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Computer Science Applications to Cultural Heritage

3D Reconstruction

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3D reconstruction & CH

3D reconstruction is about acquiring the full three-dimensional **shape** and **appearance** of an arbitrary object or scene.

Usually, this is performed with a combination of hardware-software architectures that combine depth and color information.

Why is difficult in the context of cultural heritage?

Cultural heritage objects and sites greatly differ from each other and a maximized **fidelity** of the 3D reconstruction is a core requirement.

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3D reconstruction & CH: Pivotal works

"The Digital Michelangelo Project"

M. Levoy, K. Pulli, B. Curless, S. Rusinkiewicz, D. Koller, L. Pereira, M. Ginzton, S. Anderson, J. Davis, J. Ginsberg, J. Shade, D. Fulk, The Digital Michelangelo Project: 3D Scanning of Large Statues, in: Proceedings of the Conference on Computer Graphics and Interactive, Techniques, 2000, pp. 131–144.

- Digitization of 10 statues created by Michelangelo, two building interiors, and 1163 fragments of an ancient marble map in Italy
- Combination of laser scanners, time-of-flight scanners and digital cameras
- Difficult task given the large dimension of the statues.
- Over 2 billion 3D triangles

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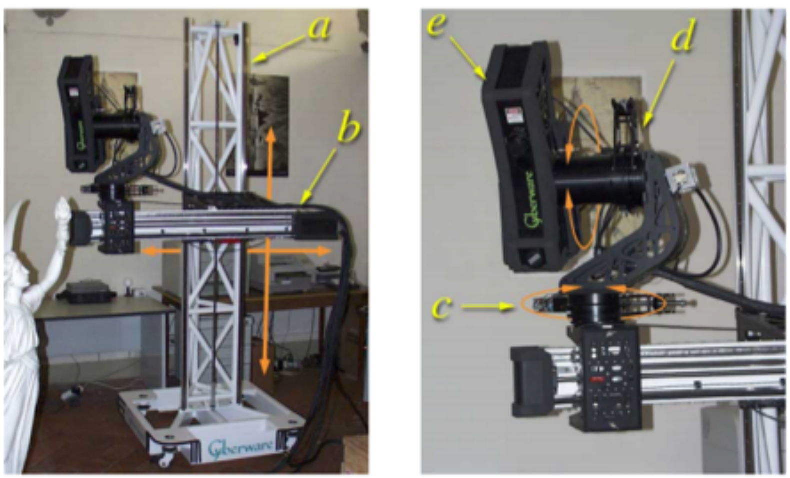

Figure 4: Our laser triangulation scanner and motorized gantry. The scanner, built to our specifications by Cyberware Inc., consisted of an 8-foot vertical truss (*a*), a 3-foot horizontal arm (*b*) that translated vertically on the truss, a pan (*c*) and tilt (*d*) assembly that translated horizontally on the arm, and a scan head (*e*) that mounted on the pan-tilt assembly, The scan head contained a laser, range camera, white spotlight, and digital color camera. The four degrees of freedom are shown with orange arrows.

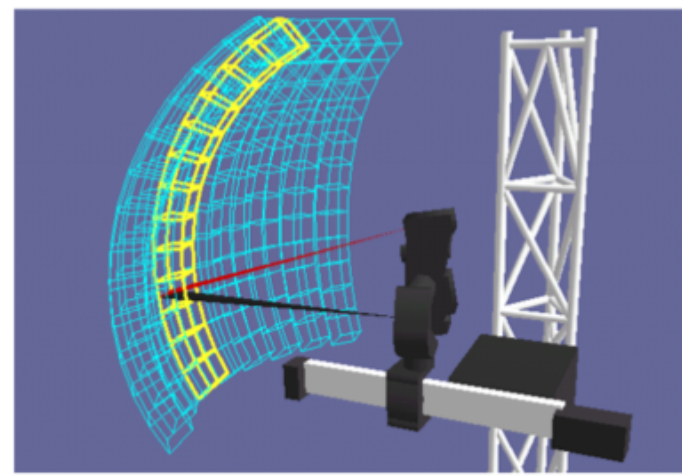

Figure 5: The working volume of our scanner. The volume scannable using our tilt motion was a curved shell 14 cm wide, 14 cm thick, and 195 cm long (yellow). Our pan axis increased the width of this shell to 195 cm (blue). Our horizontal translation table increased its thickness to 97 cm (not shown), assuming the scan head was looking parallel to the table. Including vertical motion, all truss extensions, and all scan head reconfigurations, our working volume was 2 meters x 4 meters x 8.5 meters high.

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(a) Acquiring range data. The laser line sweeps downward at 1 cm per second, acquiring 14,400 points per second. After a sweep, the head pans to the right and performs another sweep.

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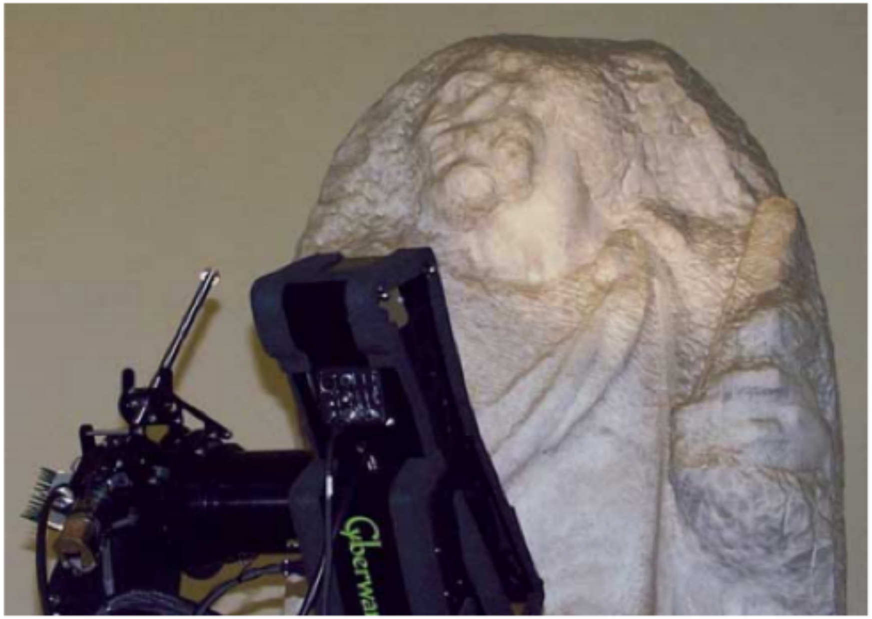

(b) Acquiring color data. One 1520 x 1144 pixel image is acquired every 3 seconds. Our white spotlight can be seen illuminating the statue. Figures (c) and (d) are taken from the upper neck.

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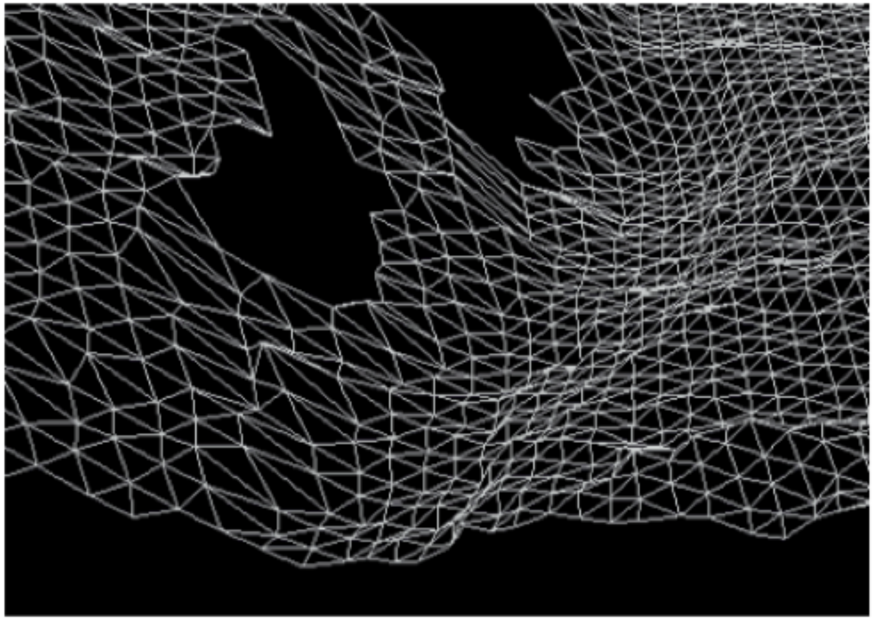
(e) Closeup of (c). This is a single sweep, so it is a regular 2D array (note that the triangles are in rows). The gaps are missing data due to occlusions.



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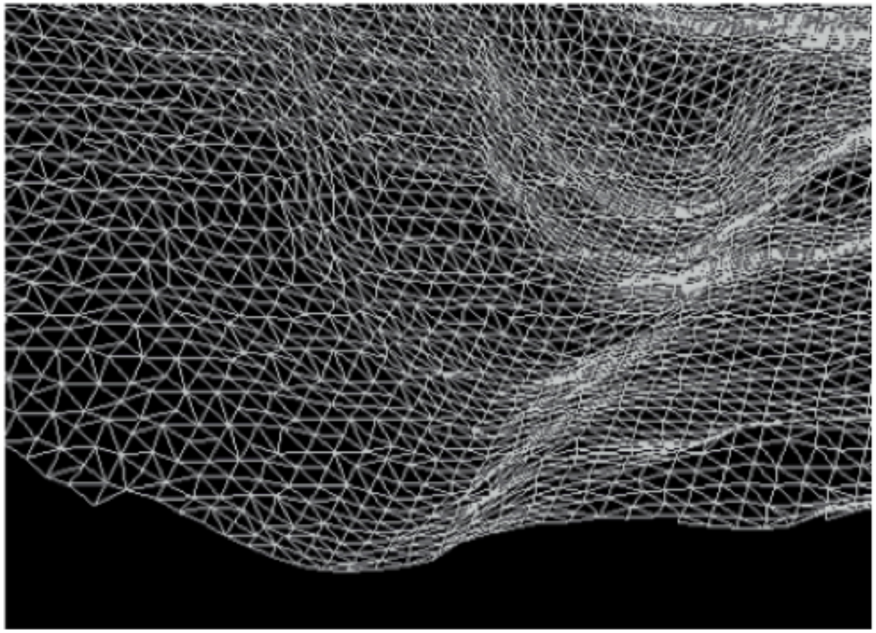

(f) Closeup of a merged mesh combining (c) and other scans. It is irregular since it is the isosurface of a volume. It is made finer than the raw scans to avoid aliasing.

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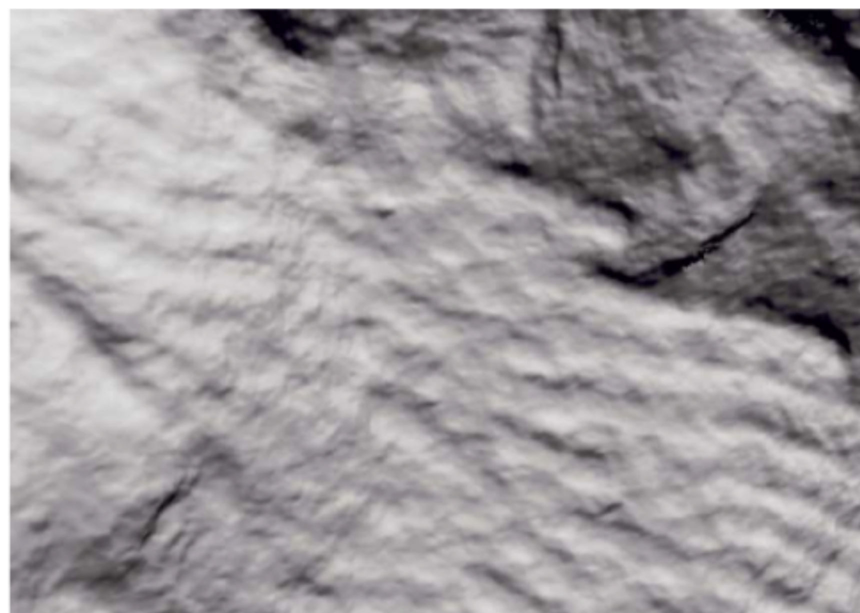
(g) Rendering of merged mesh. It is slightly blurrier than (c), due to miscalibration and misalignment of the scans, but the chisel marks are still clearly visible. Not all of our scans were used here, so some holes remain.



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(j) A non-photorealistic visualization of the chisel marks. The geometry is the same as (g), but per-vertex colors are computed using accessibility shading [Miller94].

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3D reconstruction & CH: Pivotal works

"The Digital Michelangelo Project"

Figure 10: On the left is a photograph of Michelangelo's David. On the right is a rendering made from our model. Constructed at a resolution of 1.0 mm, the model is watertight and contains 4 million polygons. Its surface reflectance was computed from digitized color images as described in section 4.2. The photograph was taken under uncalibrated conditions, so its viewpoint and illumination differ slightly from those of the rendering. The raw data for this part of the statue was acquired at a resolution of 0.29 mm and contained 480 million polygons and 2,000 color images. Using one processor of an SGI Onyx2, it took 12 hours to align merge, and map color onto this model.

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3D reconstruction & CH: Pivotal works

“The Great Buddha Project”

K. Ikeuchi, T. Oishi, J. Takamatsu, R. Sagawa, A. Nakazawa, R. Kurazume, K. Nishino, M. Kamakura, Y. Okamoto. The great buddha project: digitally archiving, restoring, and analyzing cultural heritage objects.J Comput. Vision, 75 (1) (2007), pp. 189-208

- Digitization of very large Buddha statues measuring 2.7, 13 and 15 meters in Japan
- Aiming not only at digital archiving but also **restoration**
- Challenges and solutions dealing with an outdoor environment and large dimensions (surface registration)
- Time-of-flight laser scanning

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3D reconstruction & CH: Pivotal works

"The Great Buddha Project"

Example of digital 3D restoration: "Restoring the Nara Great Buddha"

The Nara Great Buddha is one of the most important heritage objects in Japan
The original Buddha was made of bronze and covered with gold plate

Problem:
Palace was burned and the statue was melted twice due to civil war in Japan. The shape of the current Great Buddha is different from that of the original one in the 8th century

How can we reconstruct (predict) the original shape?

Solution:

- Complete 3D mesh was acquired
- Original shape of the Buddha is synthesized by mathematically morphing a new 3D mesh model from the one acquired using size hints found in literature
- Two step process:
    a. Scale of whole portions are modified according to new size constraints
    b. All vertices are moved interactively to maintain smoothness and uniformity constraints

3D reconstruction & CH: Pivotal works

"The Great Buddha Project"

(a) (b)

Figure 20. Comparison in 3D models. (a) current buddha, (b) original Buddha.

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3D reconstruction & CH: Pivotal works

"The Minerva Project"

R. Fontana, M. Greco, M. Materazzi, E. Pampaloni, L. Pezzati, C. Rocchini, R. Scopigno. Three-dimensional modelling of statues: the minerva of arezzo
J. Cult. Herit., 3 (4) (2002), pp. 325-331

- Digitization of Minerva of Arezzo, an ancient 1.55 meter-tall bronze statue located in Italy
- Aim: keep track of the variations **during the restoration process** of the statue
- Accurate 3D triangulation laser scanner
- Impressive result if we consider that the project was conducted in 2001

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"The Minerva Project"

Example of digital 3D analysis: "What is the probable original position of the right arm?"

"The Minerva" was discovered in 1541 in Arezzo, during the excavation of a water well near the S. Lorenzo church.

The inferior part of the statue was entirely restored with wood and plaster.
The right arm, from the shoulder, was integrated in 1785 and is made of bronze.

From a philological point of view, the Minerva restoration dated 1785 is incorrect!

A previous plaster repair, whose evidence is given by a printing dated the beginning of XVIII, put the right arm of the Minerva along the trunk and the forearm up to hold a lance

Using a computer simulation program, we can modify the 3D digital model after the acquisition to visualize probable original positions of the right arm

3D reconstruction & CH: Pivotal works

"The Minerva Project"

Example of digital 3D analysis: "What is the probable original position of the right arm?"

Fig. 7. Probable different positions of the Minerva statue's right arm. The model has been realized from the 3D digital model obtained with the laser scanner (digital modelling and computer animation by *Numeri srl*, Pisa, Italy).

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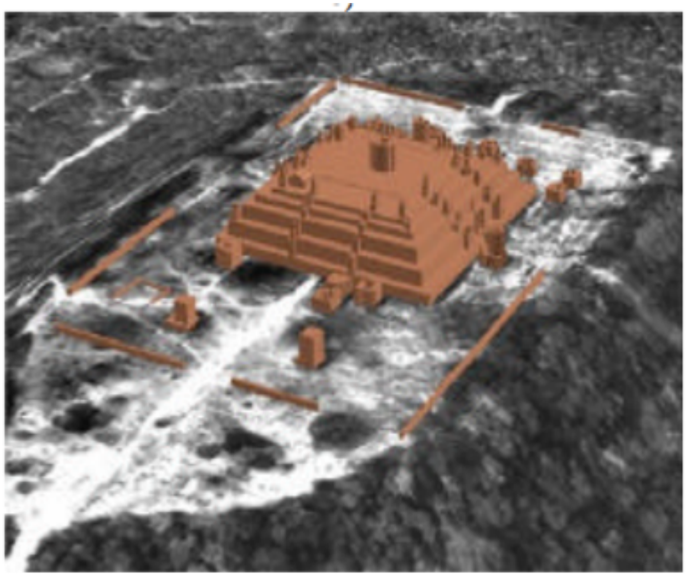
"The Angkorian temples project"

T. Sonnemann, M. Sauerbier, F. Remondino, G. Schrotter, S. Campana , M. Forte, Reality-based 3d modeling of the angkorian temples using aerial images, British Archaeological Reports International Series, vol. 1568, 2006, pp. 573–579.

- Reconstruction of a large area containing more than 1000 historical structures in Angkor, Cambodia
- 3D reconstruction performed from aerial images using structure-from-motion techniques
- **Aim:** archaeological landscape documentation of large cultural heritage sites



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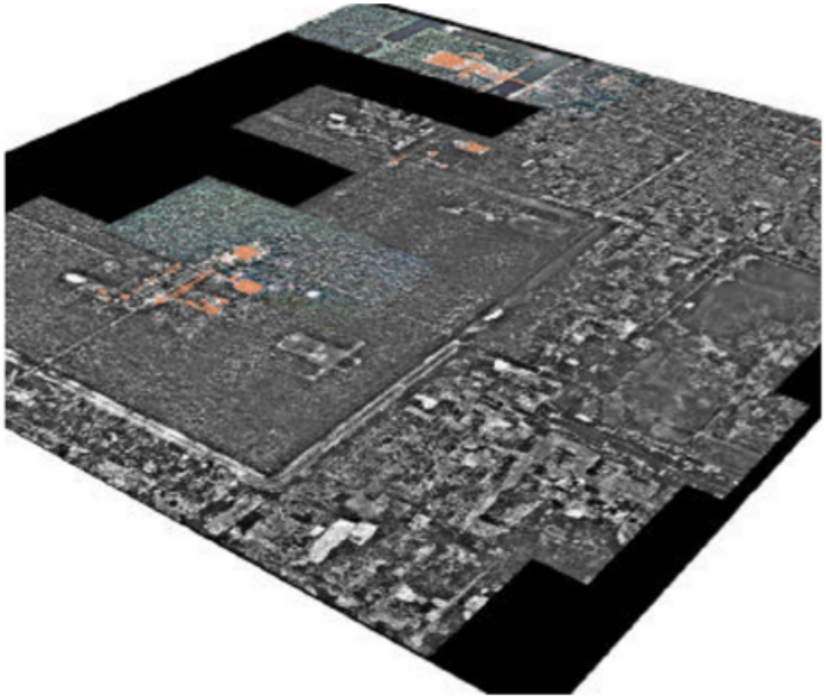

Fig. 2 The orthomosaic combines all aerial pictures that were included in the modeling. In the front lies the northwest corner of the Angkor Thom moat, in the far back is the temple of Angkor Wat. The blackened areas represent missing images in the available data set or images that could not be included due to orientation problems.

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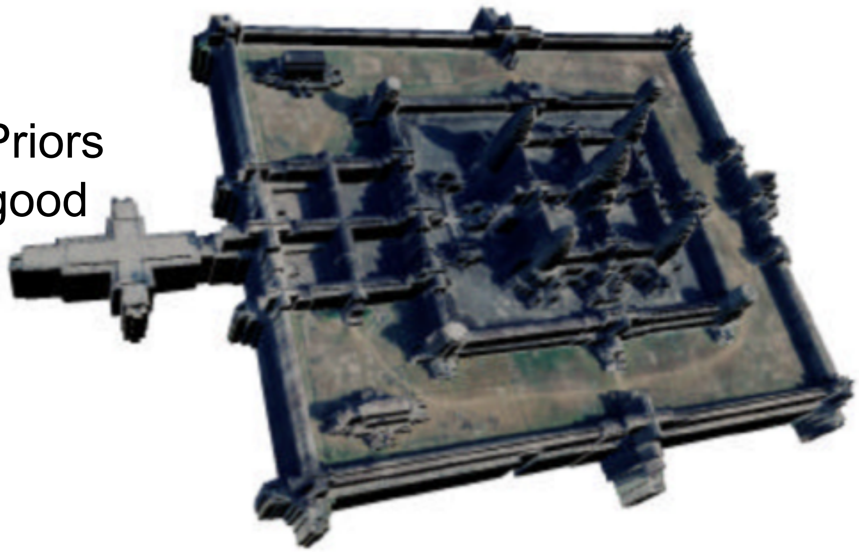
- The 3D reconstruction was obtained by means of stereo triangulation between different views
- Low-resolution of the images. Priors must be imposed to provide a good reconstruction



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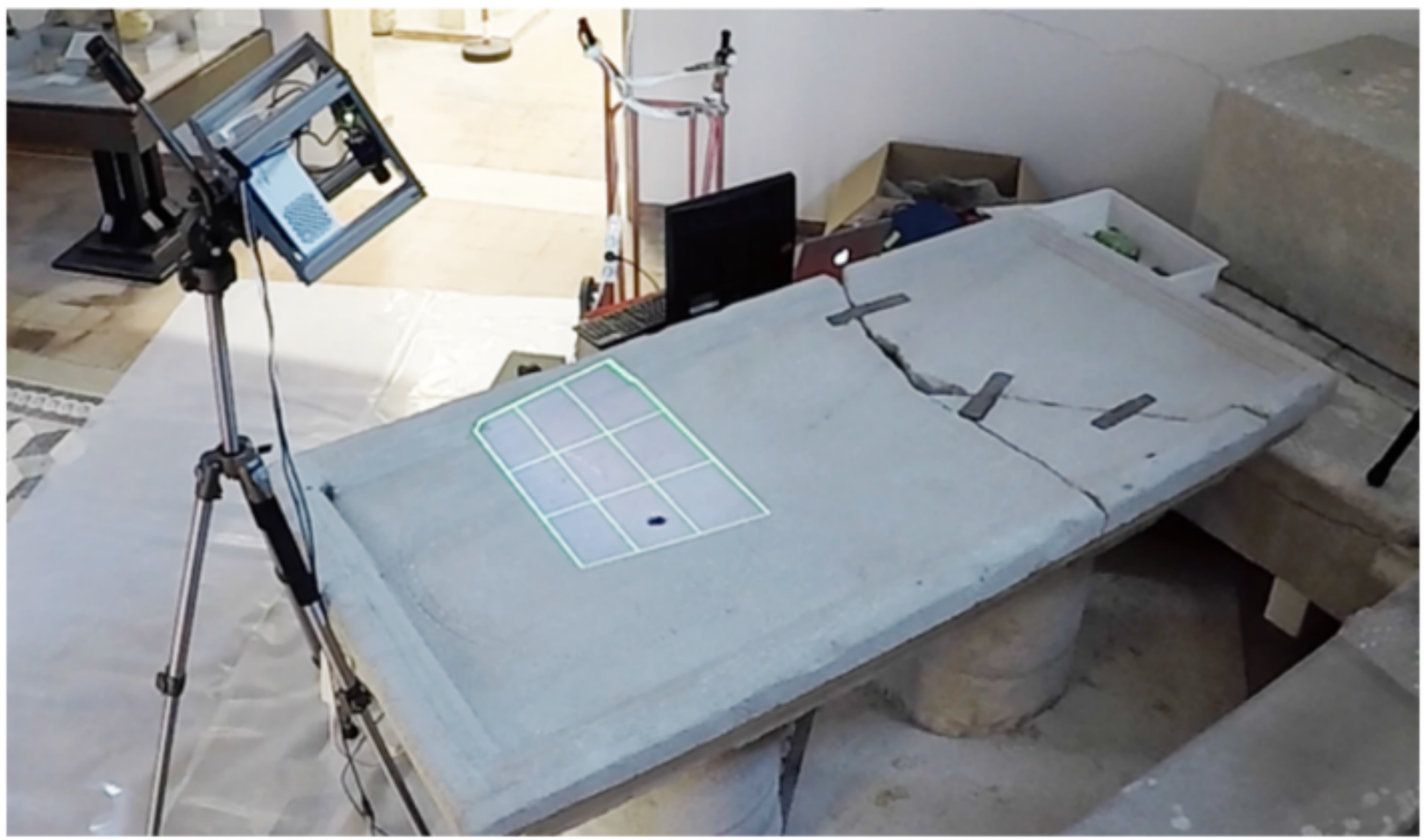
Ca' Foscari case studies

Scanning of a limestone Roman sundial discovered in Aquileia (Italy) at the end of the 19th century.

Published soon…



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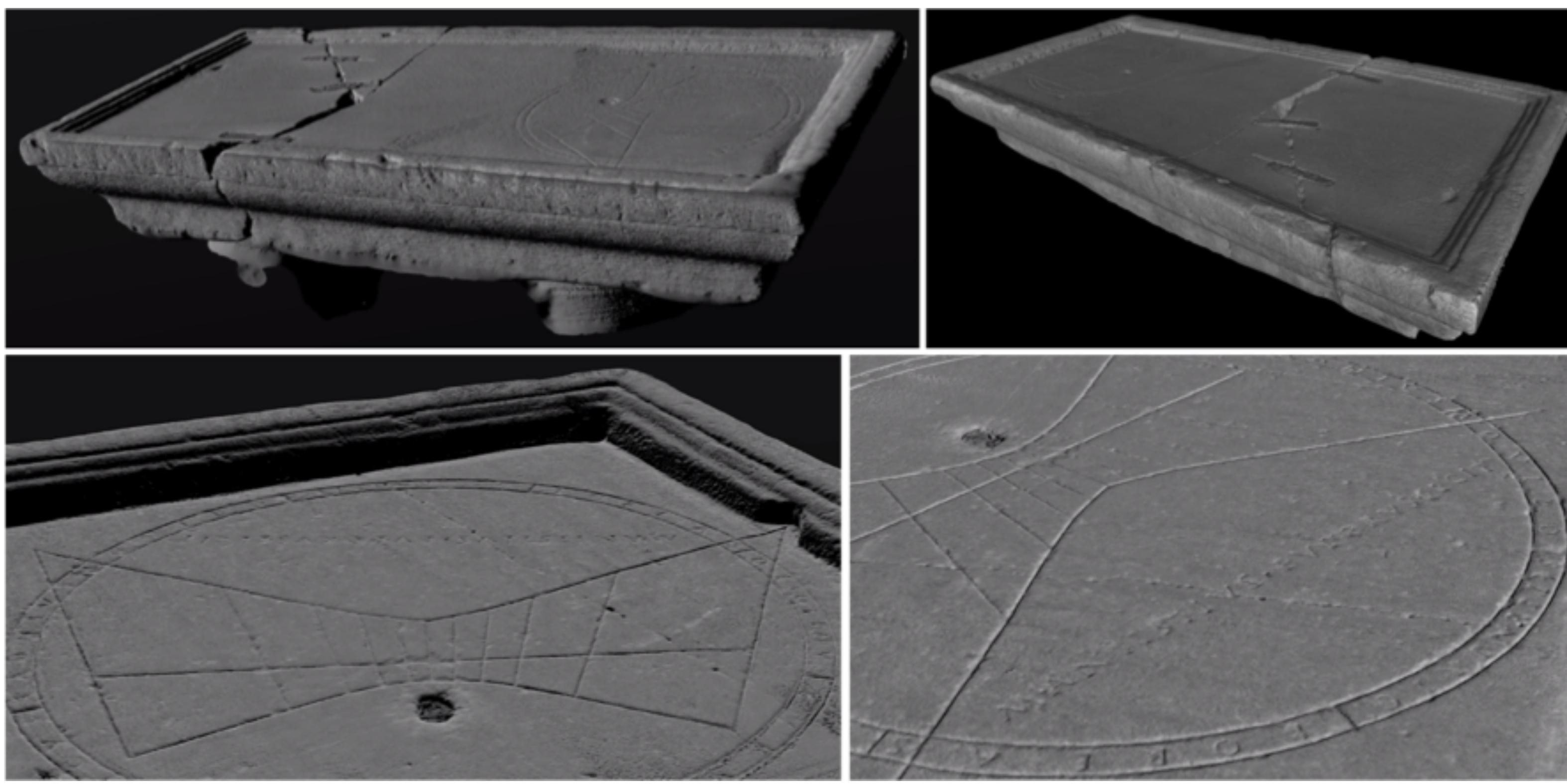

Ca' Foscari case studies

Sundial reverse engineering (ie. Recovering the gnomon shape and its most probable geographic position)

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3D reconstruction techniques

3D reconstruction is usually performed in two ways:

1. Using dedicated "depth sensors" or scanners.
   a. Light (laser or normal) is projected onto the object surface to be acquired
   b. Based on triangulation or time-of-flight
   c. High accuracy and point resolution
   d. Each acquisition have a limited coverage, thus a global registration procedure is needed
2. Using a collection of photos of the same object/scene (photogrammetry)
   a. Camera motion is estimated simultaneously with the reconstructed geometry
   b. Not particularly accurate but feasible for large object/areas (good for airborne photography)

3D reconstruction pipeline

3D reconstruction is a complex task that require **multiple steps** to obtain a complete 3D mesh of an object.

These steps are usually one sequent to the other. All together form a "pipeline"

When using depth sensors, the pipeline is usually composed by 5 steps:

1. acquisition, 2. pair-wise registration, 3. global registration, 4. mesh generation, 5. texture generation.

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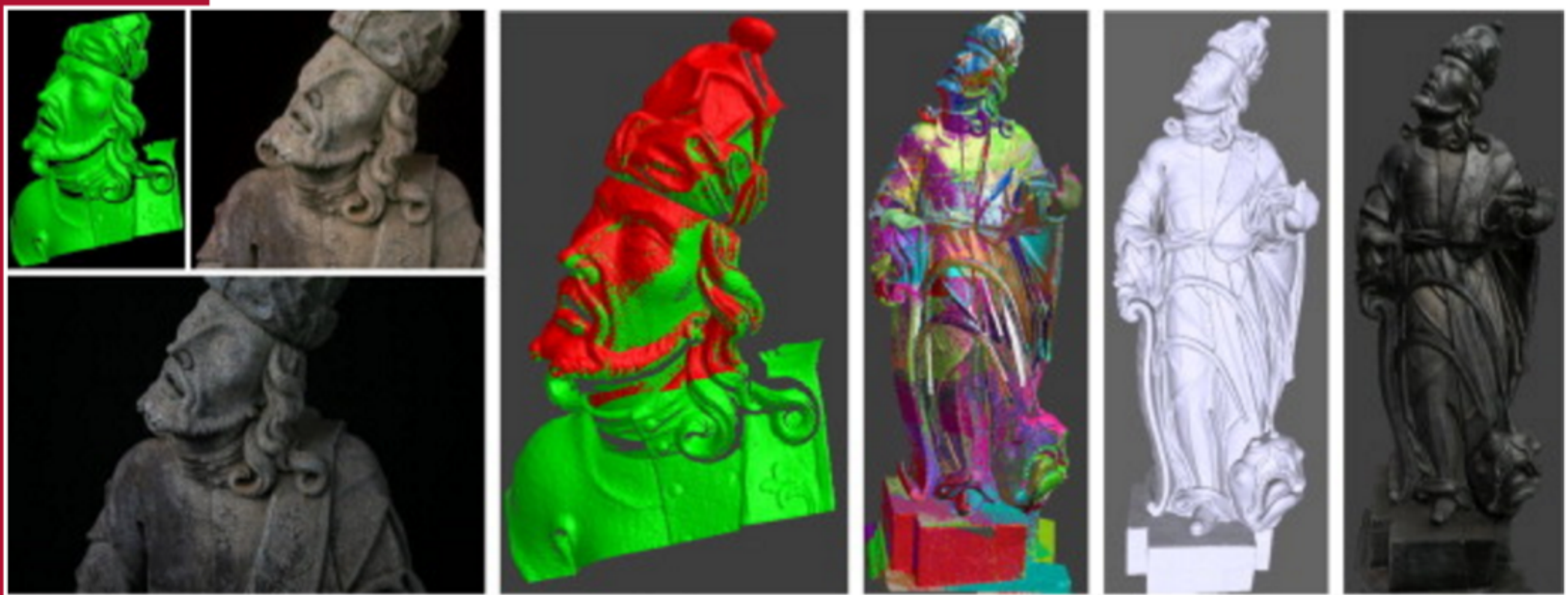
3D reconstruction pipeline



1 2 3 4 5

1. Acquisition

Many different technologies emerged during the last decades.

Different scenarios demand different solutions: there is no single sensor best suited for all applications.

What are the properties to consider?

Quality: Resolution? Point accuracy?

Price: From few hundred to 100K Euros

Portability: Power? Size? Weight?

Acquisition time: can be a problem in sites with lots of visitors that limit the availability

Flexibility: Can the same sensor deal both with large part and small details of an object?

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1. Acquisition

Quality is probably the most important characteristic when digitizing complex sculptures or sites

Attributes of quality according to Cureless et al.[1]:

Resolution: Number of samples per unit area

Accuracy: Statistical variations among repeated measurements of a known value

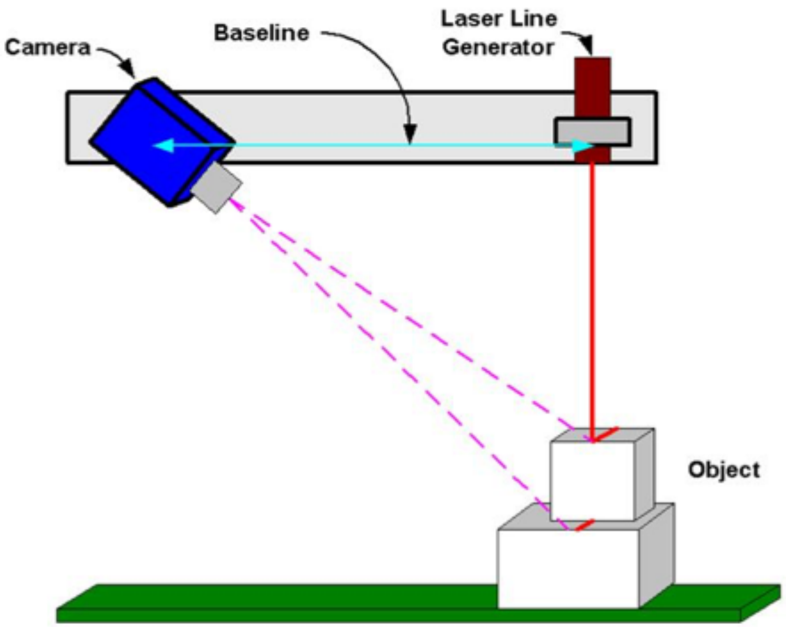
Repeatability: Relating to drifts of the measured value

Environmental sensitivity: Relating to robustness under brightness, wind, temperature, and pressure changes.

1. B. Curless, 3D Photography, Tech. rep., Special Interest Group on Graphics and Interactive Techniques, Course Notes, (2000).

Triangulation laser scanner

A laser beam is projected onto the surface and acquired by a camera. Since both the laser and camera are geometrically calibrated, it is possible to calculate the depth information by simple triangulation



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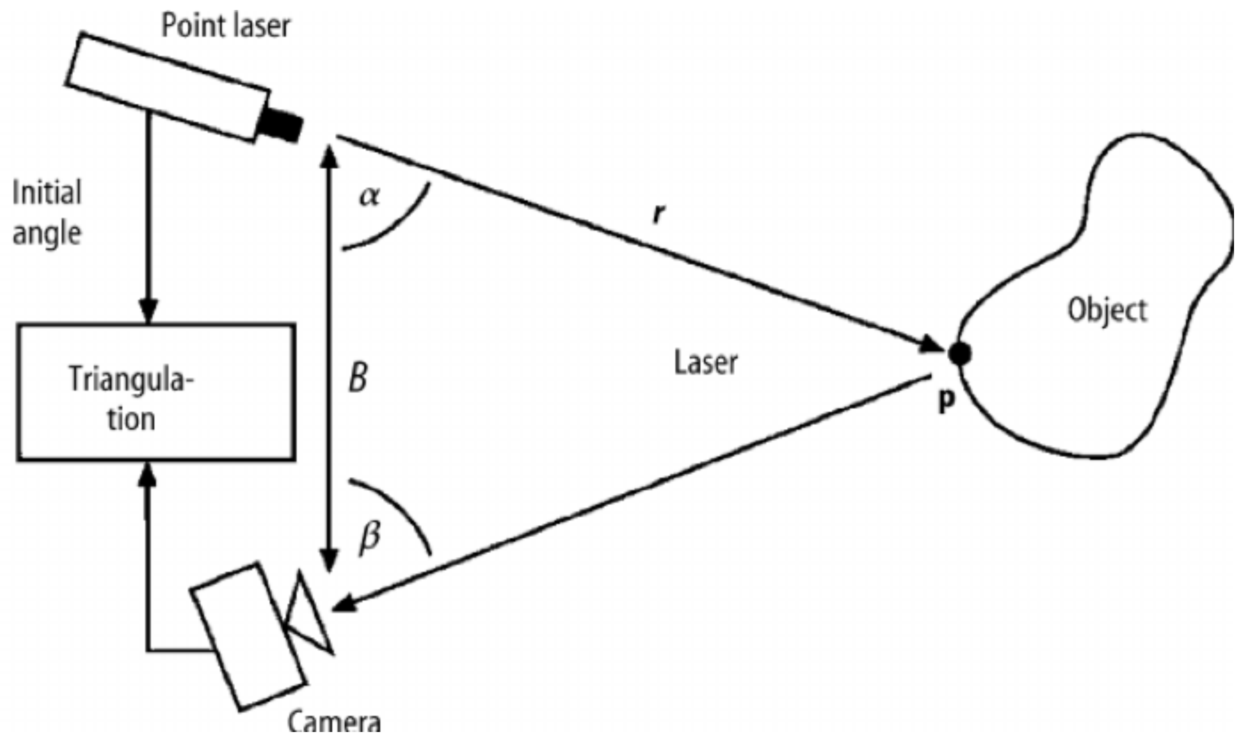

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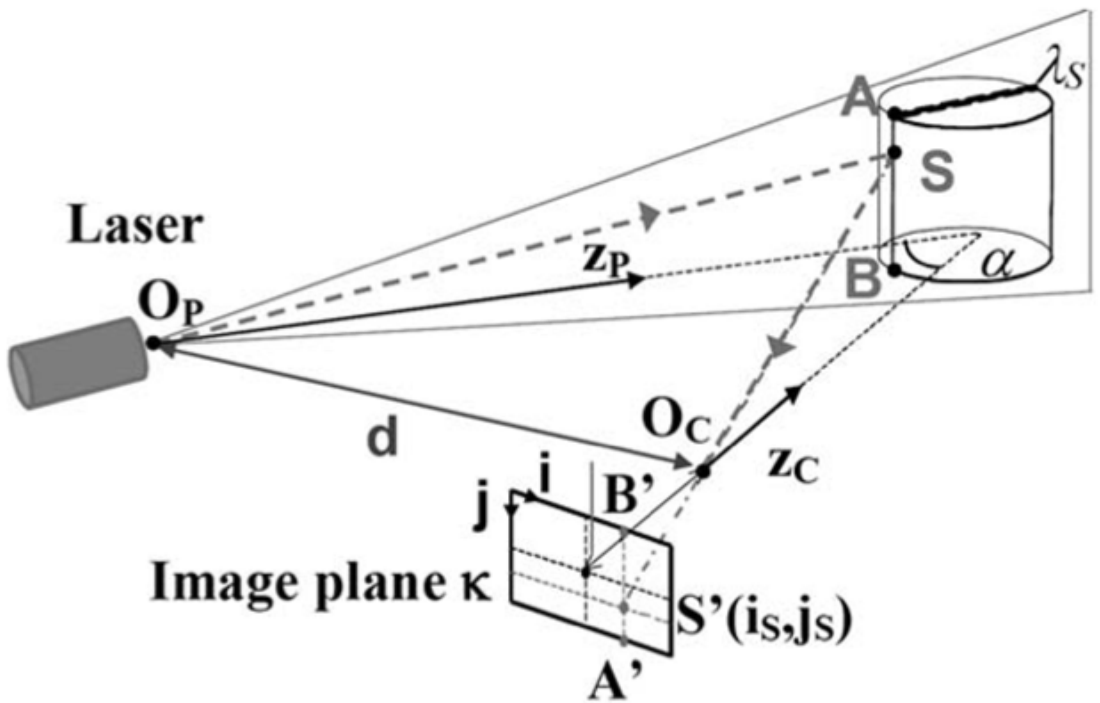

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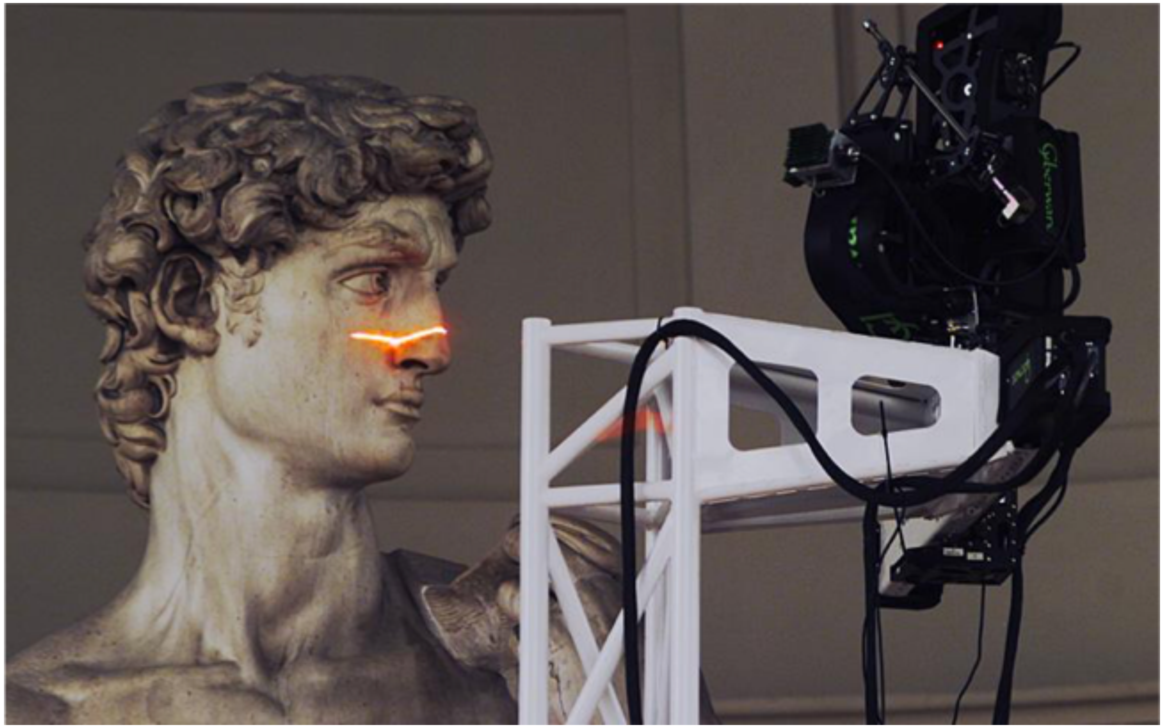

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Triangulation laser scanner

Pros:

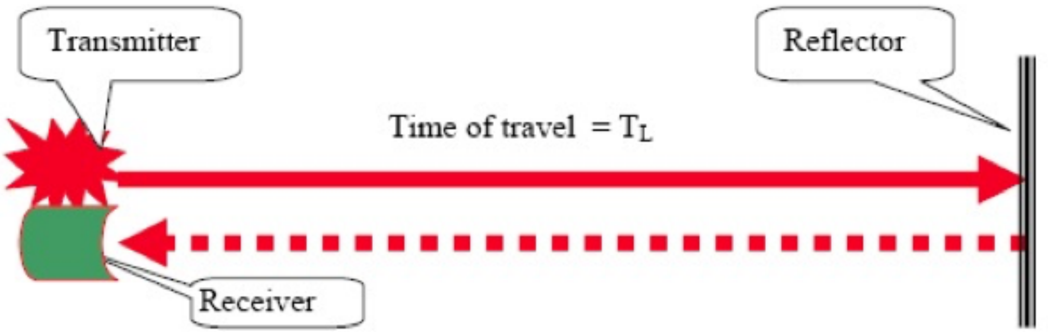
- Very accurate (sub-millimeter precision)

Cons:

- surface properties like reflectance and transparency may cause wrong measurements
- High cost
- Long acquisition time
- Relatively small scan area

time-of-flight laser scanner

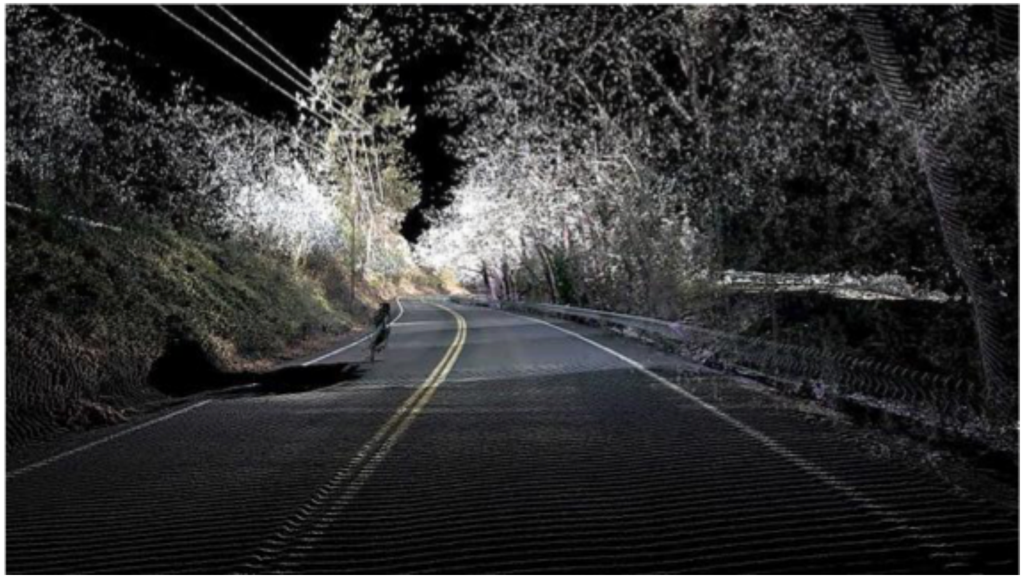
A laser pulse is projected on the surface and the round-trip time is measured to determine the distance of the surface from the emitter



time-of-flight laser scanner

Usually tof laser scanner is used for a surveying method called **LIDAR** (Light Imaging, Detection and Ranging) for acquiring high resolution 3D maps.

Laser beam is swept back and forth similar to standard radars. The laser scanner itself is usually mounted on a moving vehicle to survey a large area



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time-of-flight laser scanner

Pros:

- Can operate over large distances
- Well suited to reconstruct building and large sites

Cons:

- Noisy data
- not as accurate as triangulation scanner

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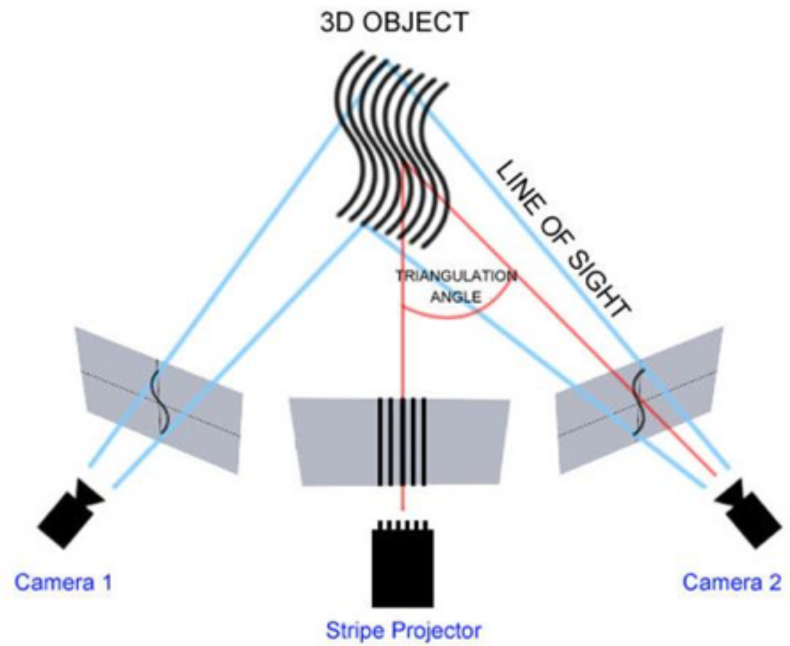
Structured-light scanner

Light patterns are projected on the surface and acquired from a camera. Signal encoded by such patterns allows the scanner to disambiguate each imaged point and reconstruct the 3D geometry by triangulation



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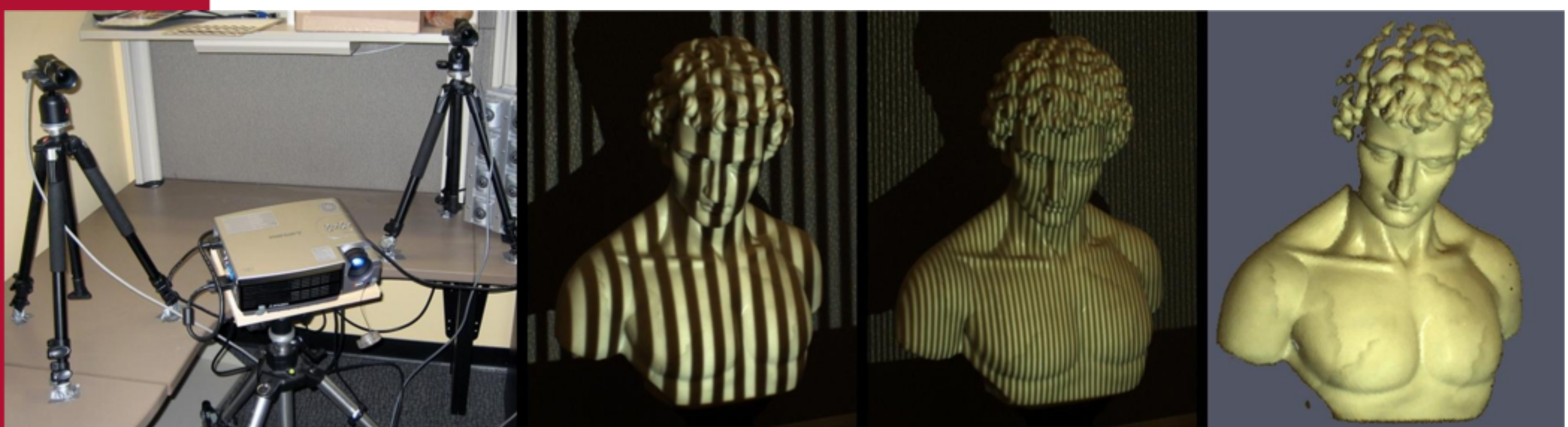

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Structured-light scanner

Pros:

- Very accurate
- Usually faster than triangulation laser scanner as a whole depth image is acquired for each projection (no laser beam swipe)
- Can acquire texture

Cons:

- Small reconstruction area (usually limited by the projector power)
- Sensitive to ambient illumination and material properties

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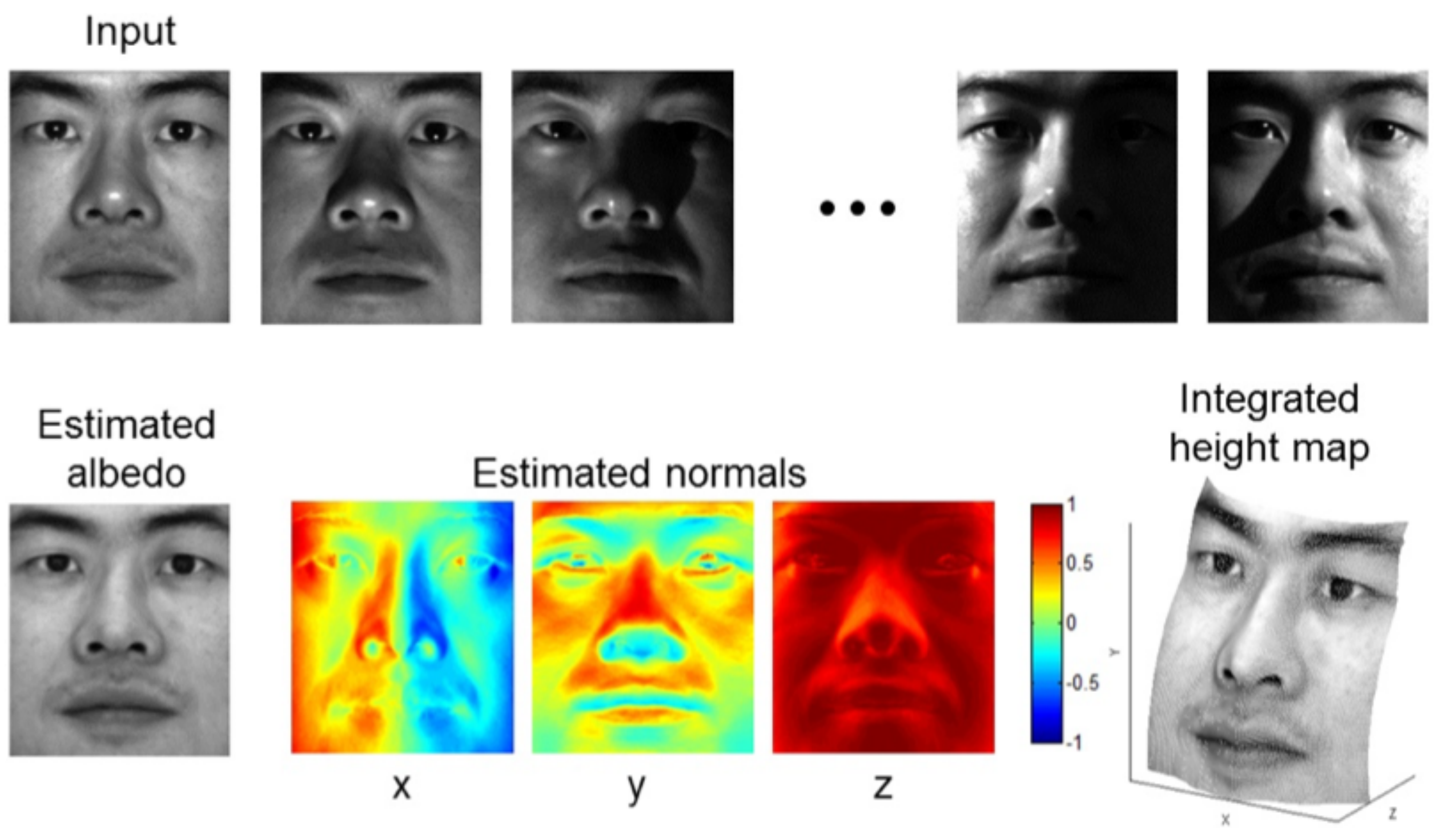
Shape from shading

Set of algorithms that deduce the geometry of an object by analyzing multiple images under different illuminations



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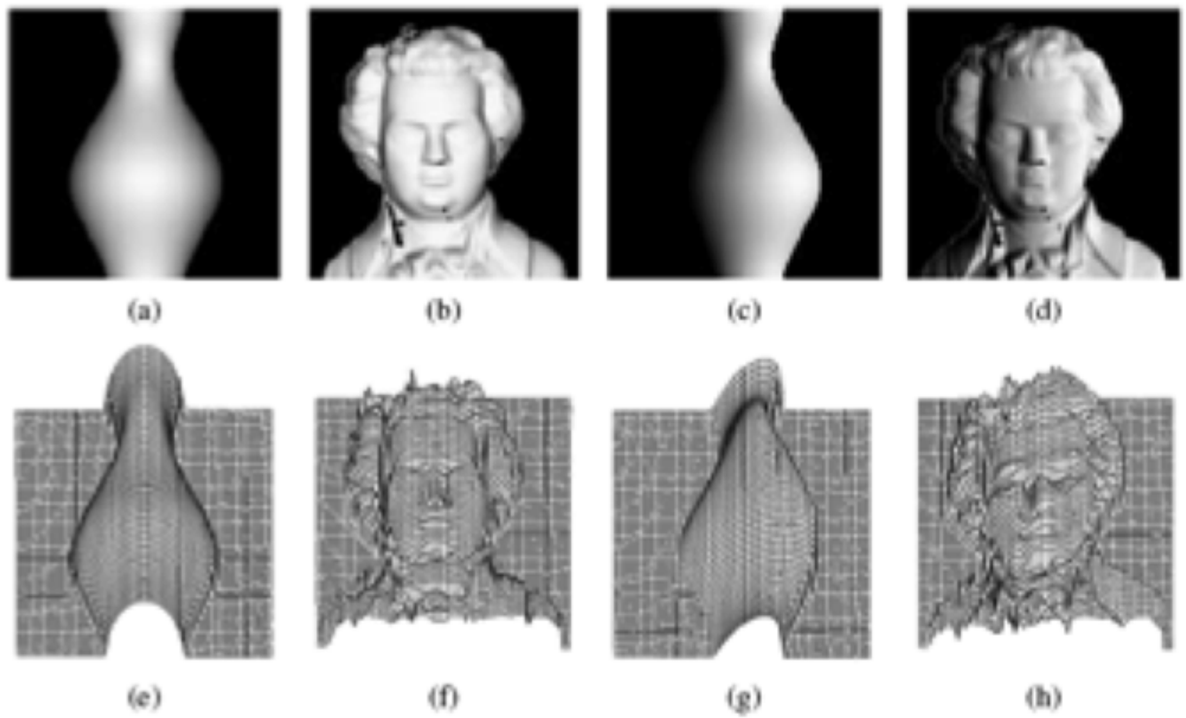

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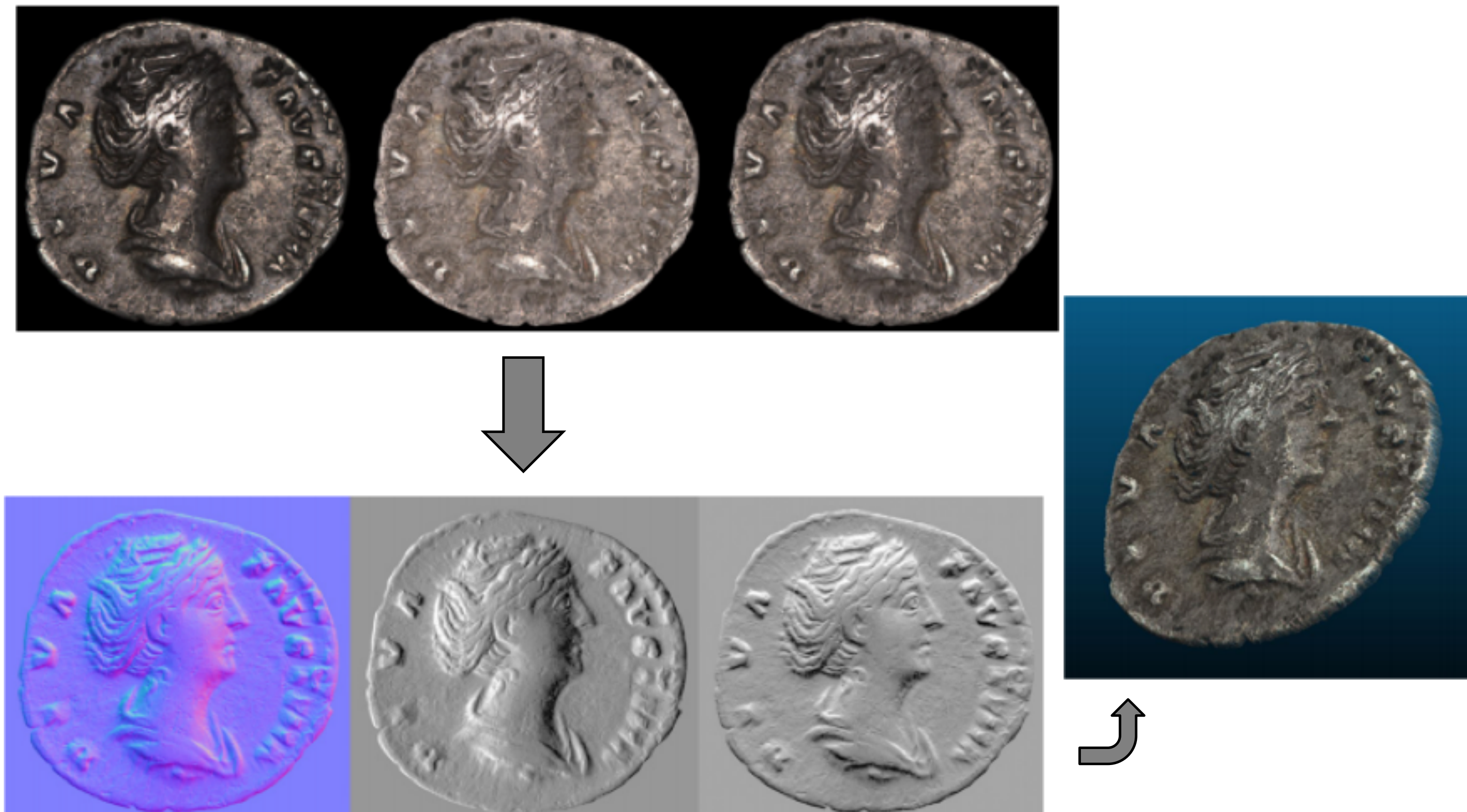
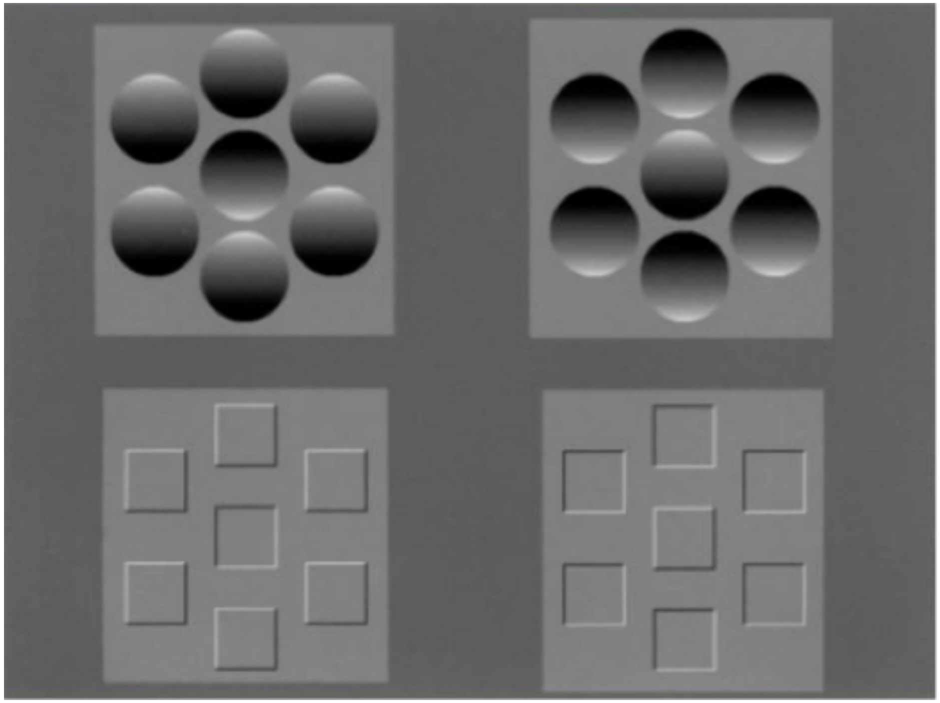
Shape from shading

Lindsay MacDonald, Vera Moitinho de Almeida, Mona Hess, *"Three-dimensional reconstruction of Roman coins from photometric image sets"*, Journal of Electronic Imaging 26(1), 011017 (3 February 2017). http://dx.doi.org/10.1117/1.JEI.26.1.011017



Shape-from shading

Ambiguity may raise when considering a single non-calibrated light source:



Bumps or indentations? Our brain always assume the light source is coming from the top

Shape from shading

Pros:

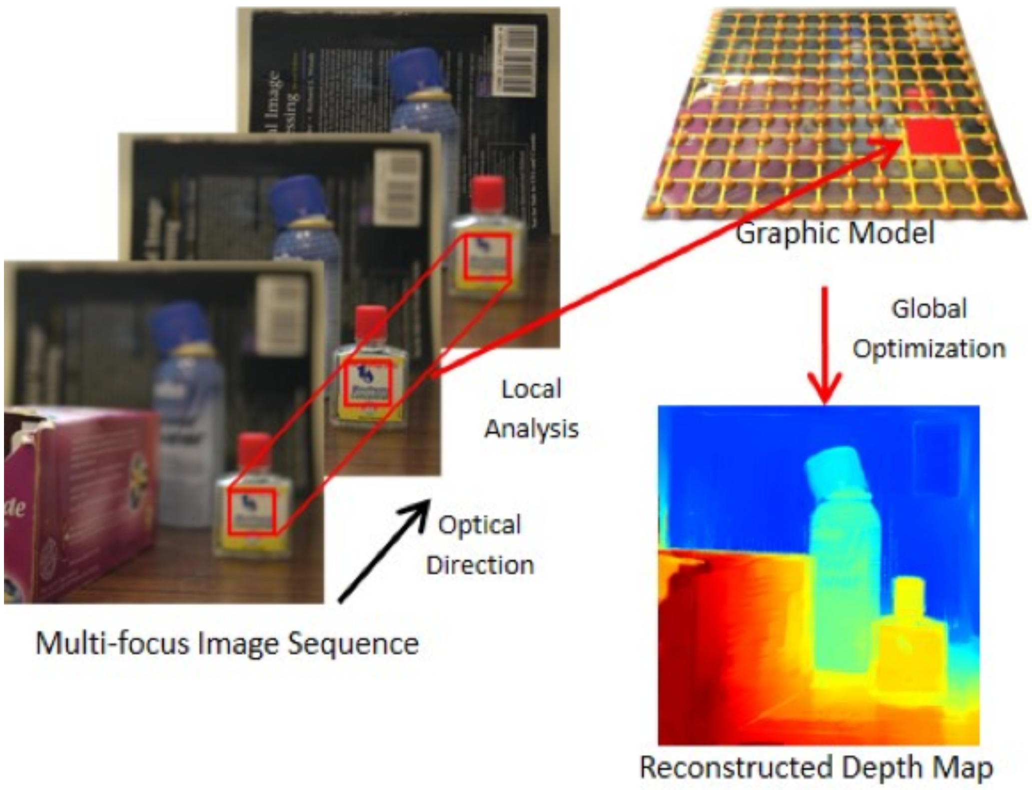
- Very low cost (can work with simple webcams)
- Texture can be acquired

Cons:

- Intrinsic ambiguity may rise
- Very low resolution and accuracy

Shape from focus

Set of algorithms that deduce the geometry of an object by changing the lens focus distance



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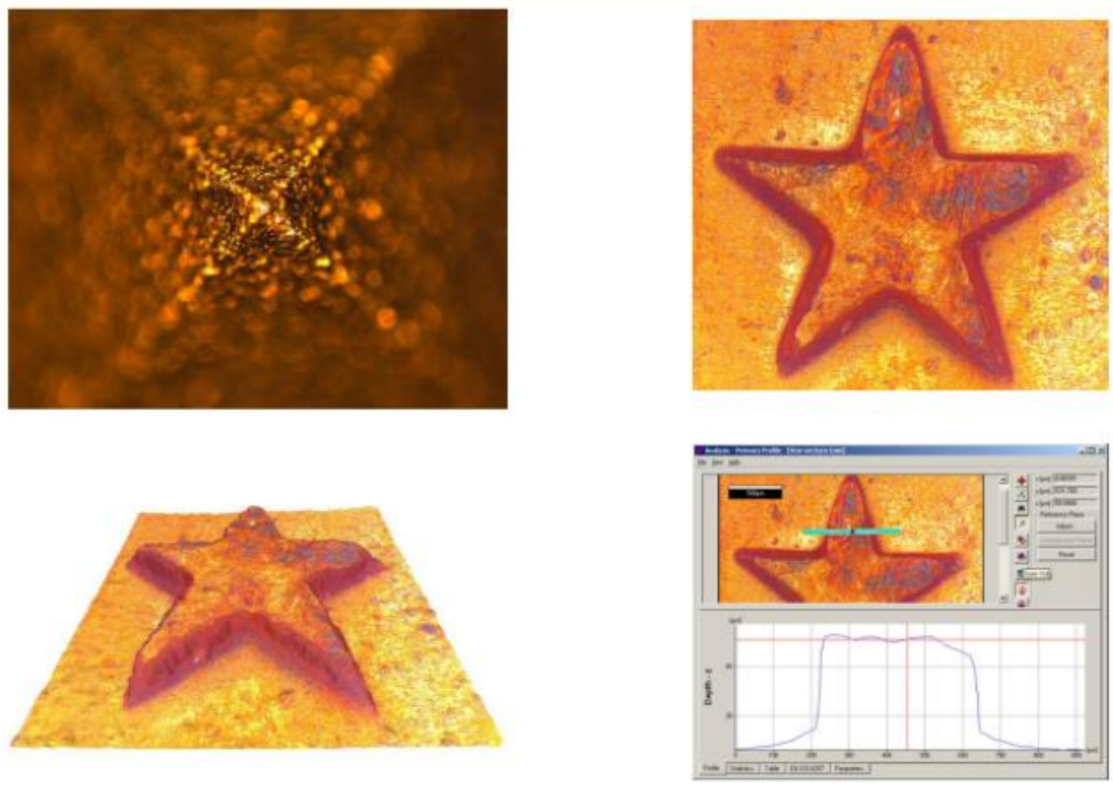

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Shape from focus

Pros:

- Can work with very small objects and a microscope

Cons:

- Limited applicability
- Noisy data

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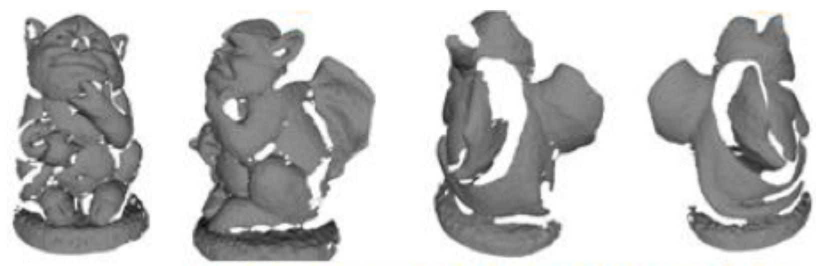
1. Acquisition

All the methods described so far are able to generate a 2D grid, called **range image**, showing the distance of each point in the scene from the viewpoint of the sensor.



Fully digitized 3D objects are created by combining multiple range images from different point of views into a single spatial reference frame

This operation is usually called **registration**

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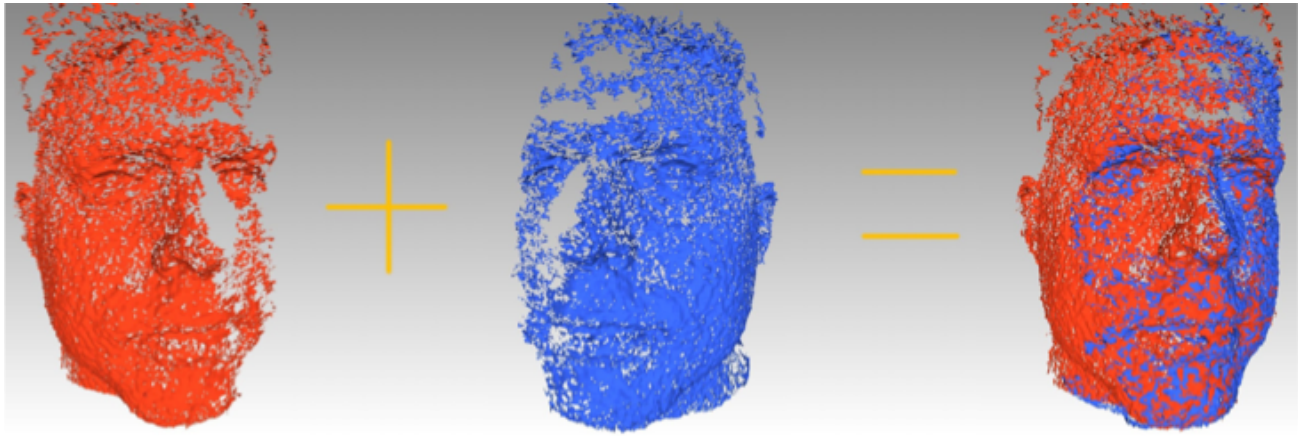
2. Pair-wise registration

Range images are processed in pairs trying to compute the most accurate possible alignment.



Usually an initial coarse registration is performed by using hints from the scanning device (markers, GPS/IMU, rotating plate, etc)

A fine registration is performed on the range map data itself with different algorithms. The most common technique is called **ICP (Iterative Closest Point)**

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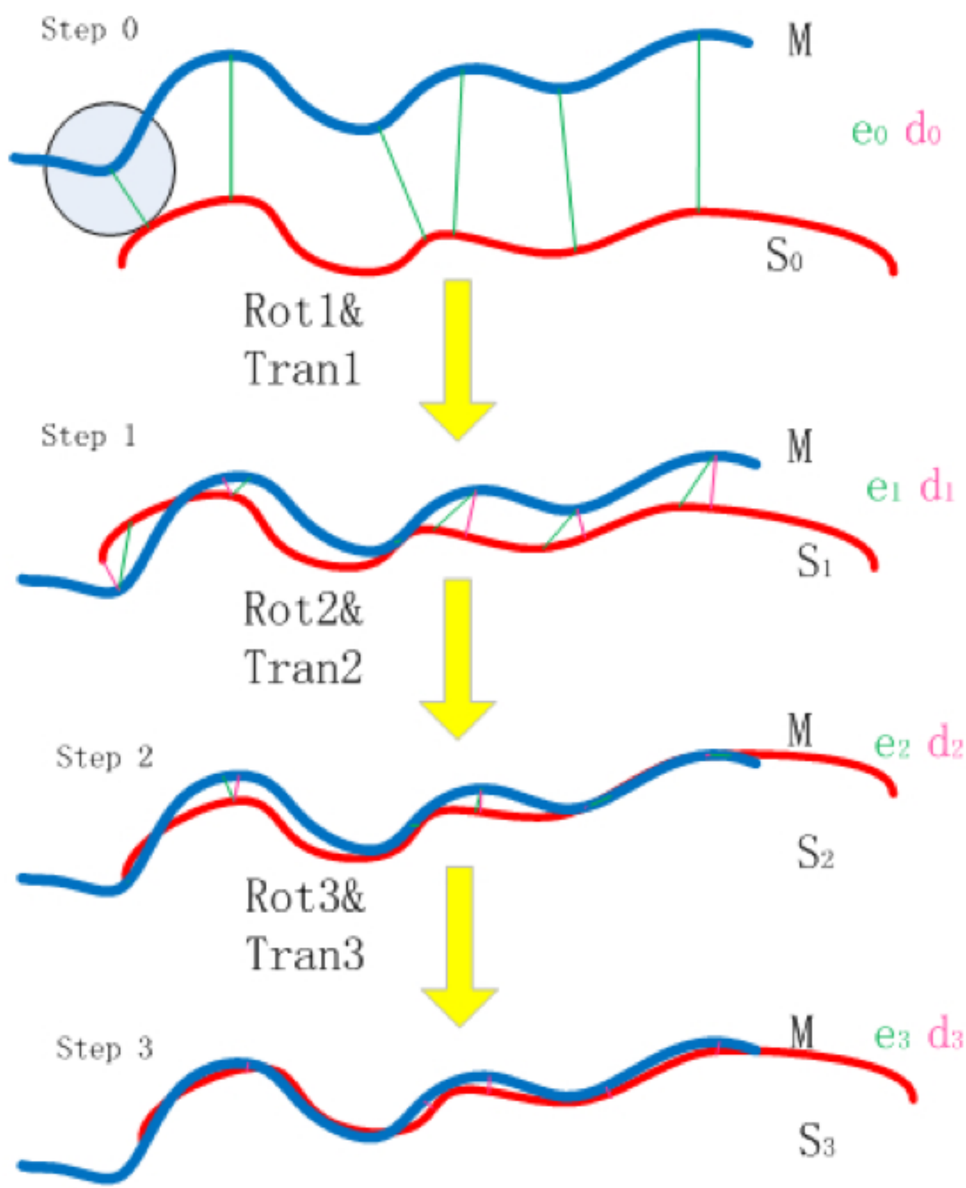
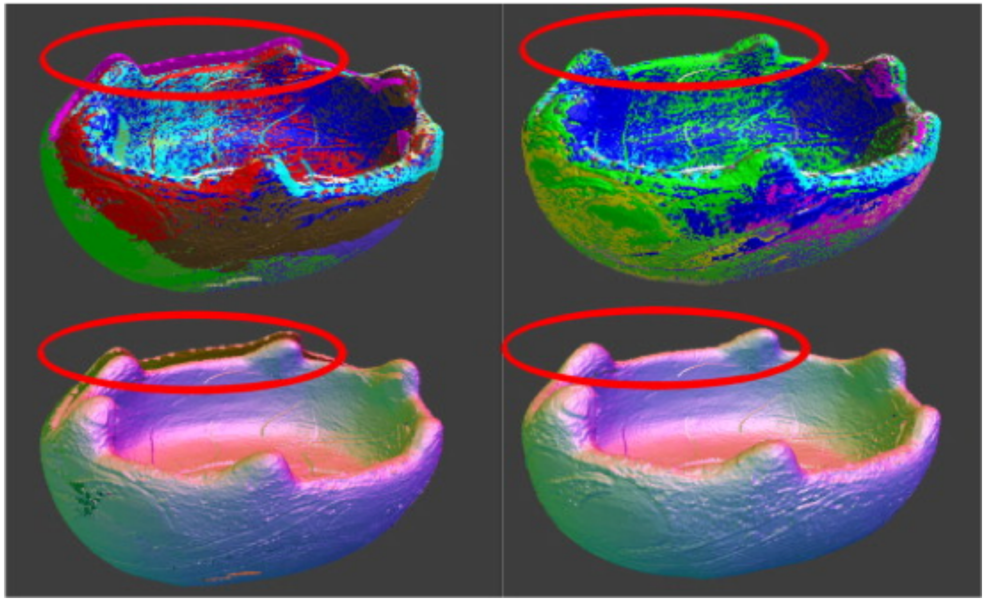
2. Pair-wise registration: ICP



3. Global registration

Errors can accumulate when we compute pair-wise alignments so that the transformation between all the pairs are not closed transitively



The goal of the global registration is to distribute the accumulated error among all the views. Different algorithms, one of the most commonly used is:

K. Pulli, *"Multiview registration for large data sets"*, in: Proceedings of the Conference on 3D Digital Imaging and Modeling, 1999, pp. 160–168.

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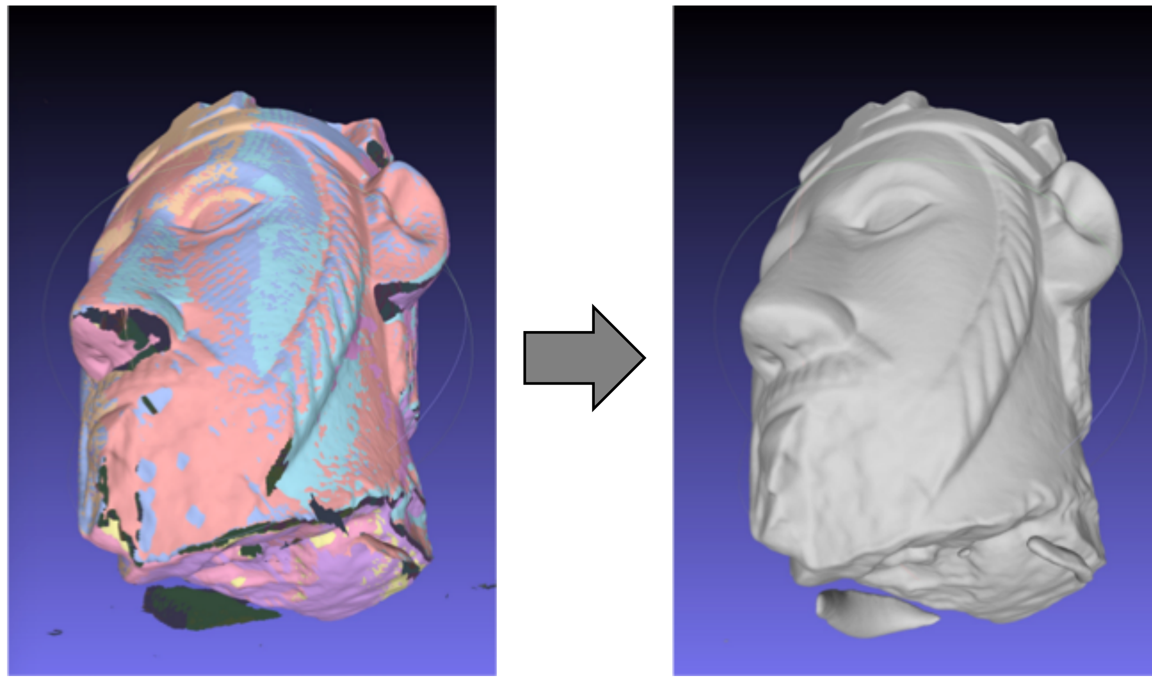
4. Mesh generation

Once we have several range images in the same coordinate system, the next stage is to integrate these views in a single triangular mesh



Problems:

- outliers generated by imprecision in the former stages
- non-digitized areas (holes) that affect the fidelity of the digitization.

4. Mesh generation

According to Bernardini et al:

F. Bernardini, H. Rushmeier, *“The 3D model acquisition pipeline”*, Comput. Graphics Forum, 21 (2) (2002), pp. 149-172

We can categorize mesh generation (or integration) methods in 4 classes:

1. Delaunay based
2. Surface based
3. Parametric/deformable methods
4. Volumetric methods

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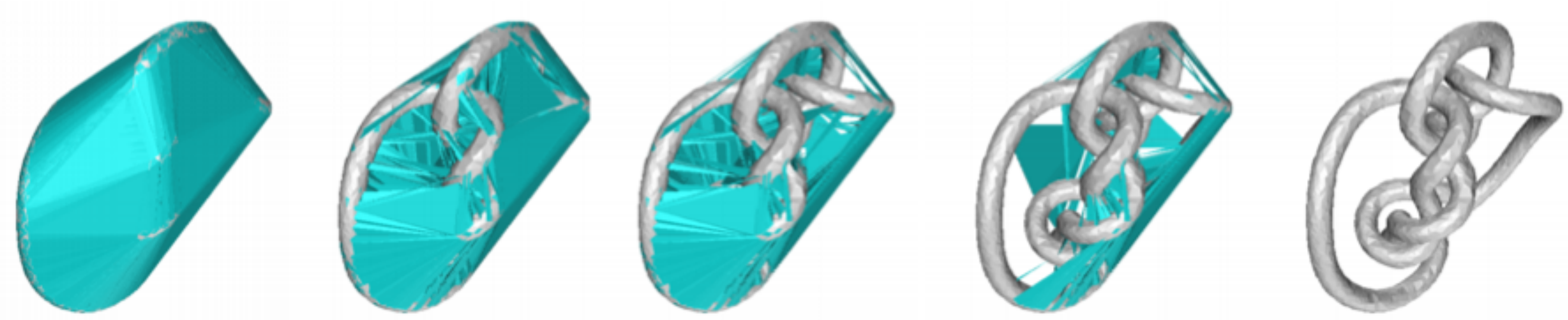
Delaunay based

1. Start from the convex hull of a set of points
2. Sculpt the convex hull iteratively to extract the final mesh



Problem:

Performs poorly in presence of noise or outliers

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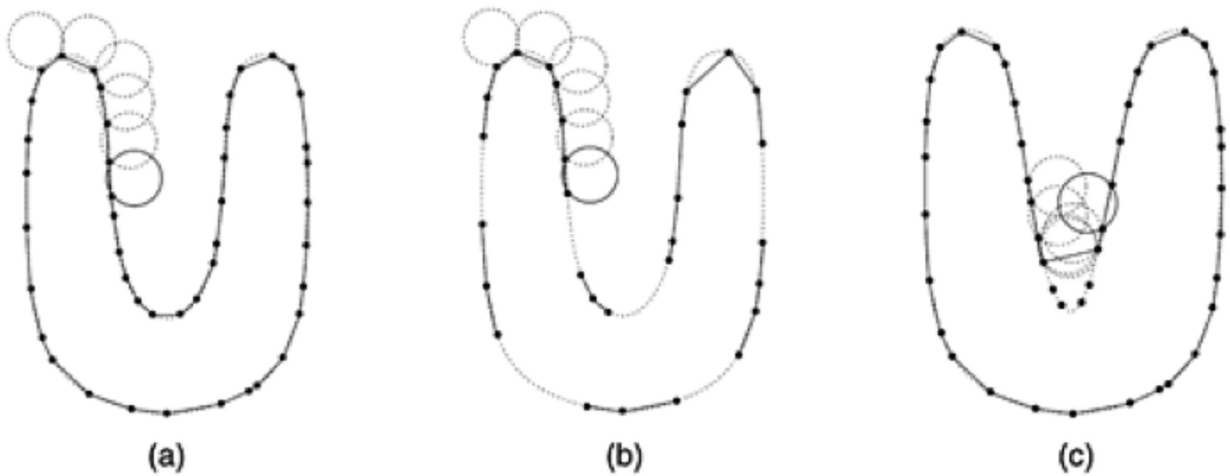
Surface based

Create or manipulate surfaces directly by local operations that connect points of different partial surfaces, such as those built from the triangulation of neighbor points in the captured grid of the range images.



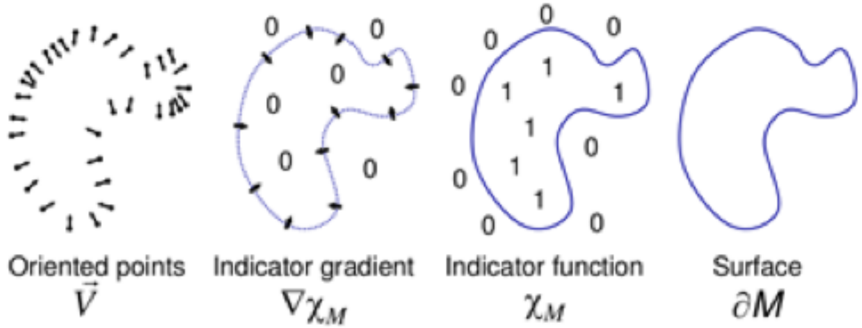
Problem:

Performs poorly in regions of high curvature

Parametric/deformable methods

Parametric: Fit an analytically generated surface to the point data

Deformable: deform an initial approximation of the object through the use of external forces and internal reactions and constraints

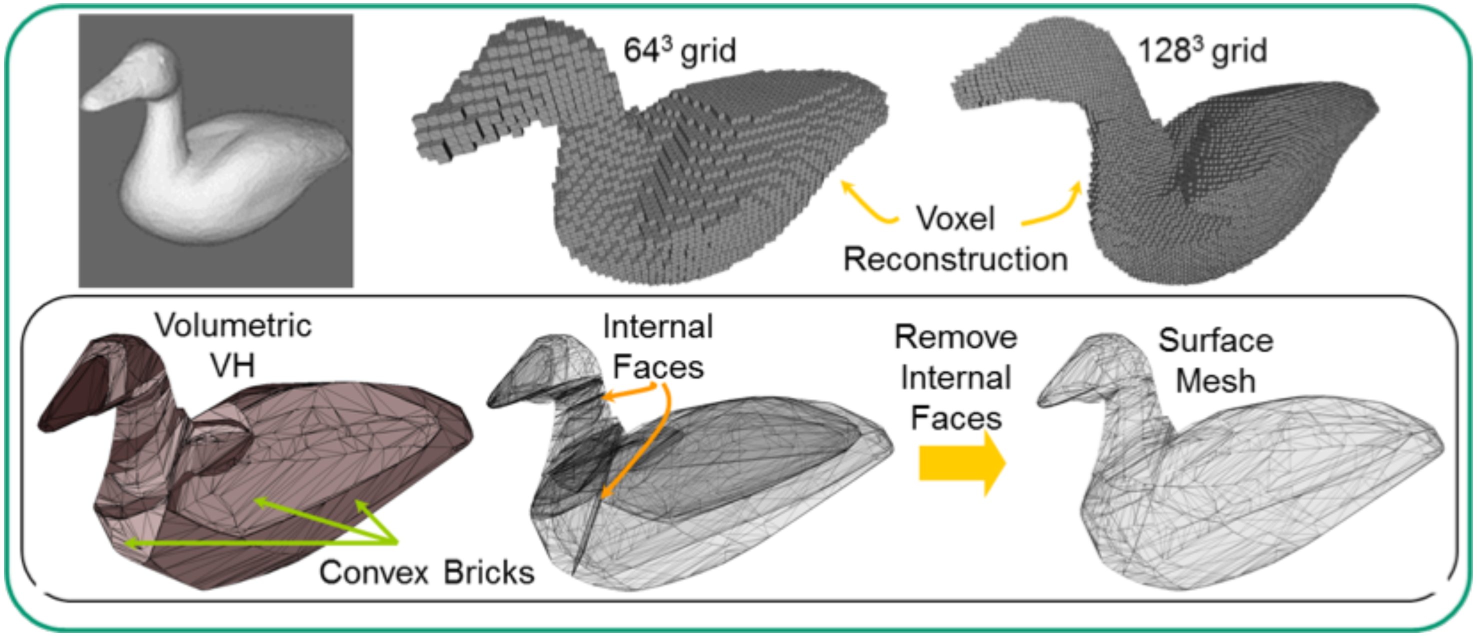


Problem:

sharp corners cannot be easily modelled since most methods fit a continuous differentiable function with smoothness priors

Volumetric methods

Create a 3D (voxel) grid of the final mesh in which each voxel value represent the signed distance with respect to the mesh surface. Positive sign: outside the surface, Negative sign: inside.



Problems:

Demanding in terms of processing power and memory

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5. Texture generation

A texture is associated to the reconstructed surface to add the color information and improve realism. This is particularly important for digital preservation of cultural objects

Usually texture data is acquired by a standard RGB camera calibrated with the 3D scanner

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