Exploring New Pathways Between Physical and Virtual Models

The Vaults at Fountains Abbey

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The first generations of computer aided design systems were largely characterized by geometrical modeling software that could, in some applications, generate physical output in the form of computer aided manufacturing. More recently the technology has expanded to include a variety of ways to reverse direction, such that physical objects are captured and translated into computer graphics geometrical models. Laser surveying methods that produce point clouds are among the newer technologies that make this possible. The interpretation of the point clouds and translation of them into a computer graphics three-dimensional model can be subject to various mediation processes. This paper reports on a translation environment that interprets the point clouds so as to not just replicate the physical world, but rather encapsulates it towards the refinement and realization of geometry design objectives. A case study of Fountains Abbey, a Cistercian Abbey in the United Kingdom, serves as the basis for experimentation and control of surface geometry.

***Keywords**: Graphics Programming; Canonical Geometry; Fountains Abbey; Point Clouds; Custom Objects*

Determining the Geometry of the Vaults at Fountains Abbey

The project of determining the geometry of the vaults at Fountains Abbey has a number of objectives. First, there was a desire to create a "reconstructed" model for lay interpretation of the historic monument for tourists visiting the site at the English National Trust. Second, it was hoped this "reconstruction" might involve a comparison between the surveyed geometry and an idealization based on canonical forms. Third, the capturing of a geometric phenomena and its rationalization/interpretation is an important part of the contemporary architectural process and therefore the techniques described in the paper are of broader relevance. Fourth, the interpretive process can be considered as a series of transformations. Each transformation has its own control parameters and takes the output of preceding transformations as input. The transformation system, data flows and control parameters can be visually presented as a symbolic model.

The project has been developed in four steps:

- develop a program to generate canonical geometry for the quadripartite vaults at Fountains Abbey;
- survey the vaults;
- interpret the survey relative to the canonical geometry;
- refine the canonical geometry to reflect the findings of the survey.

This paper reports on the current state of the project and future technical issues that still need to be addressed. Some implications for design methods are discussed.

Canonical Geometry

Several architectural historians have formulated basic assumptions about vault geometry helpful to this study. James Acland speculates on vault construction methods and gives insight into a rational basis for their form (Acland). Francis Bond makes important distinctions between native English and French influenced methods of geometrical vault construction, some of which is in evidence at Fountains (Bond). In his famous twelfth century sketches, Villiard de Honnecourt gives a schematic basis for vault geometry over which I have superimposed a diagram for clarification (see figure 1). Note that the diagonal crossing arch of a typical vault is depicted in the semi-circular arc. The other arcs depict the pointed arches at the ends of the vault. These arcs are maintained at the same radius as that of the diagonal crossing arch. In the case of Fountains abbey, unlike the situation depicted in figure 1, the apex height of the pointed arches is roughly equal to that of the central crossing arc (Mark).

In the vaults of the lay brothers refectory at Fountains, it appears that the radii of all the ribs are relatively constant. As explained in a more general case by Bond, it also seems that the side ribs are pointed to fit the constraints of maintaining the side apex heights roughly equal to the

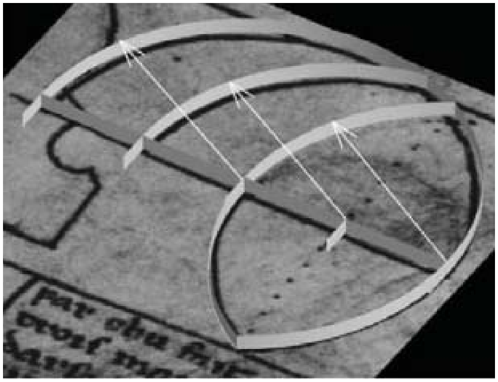


Figure 1. Sketch with superimposed diagram.

apex height of the semi-circular diagonal crossing arches. A few additional constraints can be added to reflect observations about the particular vaults at Fountains. A computer graphics program was written to generate these vaults given any ground plan. Figure two depicts the vaults generated by this program superimposed on a plan. The actual vaults represented by this program are relatively intact today. In figure three a perspective match of the computer-generated vaults is made against a photograph of the actual vaults taken at the Fountains Abbey site.

The close fit of the perspective match, however, is deceptive. The methods of perspective matching easily fool the unaided eye. If we take

Figure 2. Superimposition of the vaults over the plan of Fountains Abbey.

Figure 3. Perspective match of computer generate vaults with photograph

into account additional information about how the masonry is laid out, seemingly according to a French method described by Bond, it becomes even less certain how useful this initial approach is in coming to terms with the geometry of the actual vaults. For example, note in the photographs below that there is a wide variation in the vault webs. In some cases the vault webs are relatively flat and in other cases more rounded. In some instances the masonry appears to maintain a horizontal course and fits the French method described by Bond. In other cases the masonry appears less regular.

In an attempt to more closely approximately the surface geometry of the vaults, further refinements to the program were made. The web surfaces were divided into smaller degenerate Coon's surface patches. The arcs defining the ribs were converted in the bsplines. The control points of the surfaces were placed to connect corresponding locations along parallel edges of the ribs to mimic what seemed visually evident in the masonry during the visits to the site. That is, the French influenced approach of having the masonry move in a parallel fashion along the ribs, such that there was a splay along the diagonal, was simulated. These vaults are generated in figures 5a and 5b.

The new geometry appeared at least conceptually to match the conditions of the vaults at Fountains Abbey, but several problems remained. First, the computer-generated geometry is purely an idealized description and bears no relationship to the specific rib displacements evidenced at the site. Second, the masonry conditions vary considerably from vault to vault as noted in figure 4. These observations lead to the difficulty of making progress without developing an accurate survey for comparison with the computer-generated geometry.

Surveys of the Vaults

A visually compelling survey is provided by a method that has been used by English Heritage. They conducted a survey by means of total station theodolites in spring 2001, equipped with a reflectorless electro magnetic distance measurer (REDM). The data is manageable, and the specific information sought is readily isolated in the surveying technique. The surveyor team selected

Figure 4. Some photographs of the vaults and different masonry conditions.

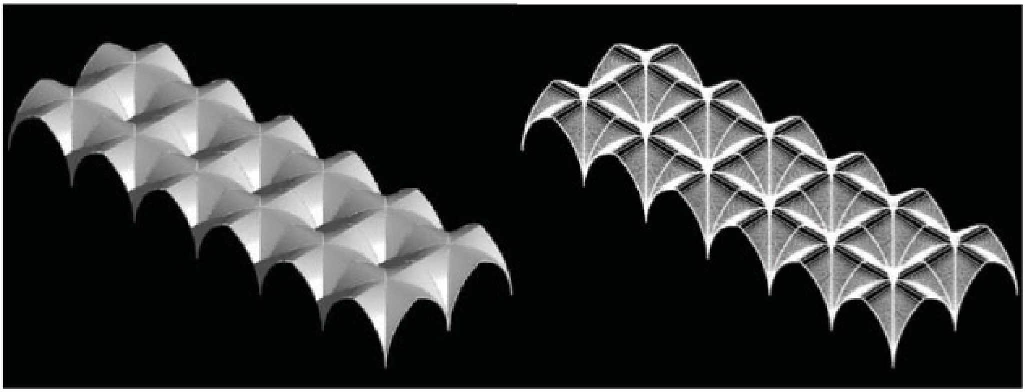


Figure 5a, 5b. Vaults generated with modified bspline surfacing technique.

two bays. The results of this method are depicted in figure 5.

Each of the different colors in figure 6 indicates different passes of the REDM survey process. The meticulousness of this survey method is evident in the capturing of the individual courses and in the clear definition of the ribs evident in wireframe geometry. However, close cross-registration of the different vault scans is less precise. Additional work is needed to correlate the different passes so that the geometry is fully consistent in its representation of the vaults. Moreover, this method is based in part on what the surveyor picks out as being significant while on site. This is generally a most reasonable approach, as the selected elements are based on educated assumptions on what data is critical to capturing the essential geometry of the vaults.

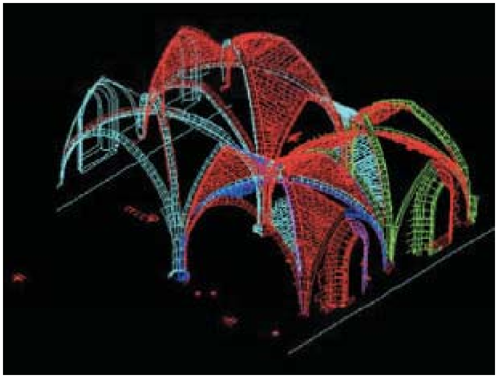
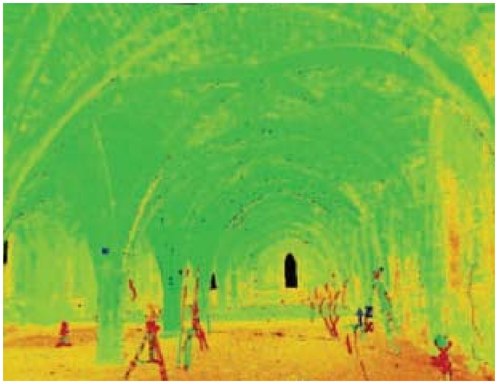


Figure 6. Survey of the vaults at Fountains Abbey.

At the same time, there is a risk of not capturing geometry that may be significant only when analyzed on a computer. This motivated a more complex and data intensive method of a newer laser surveying technique that results in the generation of point clouds. Two bays of vaults were again surveyed in spring 2002. The geometry of each vault is somewhat distinct, once the shape of individual stones and patterns generated by particularly trained masons and also vault settlement is taken into account. These subtle variations give the vaults their ultimate aesthetic look and need to be considered in making a general characterization. Yet, at the same time, if the objective is to arrive at a generalized canonical description, it is necessary to see the “forest from the trees”, and so some assumptions about primary determinant geometry, boundaries and general surface type are needed when interpreting the point clouds.

Interpretation of the Surveys

In the next step, the interpretation the point clouds underwent a translation into less idiosyncratic forms than the initial data cloud geometry. It seems impossible to pick-up every depression



in the surface area, every crack in the masonry, every apparent ridge in the surface of the vaults and come away with a canonical description. Rather, the translation reflects an approach that allows for the representation the vaults into a more generalized set of surfaces that can lead to speculation about basic principals of geometrical order. On the one hand, a surface model directly created off the point cloud is clearly descriptive and gives us much information visually. On the other hand, the surface model alone isn't directly based upon a generalized set of rules.

The interpretation also might involve some speculation in real time. Towards this end, an approach is incorporated that allows for the real-time control of variables determining the computer generated vault shape. That is, twenty-one points of control over the computer program were developed in response to some of the circumstances found on site and in response to some advise by structural engineers Heyman and Ochsendorf specializing in historical Gothic vaults (see acknowledgements). The points of control consist of the four ground points, the five apex points, and twelve points of potential hinging along each of the ribs.

In figure 10, the hinged vault shown in lime green mesh is fitted to the specific conditions of the point cloud.

Figure 7: Laser Survey yielding a point cloud of the vaults at Fountains Abbey

Figure 8: Surfaces generated from point cloud

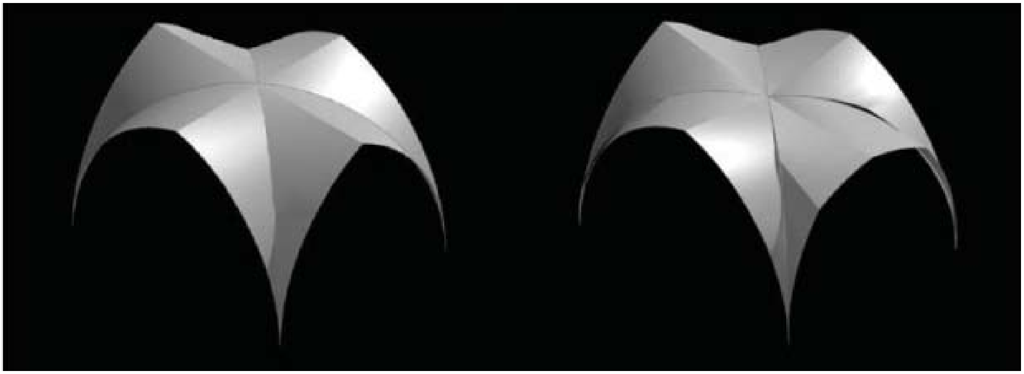


Figure 9a and 9b. Canonical geometry in fully erect and hinged form.

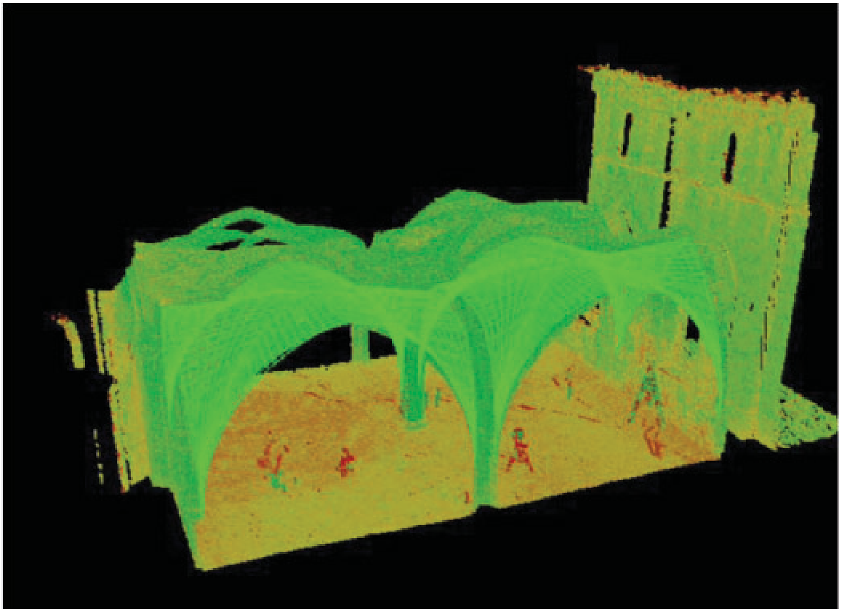


Figure 10. Refitting canonical geometry to the point cloud

Refinement of the Canonical Geometry

At the time of writing this paper, our goal is for the twenty-one variables to be more completed represented in a symbolic graph accompanying the geometrical model. In order to achieve this, we have ported the software into a new "custom objects" environment that is an early prototype of a system under development by Aish at Bentley Systems. In the first implementation below of the new system below, four of the ground points are highlighted and also are accessible in the symbolic model. The entire model can be modified in real-time dynamics while preserving the geometrical rules established in the vault generation algorithm.

The final part of this research is to test the value of the symbolic model as an essential management tool that can represent the interpretive process, and enable the user to visualize the interrelation of various sub-techniques and control parameters. The symbolic model allows the whole process to be fine-tuned in real-time without having to always start again with the raw data. (The symbolic model will be shown at eCAADe 2002).

The case study found a method of breaking down the vaults into fragments along the ribs that mimicked what appeared to be a general settle-

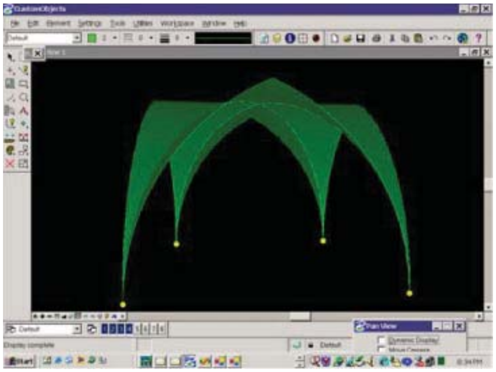


Figure 11. Custom object with symbolic model not shown

ment of the vaults, which primarily occurs well within the first fifty years of its construction (Heyman). One difficulty with the point cloud surveying technique at present is the lack of a well-integrated edge detection method. It seems evident that this technology will be more tightly integrated and will play a significant role in helping to pick out significant vault ribs and other shapes useful in this study.

Within the methods established for this project, there lies a potential to reflect on how traditional physical models and virtual computer graphics models can both be used in a contemporary design project. The physical models are the one hand tangible and highly malleable. Yet, on the other hand, they can readily be translated through point cloud surveying into canonical computer models approximated with precise points of control. Relating the two models together may provide a hybrid design medium that is flexible in a physical model form and subject to sufficient regularity of control in a computer graphics model form. This hybrid approach seems potentially well suited to CNC use in a design modeling and ultimately building fabrication process. The computer generated canonical description of geometry ensures that this approach is not arbitrary, but potentially subject to a precise rules. The physical model ensures that that the process can be enhanced by hand and is not overly constrained by the absolute limitations of the computer graphics program.

Future efforts on this project will include a more complete implementation within custom objects, smart edge detection methods for finding ribs, statistical sampling of the point clouds along the rib edges, and representation of multiple hinge points on each rib. However, even with a better canonical vault generation program, it may be important lesson to understand where the individual and fine craft of the masons may yet escape the precision of computer-controlled modeling.

Acknowledgements

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During a recent discussion in Cambridge, Jacques Heyman stated that much of the vault settlement occurs within the first fifty years of construction.