Virtual unwrapping: Reading the scroll from En-Gedi

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Background

In 1970, archeologists made a dramatic discovery at En-Gedi, the site of a large, ancient Jewish community dating from the late eighth century BCE until its destruction by fire circa 600 CE.

The settlement was completely burned to the ground, and none of its inhabitants ever returned to reside there again, or to pick through the ruins in order to salvage their property.
Excavations within the settlement’s synagogue uncovered the synagogue’s Holy Ark, inside of which were multiple charred lumps of what appeared to be scroll fragments.

Each fragment’s completely burned and crushed, had turned into chunks of charcoal that continued to disintegrate and crumble every time they were touched.
To decipher the charred remains, the IAA began working with Merkel Technologies Company, Ltd. Israel, which performed high-resolution 3D scanning of some Dead Sea Scrolls fragments and phylactery cases via a Micro-CT scanner.

After the fragment of the Ein Gedi scroll was scanned, the IAA sent the results to Professor Brent Seales of the University of Kentucky.
The chemical composition of the ink within the En-Gedi scroll remains unknown because there are no exposed areas suitable for analysis.

However, the ink response within the micro-CT scans is denser than other material, implying that it likely contains metal.
Terms

Mesh - a collection of vertices, edges and faces that defines the shape of an object in 3D computer graphics.

Texture- A texture map is an image applied (mapped) to the surface of a shape or polygon.

Voxel – a 3D pixel
Polygon model vs Voxel Model

Polygon model/mesh

Voxel model
Virtual unwrapping

Is a generalized computational framework

Allows text extraction while avoiding the need for injurious physical handling.

Based on paper by: William Brent Seales, Clifford Seth Parker, Michael Segal, Emanuel Tov, Pnina Shor, Yosef Porath
Stages

1. Volumetric Scan
2. Segmentation
3. Flattening
4. Texturing
Volumetric scan

The unwrapping process begins by acquiring a noninvasive digitization that gives some representation of the internal structure and contents.

For the En-Gedi scroll, a x-ray–based micro–computed tomography (micro-CT) was used.
Volumetric scan

The micro-CT provides a voxel based model of the scroll

Full scroll, side view
Volumetric scan

The micro-CT provides a voxel based model of the scroll

Full scroll, side view
Volumetric scan

The micro-CT provides a voxel based model of the scroll

Full scroll, side view
The surface as presented in the scanned volume is *not* developable.

A *developable* surface is a surface which can be unfolded into a plane without stretching or tearing.
Segmentation

Goal:
Identify and model the underlying surface of the layers from the volumetric scan, on which text is presumed to appear as a developable triangular mesh.

They aim to make an estimate for the surface using 2nd degree symmetric tensor and associated feature salience measures.
Segmentation

Challenges:

Layers of the skin that are close together create ambiguities that are difficult to resolve from purely local, shape-based operators.
Segmentation

Start with an initial set of seed points that will propagate through the volume guided by the symmetric tensor.

This is done to trace out the surface over the length of the volume.
Segmentation

Start (top down view)

Select a set of seed points
Segmentation
Segmentation
Segmentation

The user can tune the various parameters of this algorithm at any time during the segmentation process.

This allows for the continued propagation of the chain without the loss of previously segmented surface information.

The segmentation algorithm terminates either at the user’s request or when a specified number of slices have been traversed by all of the particles in the chain.
Partially localized surface:

Starting path

Ending Path

Texture generated
Accurately localized surface:

Starting path

Ending Path

Texture generated
Texturing

Goal:
Assignment of an intensity, “or brightness,” value derived from the volume to each point on a segmented surface.

This is where we see letters and words for the first time on the recreated page. Each point on the surface of the mesh is given an intensity value based on its location in the 3D volume.
Texturing

Problem:
Not every point in the surface mesh (that we get from segmentation) accurately matches a point in the volume scan.

Errors in surface segmentation combined with artifacts in the scan create the need for a filtering approach that can overcome these sources of noise.
Texturing

Solution:

Neighborhood-based directional filtering method, which gives parametric control over the texturing. The texture intensity is calculated from a filter applied to the set of voxels within each surface point’s local neighborhood.

The parameters include

- use of the point’s surface normal direction (directional or omnidirectional)
- the shape and extent of the local texturing neighborhood
- the type of filter applied to the neighborhood.
Filtering parameters for the Ein-Gedi scroll:

- Bidirectional neighborhoods (voxels in both the positive and negative direction)
- Line neighborhood with a primary axis length of 7 voxels
- Max filter

Imperfect Intersection of the mesh with the volume

Directional texturing with above parameters
The third stage, flattening, is necessary because the geometric model may be difficult to visualize as an image.

Specifically, it will be challenging to read the text on a 3D surface shaped like the cylindrical wraps of scrolled material.
Flattening

We approach flattening through a physics-based model:

The mesh is represented as a mass-spring system, where each vertex of the mesh is given a mass and the connections between vertices are treated as springs with associated stiffness coefficients.

The mesh is relaxed (flattened) to a plane through a balanced selection of appropriate forces and parameters.
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Points along one of the long edges of the segmentation were pinned in place while a gravity force along the x axis was applied to the rest of the body. This roughly “unfurled” the wrapping and aligned the mesh with the xz plane.
Final step: Merging

In total, around 140 small segmentations were generated during the segmentation process.

These segmentations were then mesh-merged to produce seven larger segmentations. Each large segmentation was then flattened and textured individually.

The final set of seven texture images was then texturemerged to produce the final master view image.

All merging steps for this work were performed by hand.
Final Result
The full set of transformations used to generate a final master view image can be referenced.

Every pixel in the final view can be mapped back to the voxel or set of voxels within the volume that contributed to its intensity value.
The images obtained through Virtual Unwrapping reveal the En-Gedi scroll to be the book of Leviticus, which makes it the earliest copy of a Pentateuchal book ever found in a Holy Ark and a significant discovery in biblical archeology.
Other work on the subject

The recent work of Barfod et al. produced text from within a damaged amulet; however, the text was etched into the amulet’s thin metal surface, which greatly eased the process of text extraction.

The work of Mocella et al. claims that phase-contrast tomography generates contrast at ink boundaries in scans of material where the ink does not necessarily contain metal.
References

Virtual Unwrapping - [http://advances.sciencemag.org/content/advances/2/9/e1601247.full.pdf](http://advances.sciencemag.org/content/advances/2/9/e1601247.full.pdf)


Revealing letters in rolled Herculaneum papyri by X-ray phase-contrast imaging – [https://www.nature.com/articles/ncomms6895.pdf](https://www.nature.com/articles/ncomms6895.pdf)

Interview about Ein-Gedi scroll – [https://www.jpost.com/](https://www.jpost.com/)
Questions?