the total height of the monument. Given that the standard deviation of errors (i.e. the uncertainty due to random errors) is 34 cm., the overall accuracy is to about 90 cm., which is less than 0.1% of the flying height above the landscape. It must be noted that this level of accuracy is only obtainable for small areas of the full overlap between photographs, in which low frequency geometric distortion is not a major issue. Indeed, it is interesting to note that the systematic errors in the test DEMs were

found to be more severe in those monuments that covered larger ground areas. For a more thorough description of this accuracy testing, see (Redfern *et al.* 1999).

THE ANALYSIS OF CULTURAL LANDSCAPES

The Morphological Classification of Monuments

The technique of numerical, morphology-based typological classification has been applied to archaeological artefacts since the 1960s, and more recently to monuments. While the published classification schemes have tended to primarily incorporate ground survey evidence, there have been convincing arguments made for classification schemes based entirely on evidence from aerial photographs. The validity, or lack of validity, in attempting to classify monuments in this way has been heatedly discussed in the aerial archaeology literature for a number of years (see for example Edis *et al.* 1989; Whimster 1989; Startin 1991, 1992; Walker 1997). The primary weakness of the morphological classification technique is that it produces archaeologically abstract classes, and it is also significant that it disregards other important information about a site, such as cultural affinities and spatial relationships with other monuments. Morphological classification of monuments in general, and from aerial photographs in particular, is however regarded as being useful in a number of ways:

- As a means to produce *at least some* useful information from sets of raw morphological data, particularly in the case where no other information regarding a monument is available;
- In order to allow effective querying of large (regional or national) monument databases, through the selection of monument groups by class;
- To alleviate the problem of subjectivity in recording, which occurs inevitably when many different archaeologists contribute to a database;
- As a first step in the progress towards dating, function designation and the deeper understanding of monuments and their wider landscapes.

Without the attachment of any (even abstract) meaning, monuments discovered through aerial photographs provide little information until they are surveyed on the ground. Morphological classification, however, allows database queries to extract sets of 'similar' monuments, which provides the strongest

argument for the development of classifications, even if they are abstract in an archaeological sense.

The AAS Classification Scheme for Monuments Visible in Aerial Photographs

A variety of morphological and topographic metrics are considered to be significant to the classification of archaeological monuments, though some of these cannot be objectively collected because of the varying level of preservation of sites. This point is particularly relevant to the current purpose, since previously unknown sites are invariably those which survive as faint markings visible only from the air. Ground slope and aspect (facing) are important: ringforts, for example, tend to be on well-drained slopes. Size and overall shape are significant: it is suggested that larger, more accurately circular enclosures, for example, tend to be of prestigious ritual nature rather than domestic.

A number of other measurements, though considered significant to archaeological type designation, present problems in terms of objectivity. The compass direction of

entrance(s) is considered to be important, though entrances are often hard to define, particularly from remote imagery, and it is often hard to tell if they are original. Bank and ditch size (height, depth and width) are highly dependent on preservation. Measurements describing more complex structures (for example, systems of banks and ditches, or the nature of internal buildings) are notoriously difficult to collect, even from field survey, since neither structural changes that occurred during the period of occupation nor subsequent modifications of a site after its abandonment can be assessed (Barrett 1980).

The classification scheme developed for and implemented in the AAS uses 6 morphological and topographic measurements which are automatically derived from a monument's shape and DEM. These measurements, which are summarised in table 1, are those that (a) are deemed to be relevant to the morphological-topographic analysis of archaeological monuments, and (b) can be collected objectively from aerial photographs (Palmer 1976; Barrett 1980; Edis *et al.* 1989; Whimster 1989; Stout 1991).

Measurement	Calculation	Notes
Circularity	$(\text{Area})/(\text{Average distance of interior points from boundary})^2$	Maximised at 4P for a circle
Rectangularity	$(\text{Area})/(\text{Area of minimum enclosing rectangle})$	Maximised at 1.0 for a rectangle
Elongation	Length/Width	Length and width are calculated with respect to the principal axis of the shape
Total area	Pixels x area in photo of 1 pixel	The area represented by a single pixel in a photo is calculated automatically from user-supplied control points
Slope	Slope of best-fit plane	X,Y,Z ground co-ordinates of the points in the monument are submitted to a 3D linear regression (after Robinson 1981).
Aspect	Compass direction of best-fit plane	Orientation of photo/DEM is automatically calculated from user-supplied control points.

Table 1: Automatic morphological and topographic measurements made by the AAS.

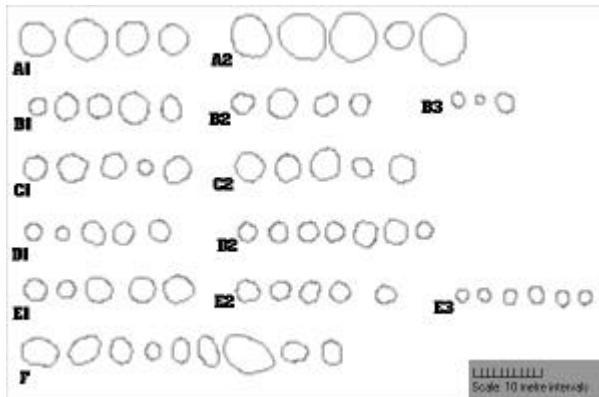


Fig. 16: Tracings of sample monuments from the classes defined by the AAS classification scheme.

	No.	Radius	Circularity	Rectang.	Elongation	Slope	Facing
Group A	11	high	high	low	low		
Group B	20					high	not N
Group C	26				tightly defined	low	
Group D	29	low				tightly defined	N or NW
Group E	28						SE, E, or NE
Group F	11		low		high	low	

Table 2: A summary of the 6 typological groups in the AAS classification scheme. 'Tightly defined' measures are those that unify a group (i.e. have low standard deviation) without actually being of unusually high or low mean value.

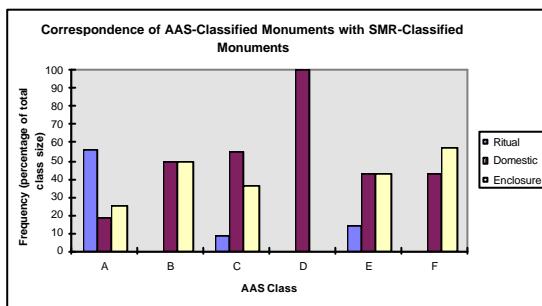


Fig. 17: Frequency histogram illustrating the correspondence between the AAS and SMR classification schemes in the Rathcroghan study.

In order to develop a typology of curvilinear archaeological features visible in vertical aerial photographs, a set of 125 monuments was selected from the Bruff Aerial Photographic Survey⁶. The data set was submitted to

agglomerative cluster analysis using Ward's method (see Everitt 1980), in order to objectively define typological groups. Six abstract monument classes, some with subclasses, were determined from this analysis (these classes are hereafter referred to as AAS classes A to F). Sample tracings of monuments from these groups are presented in figure 16, while table 2 summarises the characteristic features of the groups.

⁶ The Bruff survey was initiated in 1986 by the Office of Public Works (OPW) and the Dept. of Archaeology, U.C.C. The aim was to assess the potential of medium altitude vertical aerial stereo photographs for the recording of hitherto unknown archaeological sites (Doody 1993). The study covers

a 70 km² area centred on Herbertstown, Co. Limerick, and extends slightly into Co. Tipperary.

The statistical significance of this typology was proven using Monte Carlo simulation, though clearly archaeological significance is not ascertainable without a substantial program of field survey and excavation. The AAS implements this classification scheme through a pattern-recognition technique called Artificial Neural Networks (ANN): when the user has extracted a monument from a photograph and created its DEM, the software automatically provides a 'suggested AAS monument class'. See (Redfern 1998b; Redfern *et al.* 1998) for further information on the development, testing and implementation of the AAS classification scheme.

The Role of the AAS in Cultural Landscape Analysis

The AAS provides the digital tools to improve initial archaeological surveys of regions using aerial photographs. Although it is essentially a data-gathering package, it has the potential to improve the analysis of cultural landscapes if deployed in an integrated GIS environment. Monument complexes, for example, are not analysed by the AAS: however, by exporting monument data to a GIS in which other environmental and archaeological data is stored, the AAS provides valuable information to assist such analyses.

The morphological classification scheme as outlined in this paper clearly represents no more than a first, crude attempt at classifying Irish archaeological monuments from aerial photographs. Further photographic surveys, field work, and excavation of selected monuments, would be necessary to improve this classification. However, the cross-referencing of monuments with SMR data in the Rathcroghan survey provides some cause for optimism, if not regarding the classification scheme as it currently stands, then at least regarding the potential represented by such an approach. Figure 17 illustrates, for the monuments represented in both the SMR and AAS databases, the correspondence between class designations. There appears to be an association between AAS class A and SMR 'ritual' monuments, and between AAS class D and 'domestic' monuments. No AAS class appears to be associated with SMR enclosures: however, since the term 'enclosure' is somewhat ambiguous in that it may refer to both domestic and ritual monuments, this is perhaps not surprising.

CONCLUSIONS

This paper has described the Aerial Archaeology System (AAS), both in general terms from a functional perspective, and also more specifically in terms of its contribution to the three 'strands' of computerised aerial archaeology: monument detection and mapping, geometric rectification and topographic modelling, and cultural landscape analysis. The package is intended as a data-generation component of the archaeologist's GIS toolset, and would most usefully be deployed early in a hierarchical survey strategy.

By computerising archaeological survey from aerial photographs, a number of advantages over manual analysis are achieved. Information is also generated that is not available in many SMR entries. The key points of the system in these regards are:

- Interactive image improvement assists the detection of low contrast archaeological monuments;
- These monuments are swiftly and objectively mapped;
- Digital Elevation Model (DEM) generation is significantly easier than through traditional means;
- Morphological and topographic measurements are collected automatically and accurately;
- Monuments are automatically assigned to a pre-defined typology as they are recorded;
- All calculations and data handling is managed by the system.
- The work can be conducted within a very economic time frame⁷.

The AAS was developed as part of a research project whose primary aims were the investigation and improvement of aspects of the tasks of aerial archaeology, through the use of existing and newly developed digital image

⁷ In the Rathcroghan survey, the processes of photograph scanning, control point measurement and digitisation, and monument identification, mapping, and classifying took in total some 8 hours. The fact that the entirety of the work was carried out in an integrated digital environment involving the AAS, a GIS, and spreadsheet software, also greatly contributed to its efficiency.

processing techniques. The package is essentially a prototype which represents the integration of these techniques in a coherent and meaningful way. Significant room for improvement does however exist in many aspects of the AAS.

The fully automatic detection of low-contrast monuments in aerial photographs remains an elusive goal, and one which is perhaps beyond the current capabilities of computers. A number of improvements could be made to the DEM generation system; however, the scope of this paper does not allow a technical consideration of these issues. It should also be recognised that commercial software for topographic modelling from stereo pairs of photographs is becoming increasingly accessible for archaeological purposes. For the purposes of producing the topographic metrics of slope and aspect, the current system is fast, accurate and effective.

Clearly the abstract classification of Irish monuments described in this paper can represent only a first step towards archaeologically meaningful morphology-based classification: in order to advance further, extensive field survey and excavation of selected monuments would be required. While the Rathcroghan study served to apply some initial archaeological meaning to the classification scheme, this scheme in its current state of development is perhaps most useful as an illustration of practical techniques by which objective and automatic measurements may be extracted from monuments in aerial photographs. These are important objectives when seen in the context of regional or national databases, which can often be difficult to query since they consist of subjective and descriptive entries made by many different archaeologists. The techniques used also provide a contribution more generally to the process of morphological-topographical classification of archaeological sites: in particular, they show the way forward for fast, accurate and objective measurements, incorporating topographic metrics derived from stereo photo information.

There are a number of ways in which further research and development efforts have the potential to improve the AAS as an archaeological research tool:

- Field survey and selected excavation work could improve the abstract classification scheme and generate archaeological

'meaning'. A field survey project could also be used in order to provide the AAS with a set of unambiguous monuments and another set of unambiguous 'non-monuments', in order for its Artificial Neural Networks to learn to distinguish between them;

- The application of the AAS to more photographic surveys would also provide the potential for the refinement of its classification scheme;
- In order to prove the consistency and objectivity of description provided by the AAS, it would be useful to carry out experiments, similar to those described by Horne & MacLeod (1991), in which archaeologists independently made use of the system;
- The expansion of the AAS software in order to allow oblique photographs to be used would be useful, since obliques are an important archaeological resource and often low contrast, low relief sites are more clearly visible in them than in vertical images;
- It would be useful to expand the AAS in order to allow the detection and mapping of linear features as well as sub-circular features;
- The AAS could be modified in order to make a system useful for single-site analysis. Aerial photography has proved to be very useful in determining excavation sampling strategy within a site - the computer assisted generation of this 'pre-excavation information' could therefore prove to be valuable. Such a system could potentially make use of platform based vertical photography (see Barker 1986), or even aerial photography using model aeroplanes.

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