Thule peoples are the cultural and biological ancestors of contemporary Inuit and Eskimo groups of the North American Arctic and Greenland. By the late 12th or early 13th century, Thule groups had expanded eastward from the Bering Strait region into the Canadian Arctic. Unlike northwestern Alaska, the coastlines of the Eastern Arctic were largely devoid of driftwood. Consequently, the Thule people used whale bone to construct the roofing frameworks of their coastline winter houses. They erected the roof framework over a house pit furnished with a flagstone floor, raised sleeping platform, kitchen, and storage areas; and covered the roof frame with hide and a thick layer of turf, moss, and snow.1,2 Archaeologists know little about how these enigmatic houses were constructed because few exist intact. Reconstructing a 3D model of a Thule house can provide new insights into how the Thule people constructed and used these dwellings.

Our reconstruction of a Thule whalebone house provides a good case study of laser scanning’s use on an object of complex geometry. The reconstruction process would have been difficult, if not impossible, to resolve using 2D drawings because manual drafting or 2D computer-aided design (CAD) can’t easily solve a 3D structural system based on complex skeletal elements, such as a whale’s mandibles, cranium, and maxillas.

Early history of the project

Architectural research of Thule whalebone houses began in the summer of 1994, when Peter Dawson and a team of archaeologists from the University of Calgary constructed accurate maps of 23 whalebone houses at the Deblicquy site (Q1Le-1, shown in Figure 1a), an exceptionally well-preserved Thule archaeological site on Bathurst Island, Nunavut.3,4 We placed a grid of 3 × 3-meter units over each house mound. We then carefully measured and drew each grid unit’s structural and architectural components to scale, as Figure 1b shows. When we returned from the field, we drew plans of the site using AutoCAD software.

The value of laser scanning

In 2003, we began to explore strategies for creating 3D computer reconstructions of the Thule whalebone houses based on the earlier field study results. The ultimate goal was to test the design of houses made of bowhead whale elements—found at archaeological sites. We could construct an accurate model only if we had the major structural elements’ geometry (mandibles, cranium, maxillae, and ribs). Fortunately, the New England Aquarium in Boston has a mounted specimen of a North Atlantic right whale skeleton, as Figure 2a shows. Although the North Atlantic right whale (Eubalaena glacialis) is smaller than the bowhead whale (Balaena mysticetus), its skeletal morphology is similar. Thus, by scaling appropriately, we could use the North Atlantic right whale skeleton to model bones found during the archaeological excavation.
In the last decade, laser-scanning technology has emerged as an important tool in historic preservation and archaeological investigation. Although lasers aren’t new technology, their use as measuring devices is relatively recent.\textsuperscript{5-8} Prior to laser scanning’s development, creating a 3D model of a site or object required numerous field measurements and many weeks of data collection using optical theodolites, tapes, and calipers.\textsuperscript{5,7-11}

In creating a model of the North Atlantic right whale skeleton, a Cyrax 2500 laser scanner offered good accuracy (5 millimeters) at ranges of 50 meters.\textsuperscript{12} Reconstruction involves converting million of points into an optimized mesh, which takes several steps. Figure 2b shows the mesh model we created from the scanning data, and Figure 3 shows a flow chart of the process used to create the various parts of the model needed for the reconstruction and testing.

The exact steps encountered in the translation to mesh can vary depending on the application used for modeling, although the general issues will remain the same. In this case, we imported a point file from Cyra’s Cyclone (PTX format) into Innovmetric’s Polyworks (http://www.innovmetric.com) to create the mesh files needed for modeling. The last step of mesh optimization can be critical in scenes where high-count polygon meshes must be reduced to low-count models in order that today’s PC’s can render in real time (see Figures 2b and 3).

**Modeling in virtual space**

The electronic reconstruction process wasn’t unlike building the actual physical structure. The first step involved importing the 2D CAD file of information collected at the Deblicquy site in 1994.\textsuperscript{3,4} The plan for the largest and best-preserved house (Figure 1a) served as the basis for 3D reconstruction. This CAD data provided essential information for the reconstruction, including the subterranean pit’s topography, extent, and shape, which represent the dimensions of the enclosed space.

The list of bone types and sizes was also essential to this reconstruction. This information helped us scale the individual elements built from the laser-scanning data. Bones used in the original structure included the mandible, maxilla, cranium, ribs, scapulas, and selected vertebrae. We extracted these elements from the skeletal model using Polyworks. We used Autodesk’s 3DStudioVIZ for the actual modeling process, applying texture maps based on digital images to mesh forms to give a realistic appearance.

The second step involved extracting the pit from the topography using average depths and pit outlines in the original CAD file. We built a flagstone floor and elevated sleeping platform using virtual rocks whose shapes, sizes, and color we determined using actual rocks measured at the site. To begin the reconstruction process, we placed the major construction elements—cranium, mandibles, and maxillas—in their approximate locations found on the site. One issue that
emerged early in the reconstruction process was determining the bones’ exact locations. Over time, bones can move from their original positions, such as when a structure collapses. Given that the mandible or cranium’s spring point is critical to the reconstructed form, the bone’s initial location is only a best guess, which we refine through subsequent testing.

Our first hypothesis was to place the major supports along the pit’s perimeter. However, this arrangement made it difficult to enclose the interior space. We estimated that all of the bones would have to be 10 percent longer than their actual measurements to effectively create a tent-like structure.

We then placed the bones against the pit's...
walls, assuming the Thule builders would have excavated this subterranean area and lined it with flat stones. This arrangement results in more vertical elements than the first hypothesis. More vertical elements result in less applied force on the abutments and less splaying of the arch-like forms in these tent-like structures, as Figure 4 illustrates. Placing the major supports in a more vertical position also reduces the elements’ flexure and creates a house form with more interior space.

Although placing the bones on the pit’s inside perimeter solved the problem of spanning the smaller of the two rooms (the cooking area), two problems emerged in crossing the larger space (the sleeping area).

- Bridging the larger space with the elements found on the site proved difficult given the distance between the spring points of the crania, mandibles, and maxillas.

- The skin, which acts as a membrane over the bone structure, can’t support heavy loads of sod and snow alone. Without a ridgepole between the apexes of the domed spaces, the sod and snow’s weight would produce a sag in the structure, potentially destroying its integrity.

It wasn’t uncommon for the Thule people to move major bones from one site for use in construction at an adjacent site. Assuming bones might have been moved over time, we located several bones on adjacent sites of a size needed to enclose and span the spaces of Deblicquy House 8. The final design uses a mandible as a ridgepole supporting the skin, sod, and snow’s weight in the saddle area connecting the two spaces (Figure 4).

To construct a whalebone house, Thule builders would have lashed ribs to the major supports. Like gusset plates in a steel frame, these ribs helped create a more rigid structure. In a Thule whalebone house, the ribs are particularly important. Because the mandibles resting on the structure’s floor act somewhat like pin connections, without the ribs these elements would tend to rotate, causing instability in the entire structure. Builders would also have used the ribs to create an entrance-way tunnel with doors made from the whale’s scapulas. A mesh completed the model’s structure, representing the draped skins and layered sod of an actual whalebone house.

Prior to rendering images of the completed house form, we added lights of the intensity of whale-oil lamps to the interior space, as Figure 5 illustrates. The renderings completed in Autodesk’s 3dsMax exploit photometric-rendering algo-

Figure 4. Computer reconstruction of the Thule whalebone house showing the ridgepole design.

Figure 5. Computer reconstruction of the interior of a Thule whalebone house.
rithms that simulate light intensity and surface levels of reflectivity. Unfortunately, an estimate of a whale oil lamp’s illumination power only gives us an approximate lighting solution. Future research with whalebone lamp replicas will provide empirical data on their luminescent characteristics and should generate more accurate renderings of the interior space.

Structural stability
To go beyond the visual-inspection level, we imported mesh files representing the subterranean pit and bones into Dassault Systems’ Virtools (see http://www.virttools.com), an application for creating virtual worlds. This approach lets us assign physical properties to each structural element. Using the Havoc physics engine (a Virtools module), we assigned a mass to each whale bone and a friction coefficient to the bone and stone surfaces. To simulate the lashing of the major elements at each room’s apex, we created a series of pivots or hinges to tie the structure together. In virtual space, the structure seeks equilibrium after being assigned physical properties and will either remain standing or will collapse under its own weight. This approach let us refine the reconstruction by obtaining information on the structural elements’ locations after they’ve reached an equilibrium state, as Figure 6 illustrates. Although only a first step in a complex form’s structural analysis, adding a degree of physicality to the virtual objects can help archaeologists test a reconstruction’s validity in an interactive world.

Display and interaction
Using virtual-world authoring, a research team can create interactive worlds that they can distribute on the World Wide Web or view in Cave Automatic Virtual Environments (CAVEs). Currently, we’re testing the use of a version of the Thule whalebone house for teaching archaeology. Running the Virtools’ VRPack module, we can view the model with shutter glasses on a CRT display or project it in a CAVE environment. This active stereo format depends on sequential frame buffering of left and right views. At a minimum frame rate of 60 hertz, the image will appear in stereo.

At the University of Calgary CAVE, we’re creating the 3D effect using four projectors supported by a cluster of four PC computers. Each PC in the cluster drives a single projection screen: left, right, front, and floor. A Dell Precision 650 with Nvidia video cards (FX3000G) lets us display the complex geometry in real time. Interactive sound and atmospheric lighting all contribute to the experience’s totality.

The opportunity to view the whalebone house in an immersive environment helps students understand the dwellings’ complex geometry and consider various research hypotheses in a highly graphical context using objects with virtual physical properties. This helps them understand basic structural principles and lets them explore connections between space, light, and culture.

One issue in the CAVE environment is that interaction is generally limited to a single user, making it more of a theater for those observing without trackers and other input devices. Although few college campuses offer CAVEs, the ability to construct one from standard workstations will greatly expand this technology’s future in research and education. In a museum environment, the real challenge in creating experiences in these environments is interaction with the virtual world. With decreasing hardware costs, the only barrier will be the price of developing engaging virtual worlds, which both entertain and educate the public.

References
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