Close-Range Photogrammetric Measurement and 3D Modelling for Irish Medieval Architectural Studies

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Abstract

In Ireland, as in much of Europe, church architecture of the late medieval era is considered by architectural historians to have been designed according to specific geometric principles and methods. Research into such structures and their design methods has traditionally involved visually-based stylistic comparison of features, primarily by visual techniques. In recent years, however, more analytical approaches to these studies have developed and these procedures require accurate documentation of buildings and features.

3D models generated by a number of close range measurement techniques (terrestrial laser scanning (TLS) and photogrammetry) are appropriate for use in such studies. However, since historical research frequently requires the comparison for large numbers of objects and/or buildings, it is essential that the methods used are easily available and are of low or medium cost, while still being appropriate in terms of accuracy, speed and usability.

For the typical multi-site architectural historical study TLS is too expensive and too complex in terms of data collection, software processing and data management.

This project evaluated the suitability of a close-range measurement method for 3D modelling of medieval architecture comprising a non-metric digital camera (Nikon D70), a reflectorless total station (Leica TPS 1205) and software for stereo modelling. Stereo models suitable for the extraction of 3D details of medieval window tracery (an important stylistic and dating feature) were generated and each stage of production analysed. This paper presents preliminary results of investigations into the suitability of this method for use in Irish medieval architectural historical studies and finds that low-cost methods are capable of achieving sufficient levels of accuracy without being onerous in terms of time spent or user inputs.

1. Introduction

The development and commercialisation of Terrestrial Laser Scanning (TLS) technology in recent years is often seen as the solution to all cultural heritage measurement problems mainly because of the speed and accuracy of the method. TLS has been shown to be extremely effective in the recording of complex and inaccessible objects; both as an individual technique [PR01] and in combination with other measurement methods [EBG*05]. The method has also been successfully used in the protection and reconstruction of damaged sites, including some at UNESCO World Heritage Sites level such as the Bam Citadel, Iran [BS04].

Many of these projects have been completed as proof-of-technology and method by instrument or software developers, or by interested academics. Others have been funded through grants from national or international cultural heritage sponsors.

Based on the positive results reported in the literature a significant number of regional and national bodies (including one in Ireland) have purchased TLS systems for use in cultural heritage applications. However, for many individuals and organisations involved in the care and study of cultural objects, measurement using TLS systems is not currently realistic for two main reasons – cost and knowledge.

[Ker06] has shown that the costs involved in the production of fully rendered 3D models of heritage objects, even when accounting only for the operators’ time, would be prohibitive for all but the best-funded projects. The knowledge required by the collectors and, more importantly, users of the data is also of a different type to that required for previous measured surveys. In particular, the learning-curve involved in becoming competent in the utilisation of TLS processing software and the output of usable products from point clouds of data is excessive for many applications.

However, this project was not concerned with the production for fully rendered 3D models of complex sites but of simple objects – traceried windows. In this instance TLS could provide high quality data in a short period of time. However, for the project concerned over 100 individual sites, distributed over the island of Ireland, need to be measured and the investigators do not have access to TLS equipment for the necessary duration. Also, although
the products of the measurement will be 3D models, they are models of weathered and damaged medieval stonework, and TLS-generated data would be of higher accuracy than is required.

The investigators, therefore, have evaluated the use of other less-expensive remote sensing technologies and their ability to meet the needs of cultural heritage documentation for architectural historical investigation. In the research presented here, the contribution of relatively low cost image-based measurement methods to the field of history of architecture in Ireland is evaluated.

2. Irish Medieval Architectural Historical Studies

The study of medieval architecture in Ireland, as in many places, has typically used visually-based stylistic comparison to evaluate the methods used by medieval architects and masons in the design and erection of buildings. This method also enables the historian to trace the development of architectural styles and methods over time and from place to place.

In particular a number of building elements are often used by historians as indicators for the development of techniques and fashions. These features include window tracery and moulding profiles of windows, doors and piers.

In England Morris [Mor92] has used moulding profile analysis to assist in the dating of medieval buildings where documentary evidence is absent or scant. Similar work is ongoing in Ireland [ODo06] where evidence from buildings is often the only available information source due to the severe lack of contemporary documentation relating to the foundation and usage of medieval buildings.

Window tracery has also been used as evidence for dating buildings as well as for analysis of the movement of stylistic ideas. Fawcett [Faw84] produced a catalogue of Scottish window tracery that he used to suggest the origin of design ideas as well as proposing building dates for undocumented objects.

While by the mid-16th century English and Continental European master masons (architects) were building cathedrals with vaults 50m above ground and towers up to 153m above ground [Hey95] their Irish counterparts seemed to have trouble executing window structures less than half that height. The reasons for this limitation on Irish structures are often levelled at a lack of funding from patrons and knowledge by masons. Accurate measurement of remaining structures may provide information about the methods used by masons and the failings, in design or structure, which may have contributed to the reduced size/ambition of the buildings.

For this area of study, and a number of other specific architectural historical topics, research is beginning to focus on the abilities of modern measuring instrumentation to supplement the visually-based stylistic analysis previously preferred. Comparison of 3D measurements of objects (mouldings and window tracery) from various sites is much easier and accurate in today’s digital environments. To this end, this project is an evaluation of the ability of low-cost remote sensing methods to produce the types of data that can be analysed between numerous medieval sites to add to the body of knowledge about their foundation history and building and design methods.

In particular, the notion that geometric techniques were used in the design and setting out of built objects during the middle ages is suited to evaluation by accurate measurement. The geometric principles date as far back, at least, as the Roman Vitruvius of the first century BC, who wrote that architects were taught to strive for harmony in the design of their buildings through the use of proportion, symmetry and numeric systems to ensure that the parts related pleasingly to the whole [Mor60]. Many historians have shown that similar principles were used in the design of churches and cathedrals, both in their plans and in their details, in the middle ages in Europe [Zen02] and England [Fer76] and [His02]. Thus far studies of Irish buildings have only shown a little adherence to these principles [Sta90] but further measured studies could reveal either more examples of use or possible reasons for the lack of use.

3. Test Site

The site chosen for testing the image-based remote sensing methodology was St. Mary’s Collegiate Church, Howth, Co. Dublin, Ireland.

The building is in ruins having no roof and with much natural and human damage having been inflicted on the walls and windows (Figure 1). This is typical of many Irish buildings of the period which were allowed to fall into disrepair due to religious changes and a lack of funds from the 16th century dissolution to the present day.

The building, as it stands, extends to less than 30m in length and 12m in width and contains elements from the 14th, 15th and 16th centuries. The walls are mainly of rough masonry but the windows are constructed of cut stone. Most windows have segmental arches but one east and one west window have pointed arches, each containing tracery.

The tracery in the west window is badly damaged and only the cusps remain (although drawings from 1960 show the window in its intact state [LEA60]), thus the study focused on the east window (Figure 2). (In future work it is hoped that accurate measurement of tracery remains, combined with measurements taken from similar windows/sites, will be used to assist in reconstruction of objects using fallen stone retained at a number of Irish sites.)
4. Equipment

Since the aim of the research is to evaluate a low-cost method of measuring medieval architectural features, the equipment and software used were either inexpensive or easy availability to facilitate rental without high overheads.

4.1 Reflectorless Total Station

Photo control was collected using a Leica TPS 1205 reflectorless total station with an angular accuracy of 5’ and a maximum reflectorless range of 300m (accurate to 3mm + 2ppm). Weekly hire of this instrument cost in the region of €120 thus making it accessible to most research projects. For this project an instrument owned by the Dublin Institute of Technology was used.

4.2 Digital Camera

The camera used for photography was a Nikon D70 6 Megapixel camera with a Nikkor 18-70mm lens. For all photographs used in measurement the focal length was fixed at 24mm and the focus at infinity. (Both of these parameters were easily checked using the EXIF information displayed at the time of image capture.) Camera calibration was not carried out for two reasons. Firstly the object of interest was photographed at the centre of the image to ensure that a minimum of lens distortion effects would be present. Secondly, the accuracy required for the final measurements, particularly because of the weather-damage mentioned in section 2, was deemed to be below the threshold that would require full calibration.

The Nikon D70 has a 23.7mm by 15.6mm sensor with 3008x2000 pixels resulting in a pixel size of approximately 8µm.

4.3 Photogrammetric Software

In line with the goal of low-cost analysis of data for architectural historical applications the software tested for this project was LISA FOTO developed by Wilfried Linder of the University of Duesseldorf [Lin03]. For research purposes the latest version of the software costs ~€800 which is significantly less than the costs associated with commercial photogrammetric packages.

Although mainly developed for use by non-photogrammetrists in aerial applications the software has been used for close-range applications using non-metric digital cameras [Lin03] and [Map04].

5. Measurement

5.1 Photography

Multi-photo techniques (such as used by Photomodeler [Eos06], Shapecapture [Sha06] or iWitness [FH04]) were ruled out because they typically require the acquisition of photographs from an array of angles, including from above the object of interest [WO94]. At most of the Irish sites of interest for architectural historical studies such photographs would be difficult, if not impossible, to obtain due to issues of accessibility, safety, cost and time.

Therefore stereo close-range photogrammetric methods were used. Images were taken from either end of a stereo baseline of 1m length at a distance of ~10m to ensure a base to distance ratio of between the recommended 1:5 and 1:15 values (Figure 3).

5.2 Photo Control

Using the reflectorless total station Leica 1205 the three-dimensional co-ordinates of 42 natural control points were measured. While it is acknowledged that targeted control points would add to the overall accuracy of the restitution it was not possible to use them for this study. Typically, buildings of interest to architectural historians are protected...
structures and any interference, even sticking on removable
targets, is discouraged. Also, as mentioned in section 5.1,
building accessibility is typically very poor (even if a hoist
or other platform was available) and adhesion of targets is
not possible.
The 42 control points were well-distributed around the
tracery of the east window and its setting in the wall. The
most defined natural points were chosen, such as points on
the railings.

6. Software Processing

LISA FOTO software performs Exterior Orientation (EO)
in mono mode with the operator performing all
measurements of control points on each image separately
and the software calculating a space resection. The use of
more than 3 control points invokes a least squares
adjustment, as was the case in this project where 22 control
points were measured per photo. The remaining control
was used for validity checking.

In LISA FOTO the photos are later combined into a
stereo model using the Define Model function. In this
module the focal length, the co-ordinates of the photo
projection centres, the \( \omega \), \( \phi \), \( \kappa \) rotations and the image and
real co-ordinates of the control points are transformed via
an affine or polynomial transformation.

6.1 Stereo Processing Results & Analysis

For the Exterior Orientation 22 of the available 45 control
points were measured in each image. Table 1 shows the
results of the orientations.

<table>
<thead>
<tr>
<th>Image</th>
<th>Average Std Deviation (mm)</th>
<th>Maximum Std Deviation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>0.010</td>
<td>0.031</td>
</tr>
<tr>
<td>Right</td>
<td>0.009</td>
<td>0.020</td>
</tr>
</tbody>
</table>

**Table 1: Exterior Orientation results**

Although the results display low relative standard
deviations it is the outcome of the model definition, as
given in Table 2, that is more indicative of the quality of
the processing.

<table>
<thead>
<tr>
<th>Approximate Pixel Size</th>
<th>0.0038m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height to Base Ratio</td>
<td>4.9121</td>
</tr>
<tr>
<td>Approximate Maximum Attainable Accuracy in Z</td>
<td>0.0186m</td>
</tr>
<tr>
<td>Approximate Photo Scale</td>
<td>1: 471</td>
</tr>
<tr>
<td>Mean y-parallax before correlation</td>
<td>0.73 pixel</td>
</tr>
<tr>
<td>Mean y-parallax after correlation</td>
<td>0.01 pixel</td>
</tr>
<tr>
<td>Mean Correlation Coefficient</td>
<td>0.8809</td>
</tr>
</tbody>
</table>

**Table 2: Model definition results**

The mean correlation coefficient of 0.8809 taken in
combination with the value of mean y-parallax after
correlation (0.01) indicates that using the 22 measured
control points the software was able to reliably match the
two image positions and orientations calculated by the EO
phase. The closer the correlation coefficient is to unity the
better the result. The failing of this set of measurements
may lie in the distribution of control points towards the top
of the model (also the top of the window tracery). Unlike in
the lower parts, at the top of the model the control points
were concentrated on the central mullions and the peak of
the arch. This resulted in an uneven distribution of control
points throughout the model.

Although the model boundaries were set with the project
(the x and y extents are illustrated by the heavy lines on
Figure 4) it is possible that the limited extent of the control,
relative to the full photographs, may have contributed to
some inaccuracies in correlation.

![Figure 4: Control point distribution and model area](image)
attainable z accuracy thus calculated by LISA-FOTO is just below 2cm. This figure is at the limits of what is acceptable for analysis of the envisaged products, i.e. 2D profiles of mouldings and 3D models of tracery.

It is clear, however, that in most circumstances this accuracy can be improved upon, particularly by more careful photography. For future work a number of other digital focal lengths will be available, including both 18mm and 35mm, which will expand the range of photographs that can be taken on any site. The pixel size on the object can thus be improved from 3.8mm to enable both better control point measurement for model setup and better point/profile/object extraction from the model.

7. Outputs

Traditionally the products used in architectural historical studies were 2D in nature comprising either profiles (plan views) of particular pieces of stonework (piers, mullions, window tracery) or elevation drawings of objects. In some cases perspective drawings are used but these were visually based rather than measured.

Using the type of photogrammetry presented above once the stereo model has been created via orientation procedures 2D products such as profiles and elevations can be easily produced.

However, unlike traditional methods, these products are created in a fully digital environment and can be output in ASCII format from which they can be imported into a CAD system. Once in any CAD package profiles from different objects, which are adjudged to be similar on the basis of visual comparison, can be overlaid and compared for both size and stylistic similarity.

Research in England [Mor92] has also pointed to the repeated usage of particular feature sizes, based on typical medieval units, by individual masons or schools of masonry. With all features extracted digitally such repetition will be easily recognisable. This type of information is useful to architectural historians when tracing the movement of the “free” masons of the middle ages.

Likewise, elevations of window tracery could be compared via overlays in CAD. However in line with taking full advantage of the capabilities of photogrammetry and the CAD environment these 2 elements (profiles and elevations) will be combined into a 3D model which can be compared via 3D CAD overlay, or using another modelling language.

7.1 Evaluation of Outputs

Using the remainder of the control points measured in the field by the total station but unused in the orientation procedure it was possible to carry out an evaluation of the quality of the model (Table 3).

<table>
<thead>
<tr>
<th>Coordinate</th>
<th>Average Difference (mm)</th>
<th>Maximum Difference (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X, Y</td>
<td>0.003</td>
<td>0.021</td>
</tr>
<tr>
<td>Z</td>
<td>0.023</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Table 3: Stereo Model Evaluation

As would be expected the quality of the model in planimetry (elevation) was better than in depth. The magnitude of the difference in quality is too high but it is envisaged that in future work the quality of Z co-ordinates will be improved using the improvements in fieldwork and processing listed in section 6.1.

Another factor in this variation between field and stereo model co-ordinates is the human element. In line with the low-cost concept of LISA-FOTO stereo viewing is facilitated using Cyan-Red Anaglyph glasses. Seeing in 3D through these glasses requires more acclimatisation than is typically needed with polarisation or flicker technology.

8. Project Completion Aspects

Fieldwork for this method is rapid. Once there are no accessibility restrictions directly in front of the object of interest stereo photography can quickly be acquired. In the simplest cases where it can be judged that the object of interest is symmetrical between interior and exterior all control point measurements can be acquired from a single total station setup; thus very quickly even when acquiring a large number of redundant points as checks or even to field measure particularly important features. Thus fieldwork per object would typically take between 1 and 2 hours.

In more complex situations where two sides of an object occur on either sides of the wall of a building and the object is deemed not to be symmetrical it is necessary to first measure a geodetic network. Depending on accessibility aspects for the object – typically medieval churches had only one entrance – the network may require a significant number of setups to connect interior and exterior. It is not envisaged that many relevant sites will require this level of processing but those that do will probably increase fieldwork time by a factor of 4 or 5.

Orientation of the stereo model, once the operator is familiar with the software, is also rapid, requiring again only 1 to 2 hours.

Extraction of features typically comprises the bulk of the processing time. For the window tracery show in Figure 3 the extraction of points and lines sufficient to produce a 3D CAD model required approximately 4 hours.

Th the ratio of field to orientation to feature extraction time could be given as 2:2:4. This particular object would not be considered very complex in comparison with some to the other objects that will be measured in the future. Thus the feature extraction aspects of projects could increase from representing half of the time to three-quarters or more.

9. Conclusions & Future Work

In conclusion, the photogrammetric method using low-cost software is usable for this type of architectural historical study particularly since the accuracy requirements are not very high. However, a degree of care is needed in the acquisition of control information and photography. At some sites it may be possible to use targets to increase accuracy and reduce the total numbers of control points measured.

The usage of digital image matching methods for feature extraction, rather than using an observer, may reduce processing time but these, again, must be used with care.
Further work will involve the acquisition of 3D models of tracery from a large number of sites and the creation of a digital database. Using CAD, VRML and/or GML options models can be compared in a digital environment to look for patterns of building and design. If found these patterns could assist in the dating of objects, in analysis of building methods, and in the reconstruction of objects from in-situ remains and fallen stone; all aspects of interest to architectural historians.

References


