

3D FROM PHOTOS PHOTOGRAMMETRY

MARCO CALLIERI
VISUAL COMPUTING LAB
ISTI-CNR PISA, ITALY

3D GRAPHICS
FOR CULTURAL HERITAGE

3D FROM IMAGES

Our not-so-secret dream: obtain a reliable and precise 3D from simple photos.

Why ?

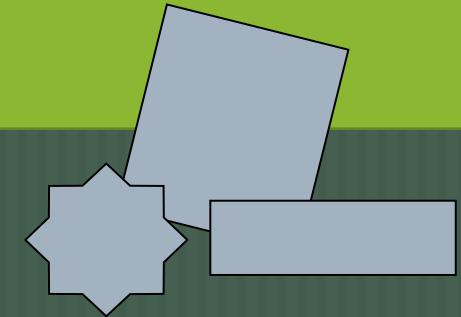
Easier, cheaper and more versatile than a 3D scanner.

We can perceive 3D shapes from “images”, why should a computer not be able to do the same?

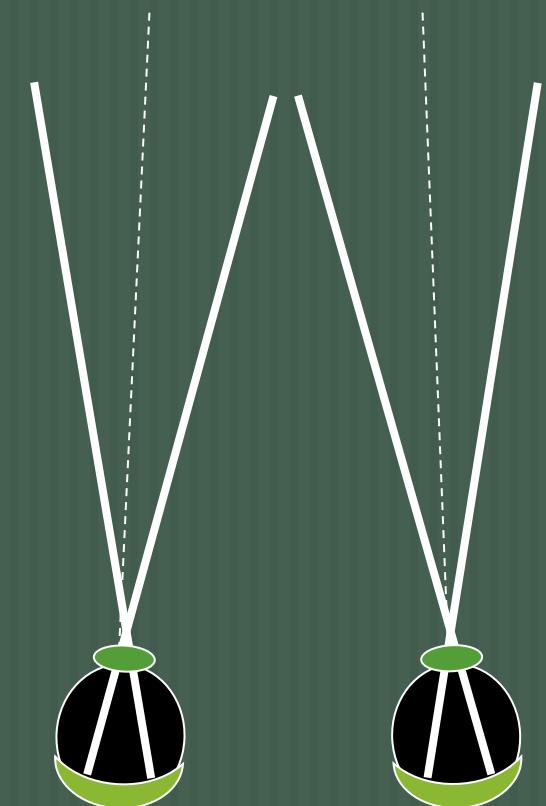
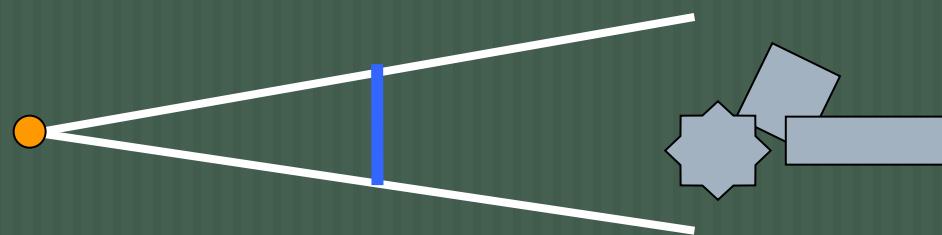
PASSIVE technique, we just look at the scene, without introducing any illumination. Geometry is determined only from “geometric” optical rules.

BASIC INGREDIENTS

We do perceive the three-dimensionality of the environment thanks to our stereo vision AND the perspective projection that occurs in our eyes..



Using the geometric laws of this two phenomena we can build the 3D geometry of the scene



PERSPECTIVE

Perspective Projection is used because it is an objective, unambiguous 2D representation of a 3D scene.

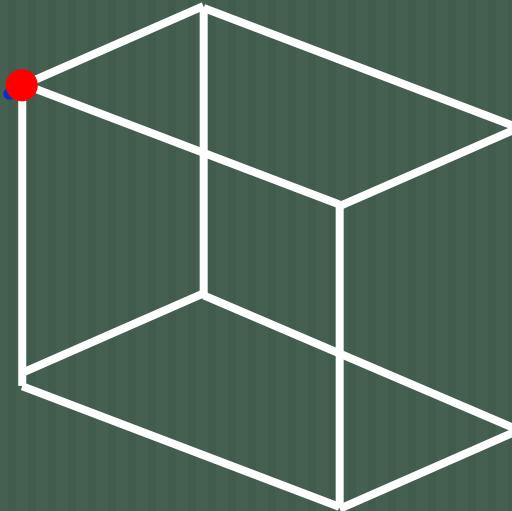
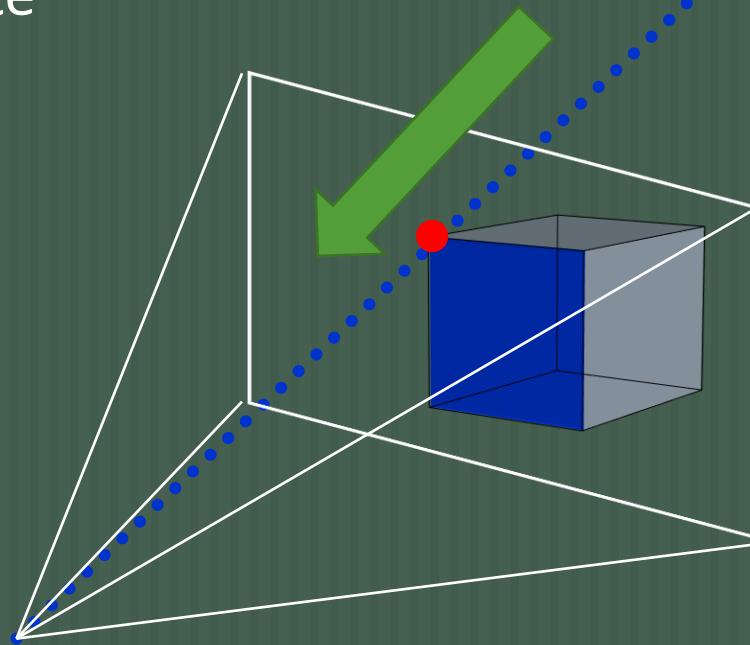
IF you know “everything” about the perspective projection used by the camera at the time of the photo, it is possible to establish useful geometric relationship between the image and the geometry of the scene.

What is “everything”? We’ll see.

RELATIONSHIP #1

Each point in the 3D scene corresponds to exactly one point on the image plane.

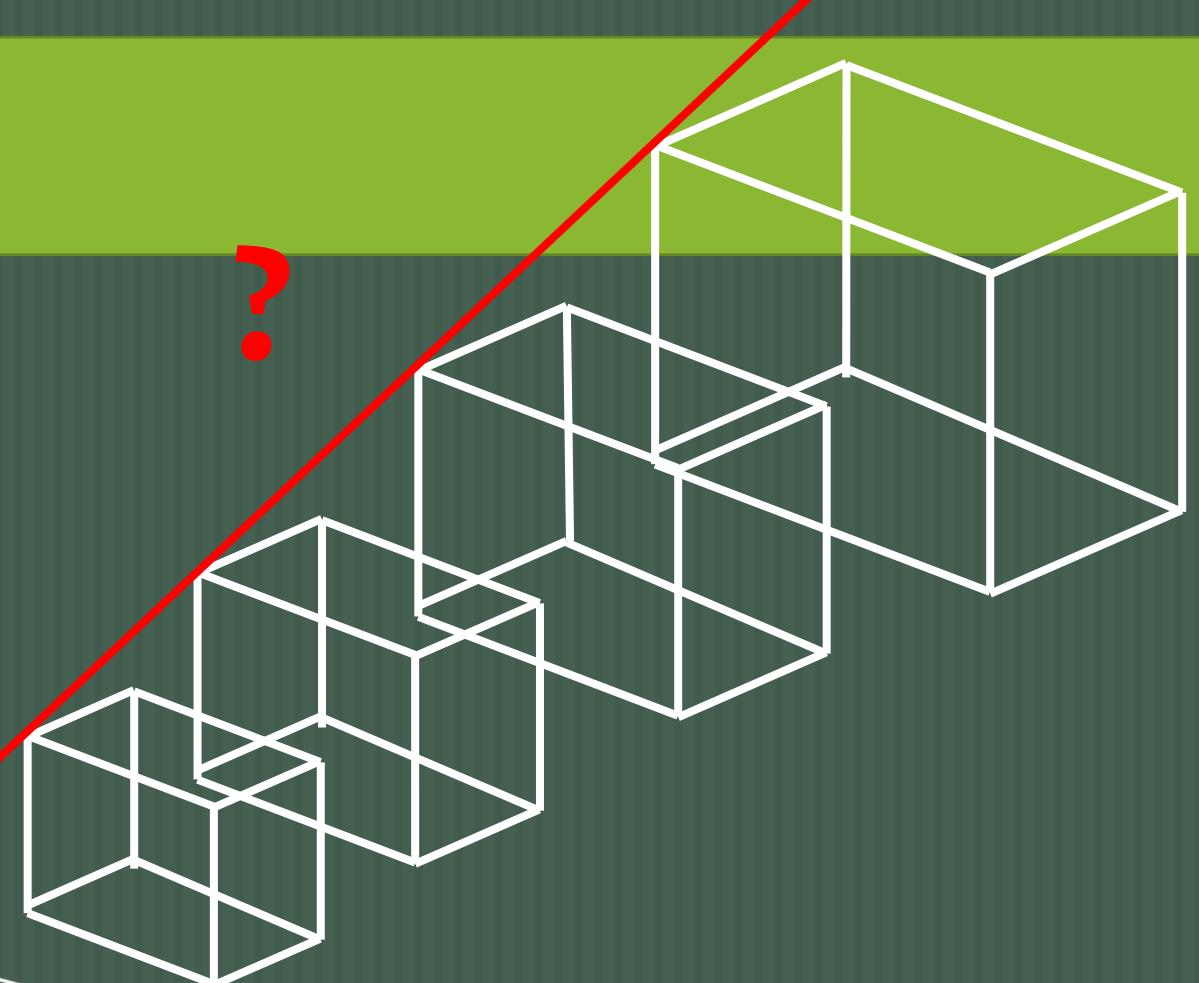
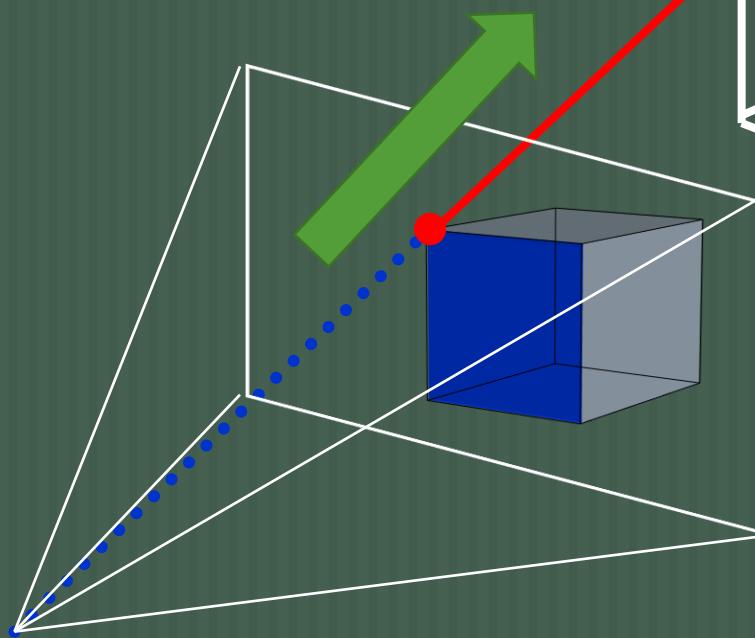
If I know the XYZ position of some point in the scene, I know which pixel in the photo it will generate



RELATIONSHIP #2

Each point on the image plane corresponds to exactly one line in the 3D scene.

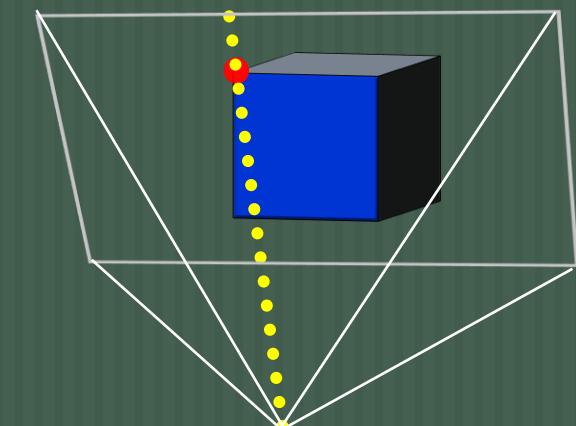
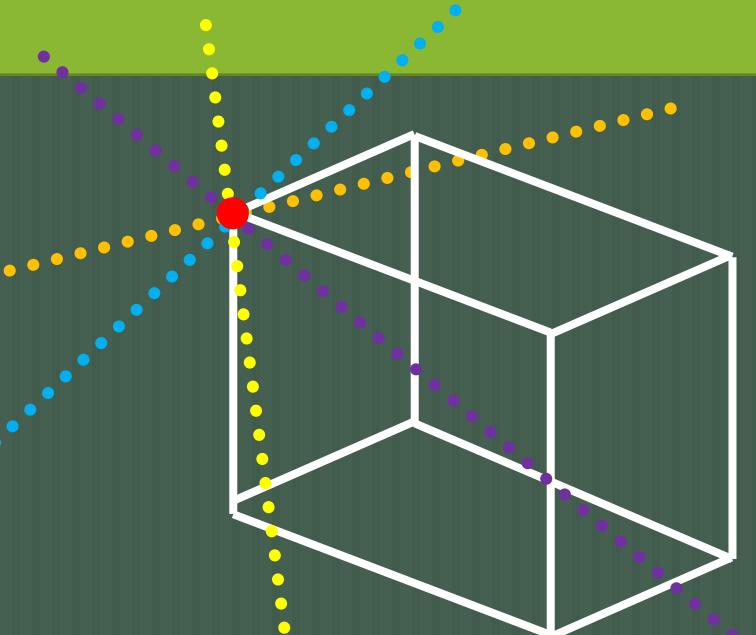
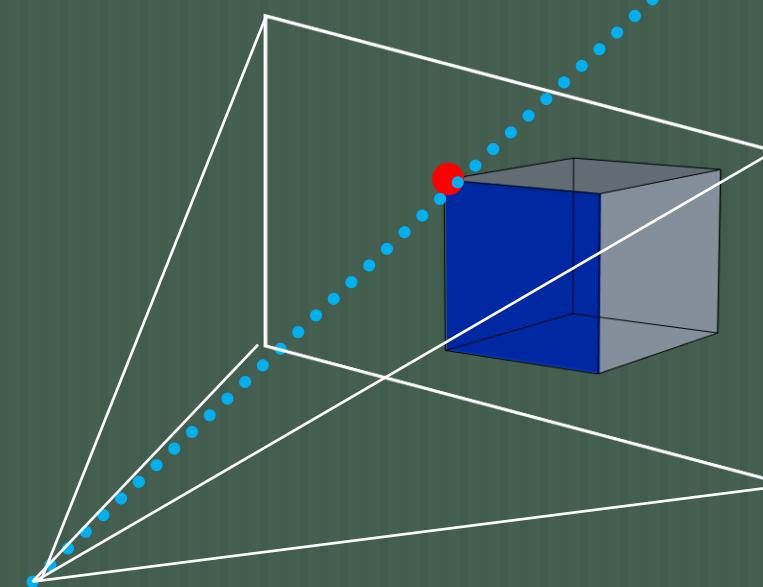
I know the entity that generated that pixel lies somewhere on that line, but I do not know where...



THE PHOTOGAMMETRIC PRINCIPLE

Even though relationship #2 is not as strict as #1, combining more photos, if I choose the **same feature** in all the images, the lines will meet somewhere in the 3D space, removing the ambiguity.

Yet another way of using triangulation

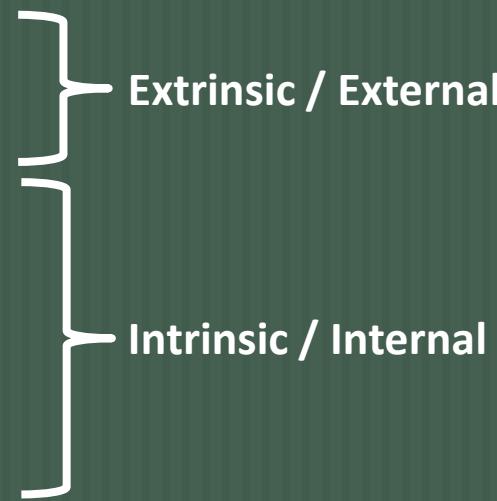


PERSPECTIVE CAMERA

But to establish these correspondences, what do I need?

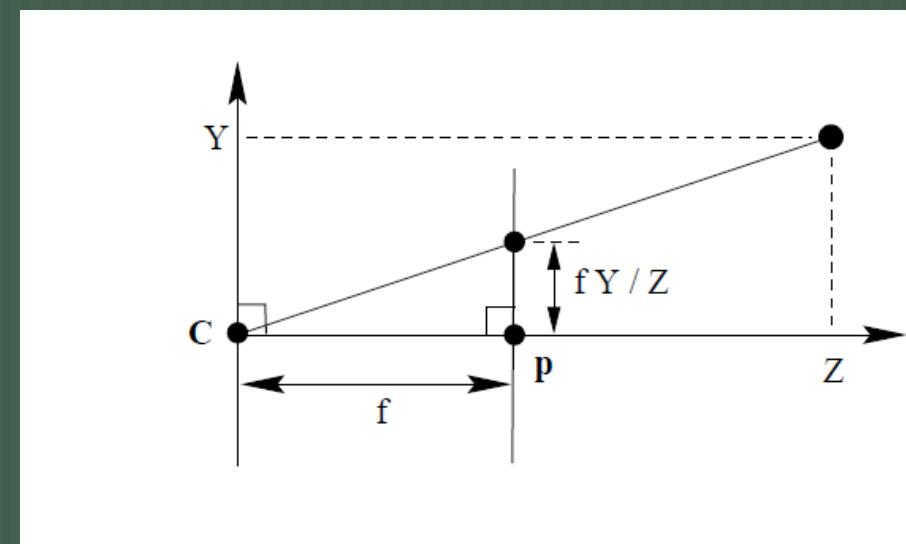
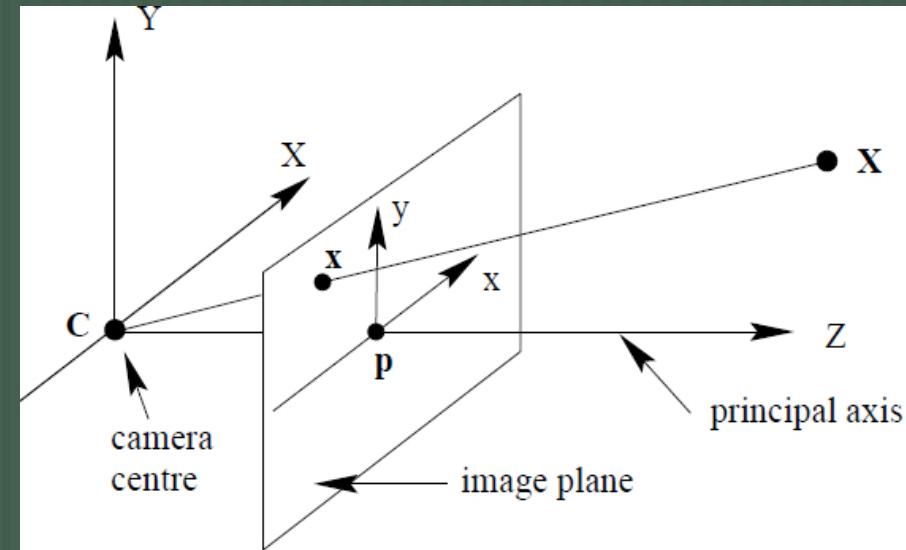
All starts here... a “camera” is defined by parameters:

- Position
- Orientation
- Focal Length
- Viewport
- Distortion
- ...

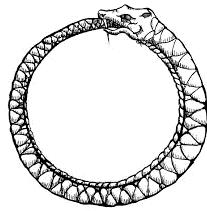


This is called **pinhole camera model**

it's not the only one, but one of the most used



UROBOROS



But, in this way, It is a snake biting its own tail!

In order to know the scene geometry, you do need to know the scene geometry...

We are lucky: by providing “semantic” information (non metric), it is possible to obtain all the data we need.

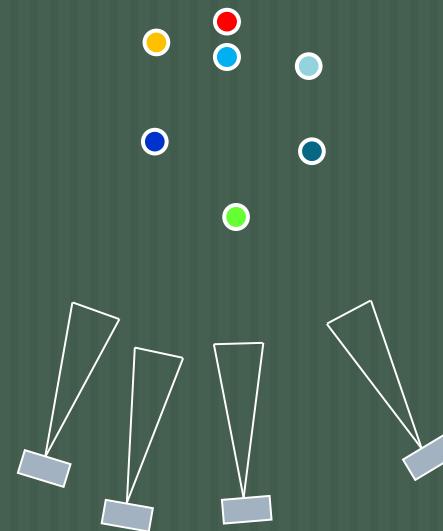
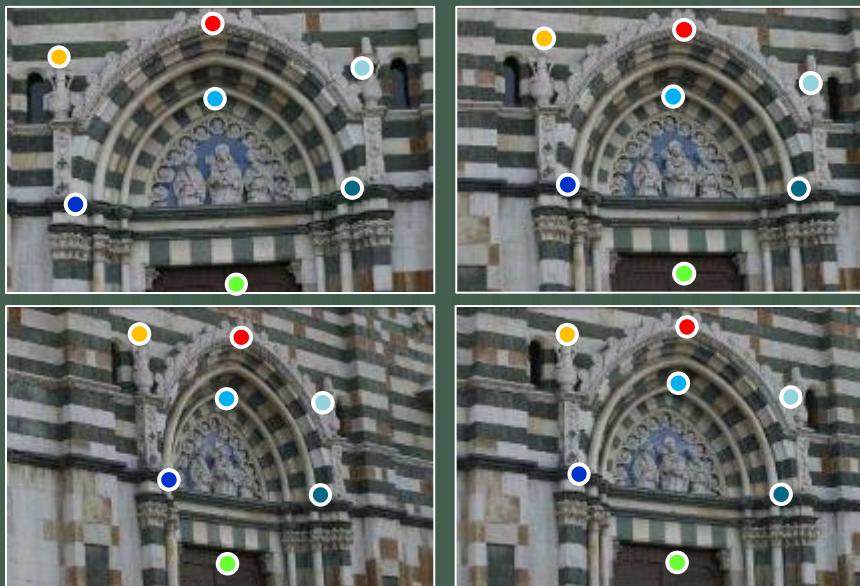
There is a mathematical-geometrical procedure that, starting from **image-to-image points correspondences**, returns the internal and external, plus the 3D location of the points picked as correspondences.

CALIBRATION + ORIENTATION

Calibration: recovering internal parameters

Orientation: recovering external parameters (position, orientation)

Starting from images, you pick corresponding points on ALL the images, then, an automatic calculation returns calibration+orientation for all the cameras, and 3D coordinates of the picked points



CALIBRATION + ORIENTATION

How many correspondences we need to calibrate-orient the cameras?

Unfortunately, the answer is: it depends....

The process is mathematically ill-conditioned, and there are many local minima and ambiguities.

To give a range, between 8 to 15 corresponding points per image.

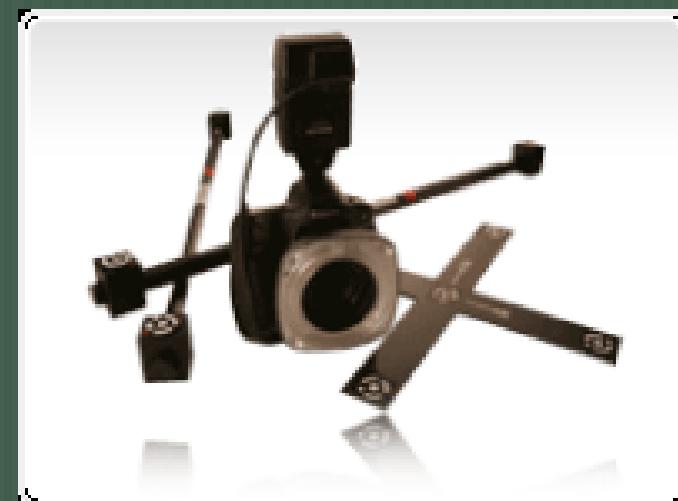
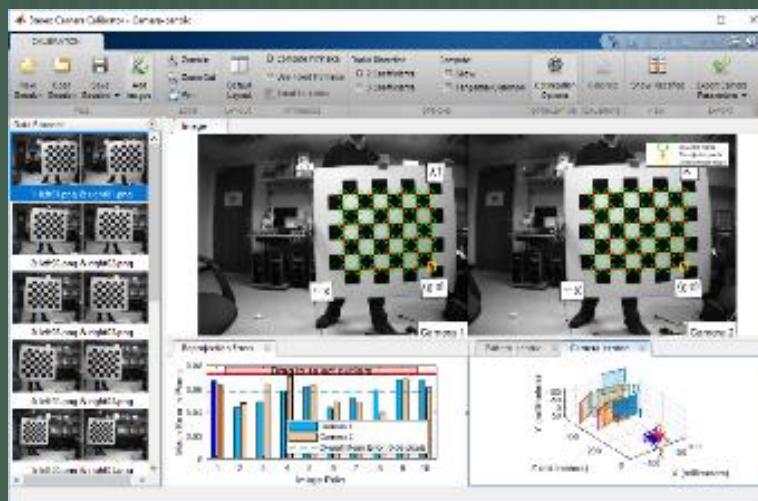
What normally happens is that you start adding correspondences, and at one point the software is able to find a solution, and it tells you.

NOT JUST "BY HAND"

Correspondences between images can be hand-picked, or can be physical markers placed in the scene, automatically recognized by the software



Often, photogrammetry uses cameras that have been **pre-calibrated** with extreme care, making orientation easier and more accurate



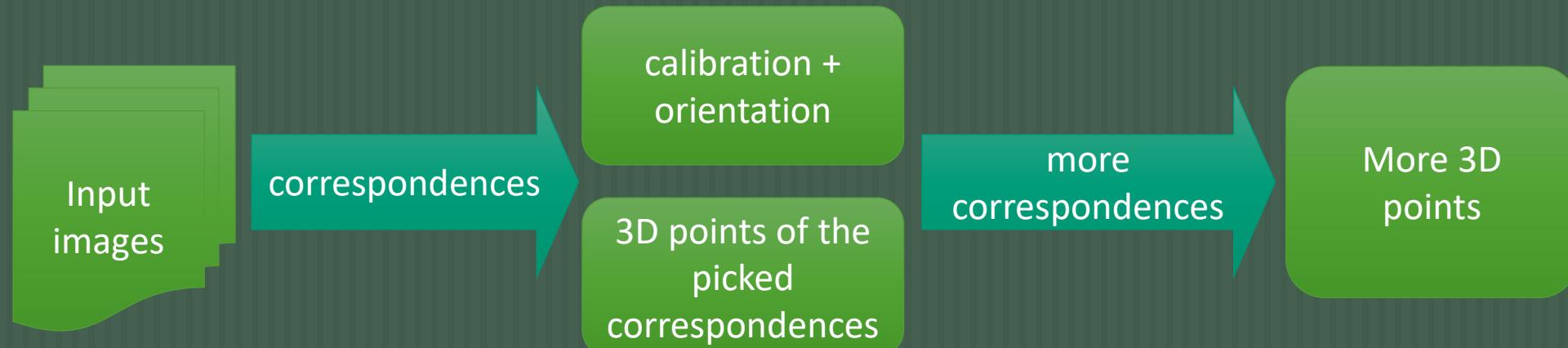
WORKFLOW

In most situations, TWO steps:

- From photos to calibrated+oriented cameras + some 3D points
- Extraction of 3D points

Both are based on correspondences. The first step is critical and require a carefully chosen set of corresponding points.

The second step of geometry extraction and measurement is possible **only** after the scene is completely calibrated.



PHOTOGRAMMETRY

Photogrammetry is the name of the *principle*; many different tools and approaches.

At first seems impossible but, with some care, the obtained precision is way below the projected size of a single pixel.

For a large building, it may be few millimetres, which is really, really good.

"CLASSIC" PHOTGRAMMETRY

- Manual or marker calibration + orientation
 - Manual determination of points

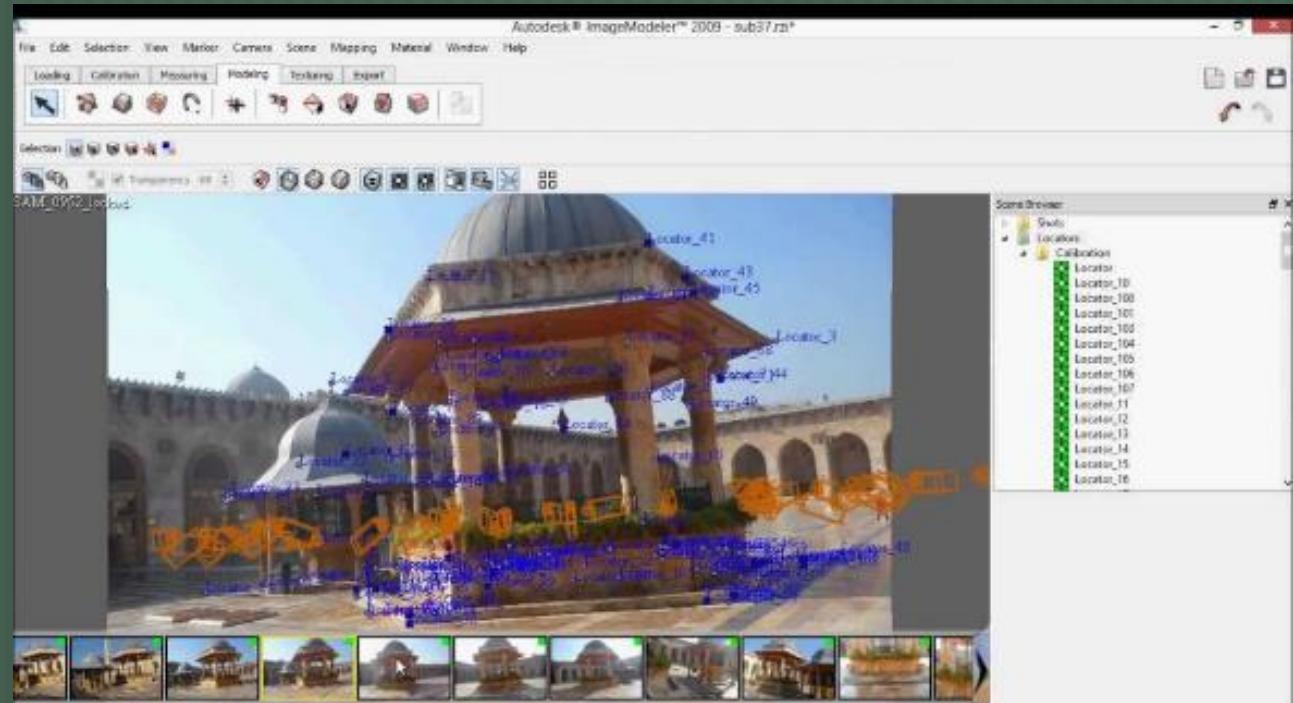


IMAGE MODELER

Photogrammetry commercial tool

Points are **manually** marked on input images, camera are fully calibrated using these points (and other constraints).

Supports panoramas and markers.

Further points are found using more correspondences, and modeling can be done using the recovered 3D points.

Acquired by Autodesk. now just a module for other Autodesk tools



PHOTOMODELER

Photogrammetry commercial tool

The tool for the professionals.

Two initial steps: camera calibration (with markers and references targets) and then camera orientation using correspondences or markers.

Modeling and measuring with lots of different tools.

Integration with Matlab, library for C++ integration.

VERY complex to use (and expensive)



XSIGNO

Shareware photogrammetry tool

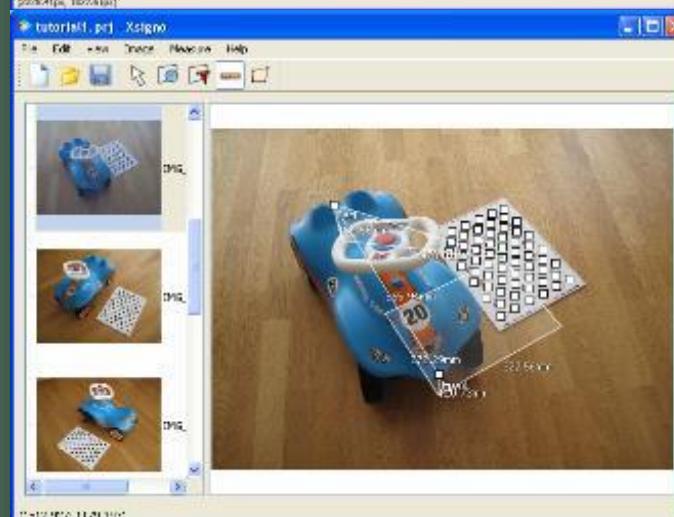
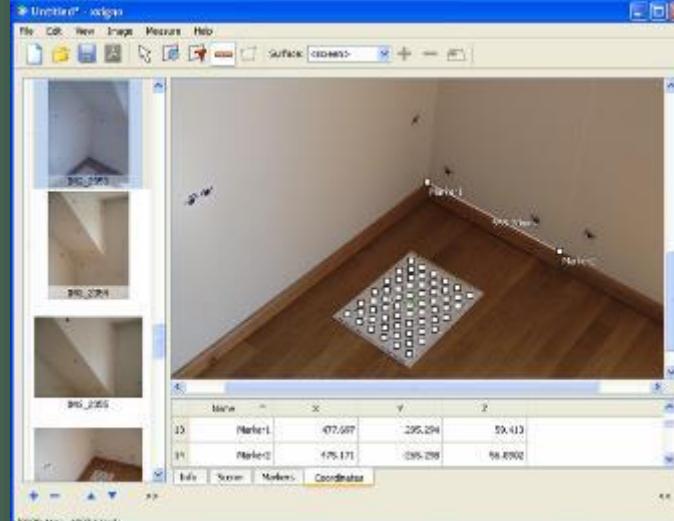
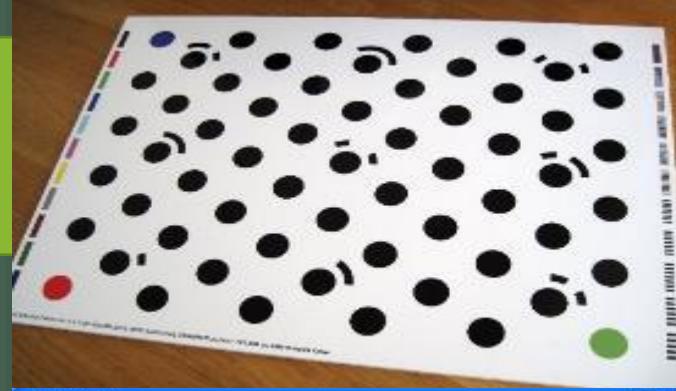
Oriented to measurement (and not modeling).

Intensive use of markers for camera calibration and orientation.

Looks promising for a small software.

But the necessity to use markers may reduce its applicability

Unfortunately, no longer supported ☹



THE SAD NEWS...

NO free photogrammetry tools out there. Sorry 😞

IMAGEMODELER: acquired by Autodesk. Now component for other tools

PHOTOMODEL: very professional tool, good support, quite costly

~~XSIGNO: <http://www.xsigno.com/>~~

~~CANOMA: a very interesting tool acquired by Adobe and disappeared...~~

- try using demo/trial versions
- hope for the best...

PHOTO-MATCHING

Beside 3D model CREATION, Photogrammetry is often used for **camera matching**: determining camera parameters and scene space, to insert virtual elements in the scene. Used A LOT in engineering/architecture.

This is not the only nor the easier way to do this, but still is a popular choice

And for videos?

Generally, automatic methods, similar to what we'll see later



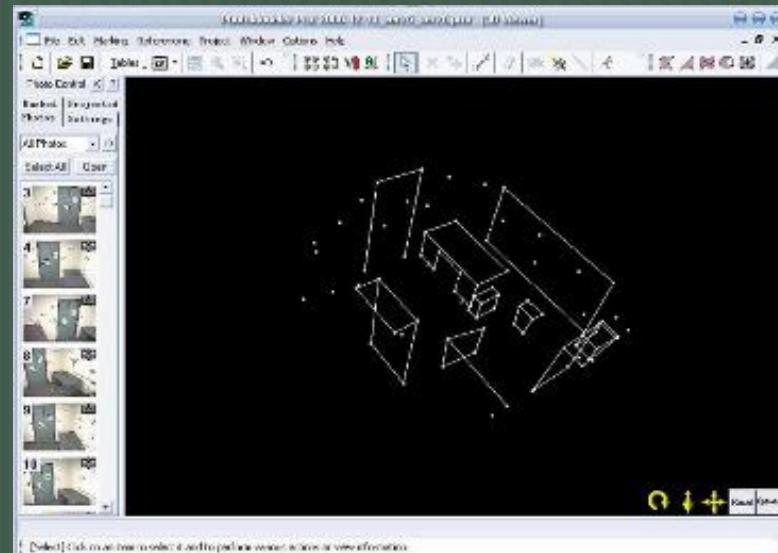
BASIC IDEAS

2 phases: CALIBRATION+ORIENTATION & GEOMETRY EXTRACTION

- both are based on correspondences
- first calibration step returns also some 3D points in the scene
- correspondences are made by user or recovered from markers in the scene

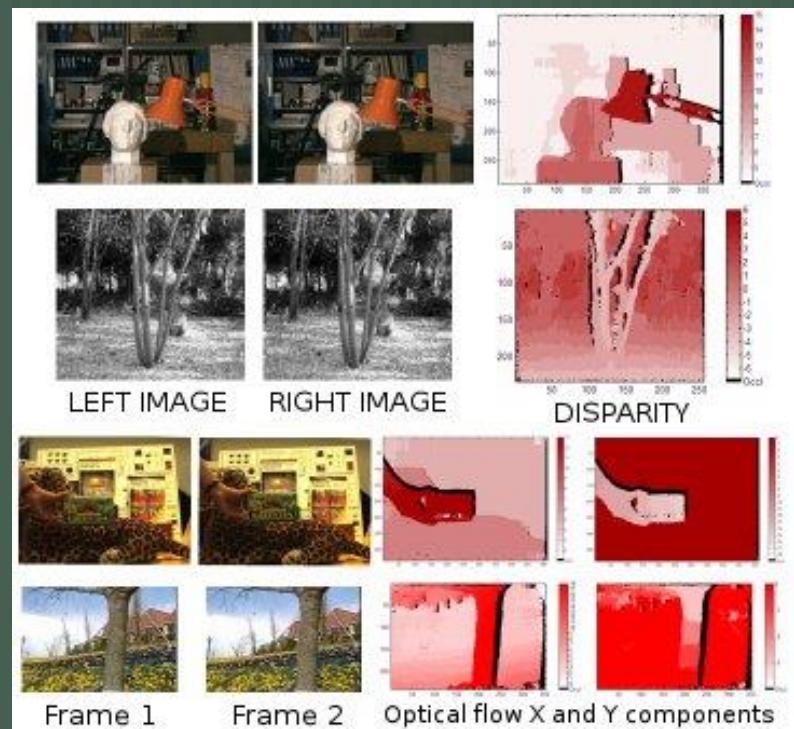
Results: a series of points in 3D

- very high precision
- only the marked points are recovered
- modeling is done on the recovered points
- primarily, a method for MEASUREMENT, not “fully” 3D capture



AUTOMATING ONE STEP

- Manual or **marker** calibration + orientation
 - Automatic determination of points



DENSE MATCHING

The calibration/orientation step is good. However, getting 3D points is tedious and does not scale well.

Idea: use some kind of automatic feature matching to perform a DENSE reconstruction. Not just rely on user-picked points, but try to match the entire surface, pixel by pixel.

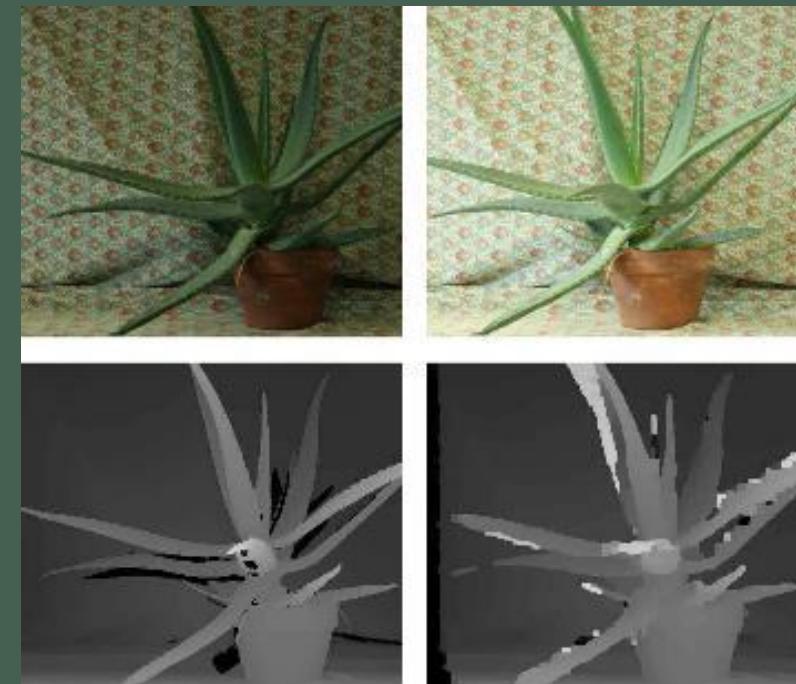
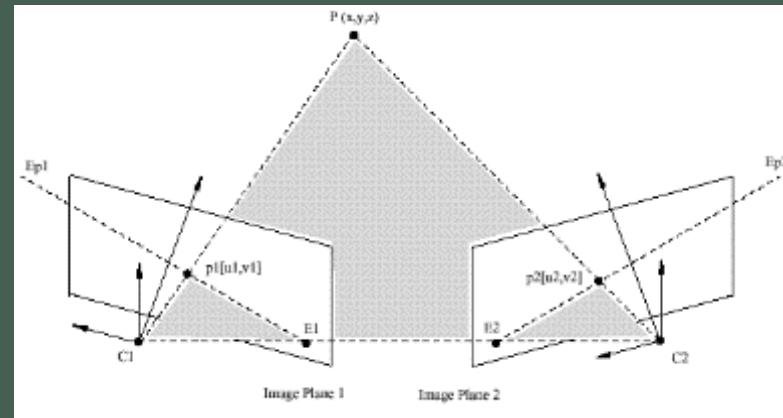
Basic situation:

- camera calibration+orientation is reached with manual correspondences, markers or somehow pre-determined.
- 3D points extraction is done through automatic matching between image pixels, to have a DENSE reconstruction

MATCHING

Difficult ? Yes and no

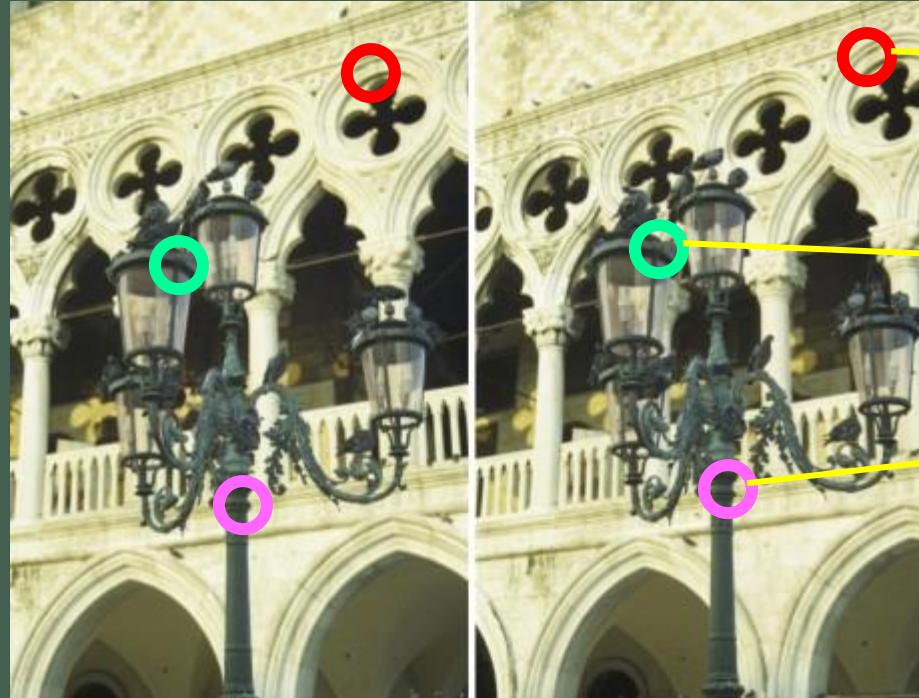
- **NO** given registered cameras, a pixel P_1 on image 1 will have its corresponding pixel P_2 on image 2 laying on a known line. This is called EPIPOLAR line (thanks to the laws of perspective)
- **YES** changes in illumination, different exposition, flat-colored areas, noise and occlusion makes difficult to always pick the right candidate



SHAPE FROM STEREO

Based on the same principle of human stereo vision: two sensors that perceive the world from slightly different position. From parallax it is possible to obtain a depth for each visible point.

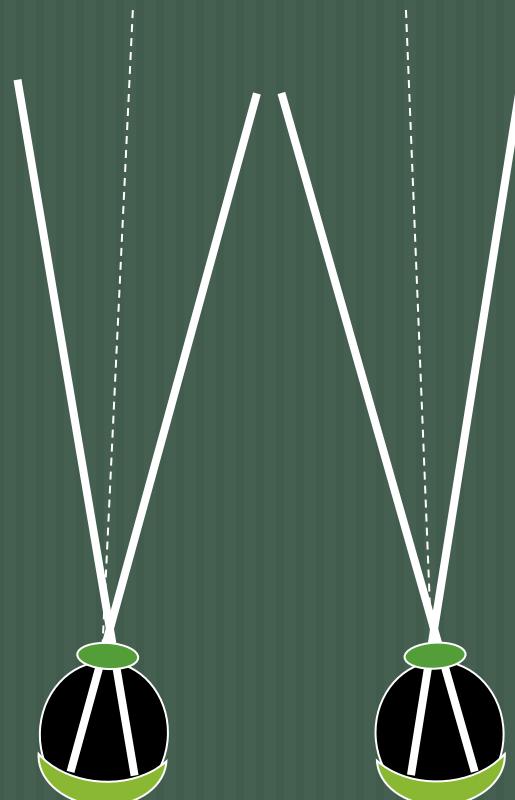
Our brain does this automatically. A machine can be programmed to do the same.



same position
⇒ Background

high variance
⇒ close

Middle variance
=> mid-scene



DEDICATED DEVICES

Various devices, available on the market, are able to perform stereo matching and giving back a depth map.

In practice:

two (or more) synchronized cameras, with a known calibration+orientation, plus a DSP for the pixel-wise dense matching.



Normally used in robotics, because they are fast but not much precise...
but hardware is getting better

PHOTOMODELER - DENSE

The tool is the same one mentioned before... after doing the camera calibration/orientation, instead of using only user-picked points, the system does a dense-matching.

The result is quite similar to a range map... you need to do standard processing in order to obtain a 3D model.



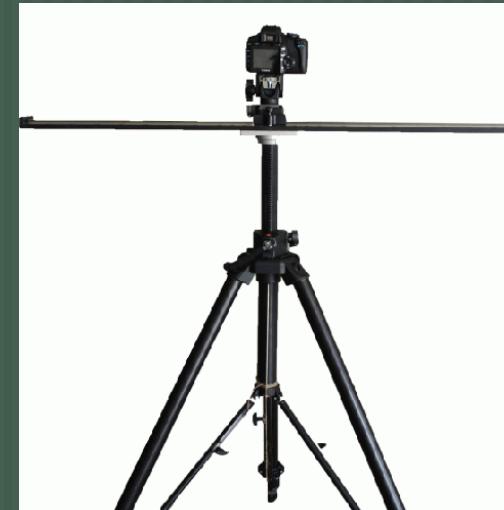
MENCISOFT

Commercial solution... Italian product (quite unusual)

Three photos from a calibrated camera sliding over a very precise railing.

Easy to use, versatile (multi-scale), fast acquisition...

Good results, but very long processing time to obtain a final, complete model



MENCISOFT

- **calibration:** camera is pre-calibrated

- **orientation:** positions are known

What remains is just DENSE, pixel-wise matching. The very regular camera placement also helps this matching

Result: fast, precise and reliable extraction of 3D data.

The real pain is data processing :)



FULLY AUTOMATED PIPELINE

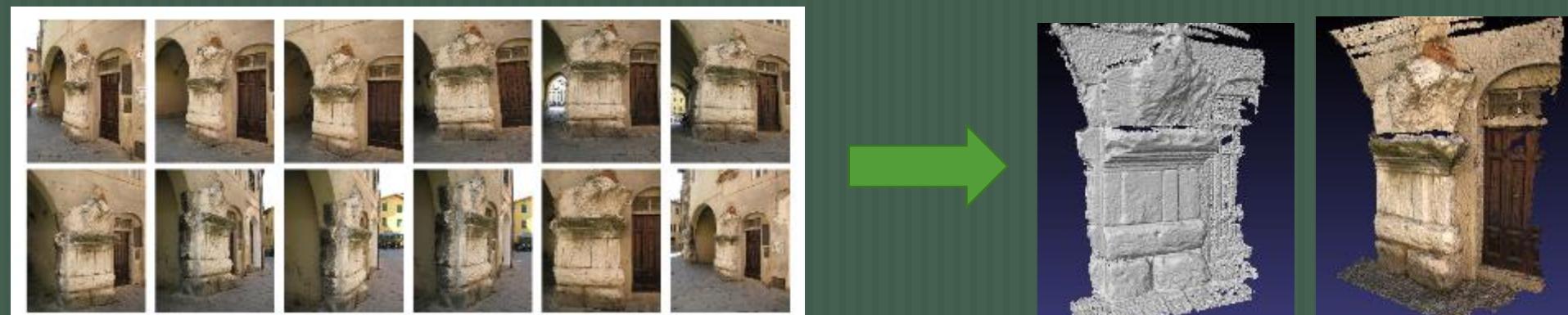
- **Automatic** calibration + orientation
- **Automatic** determination of points

FULLY AUTOMATIC

We know it is possible to do an automatic dense matching after a manual or marker-based calibration+orientation.

To have a fully-automatic dense photogrammetry pipeline, starting from uncalibrated images to create a 3D model, we need to have the computer finding the correspondences between photos needed for the calibration+orientation step

This is **MORE** difficult than dense matching, because there is no geometric information or knowledge of the scene.



CALIBRATION + ORIENTATION STEP

In the previous examples, correspondences for the calibration+orientation step were hand picked (or found using markers).

We cannot brute-force try matching every pixel of every photos. Ineffective and too long.

The computer needs to reason on a some "interesting" points, like we do.

SIFT - SURF

SIFT: Scale Invariant Feature Transform

SURF: Speeded Up Robust Feature

Local descriptors of an image “feature points”, they are used to efficiently determine salient points and match them across images.

Many variants, and really diverse is the scheme for multi-image matching from one software to another.

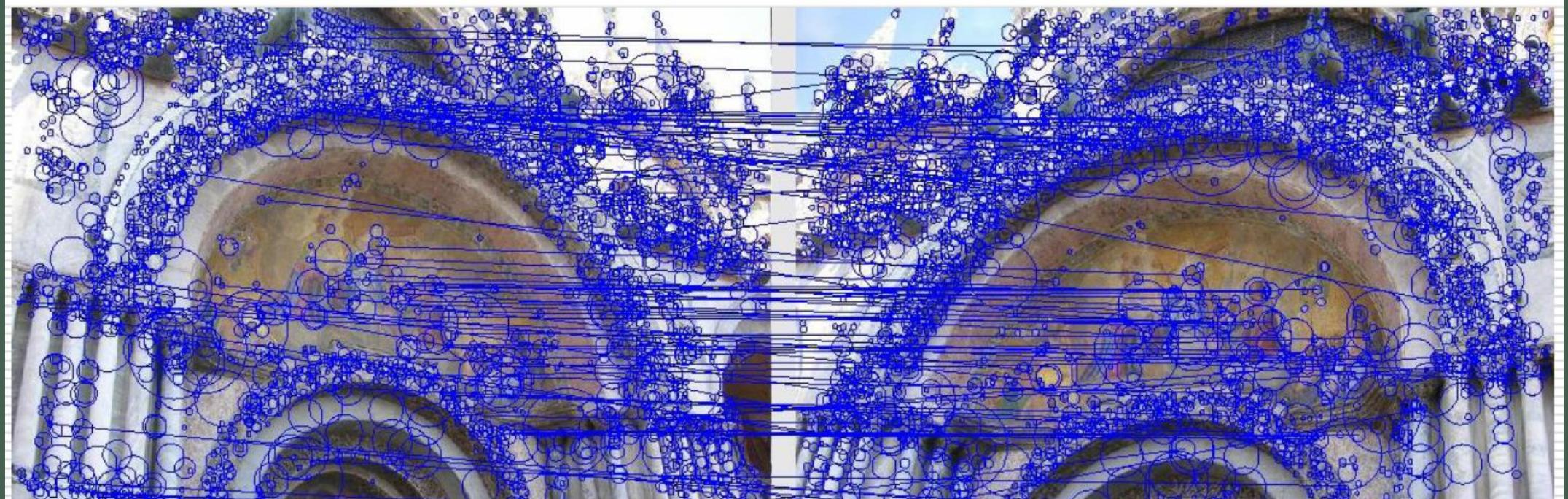


BAG OF FEATURES

A lot more correspondence points are used, with respect to manual photogrammetry.

Points matched by the computer are less accurate than human, but:

- more points -> reduction of error
- more points -> coherence check (ransac)

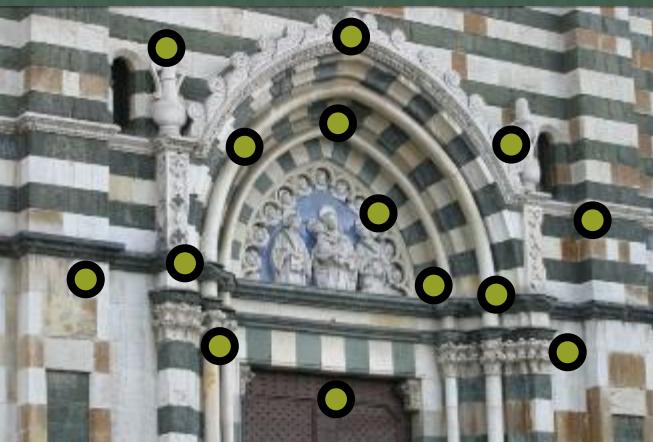
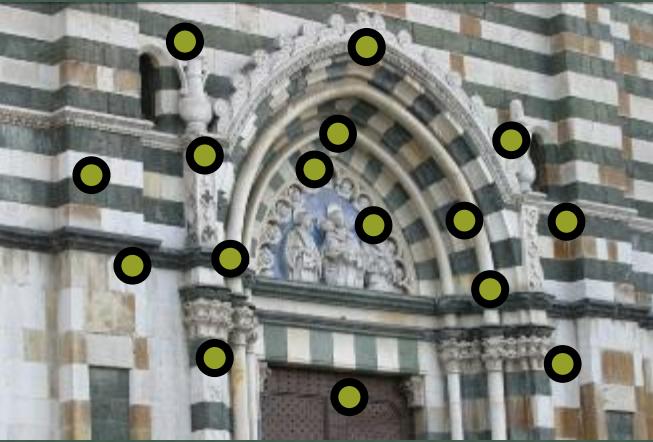
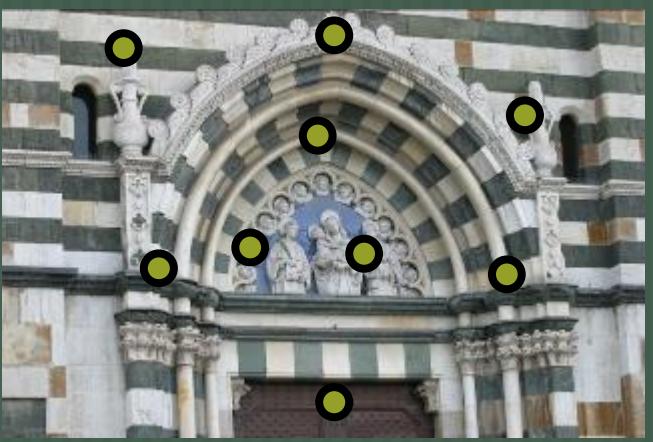
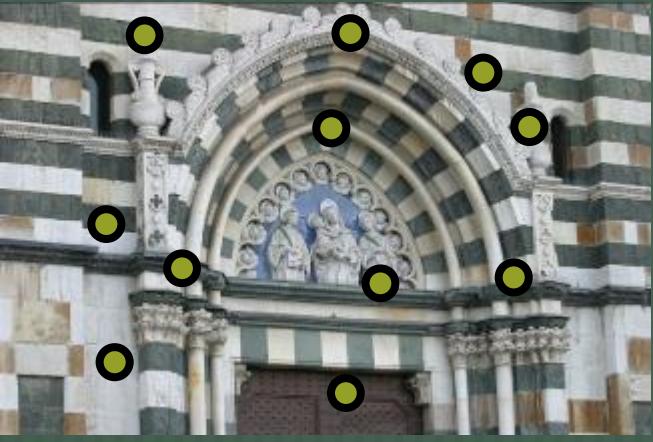
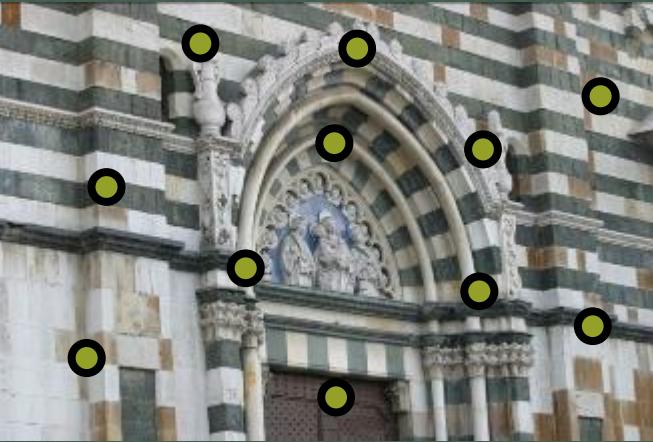


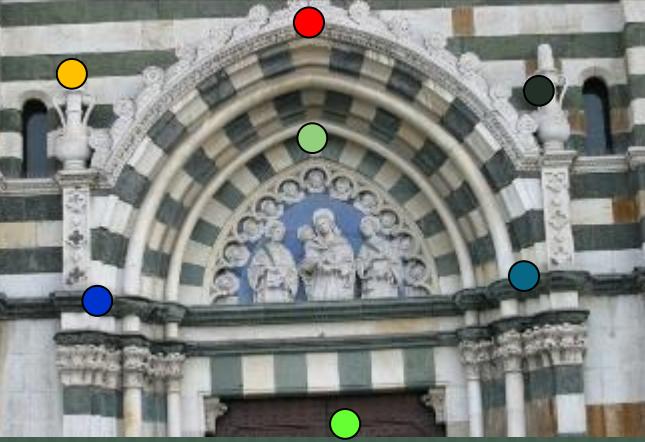
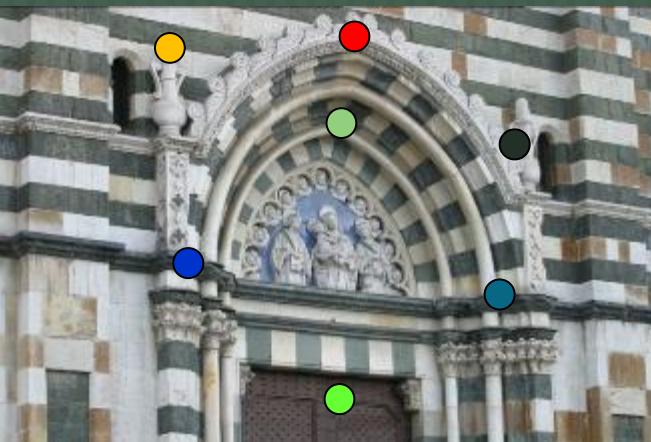
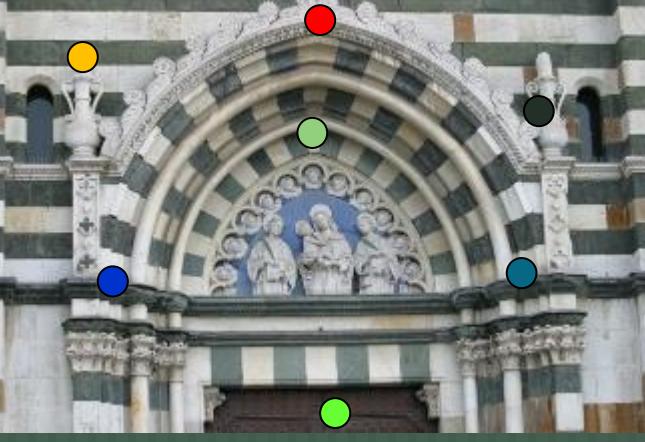
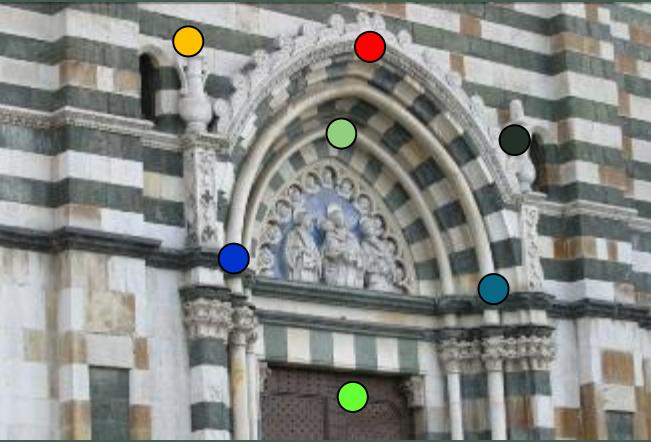
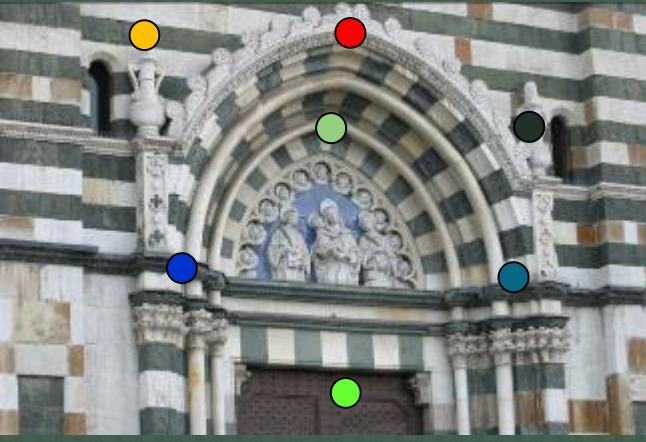
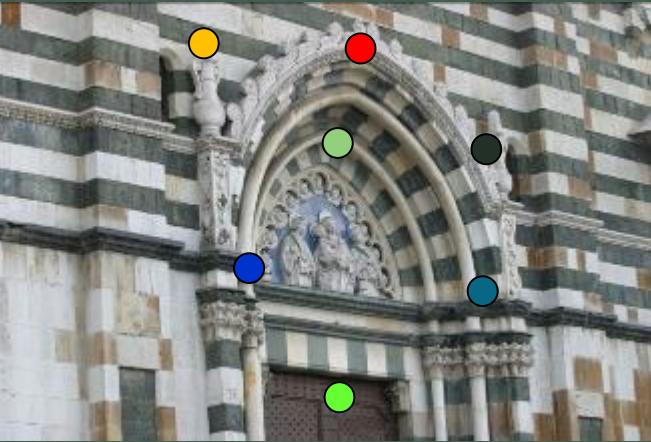
WORKING PRINCIPLE

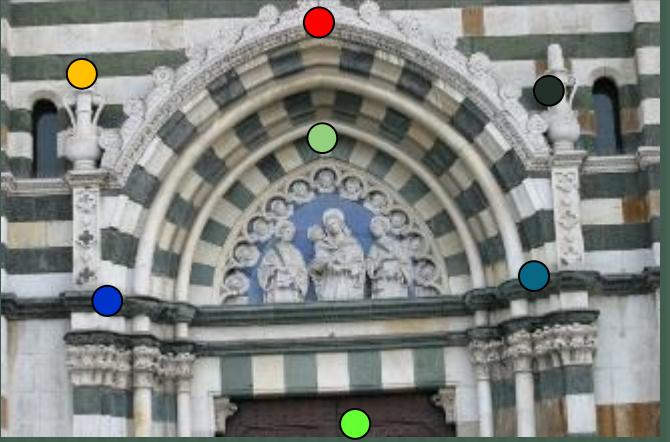
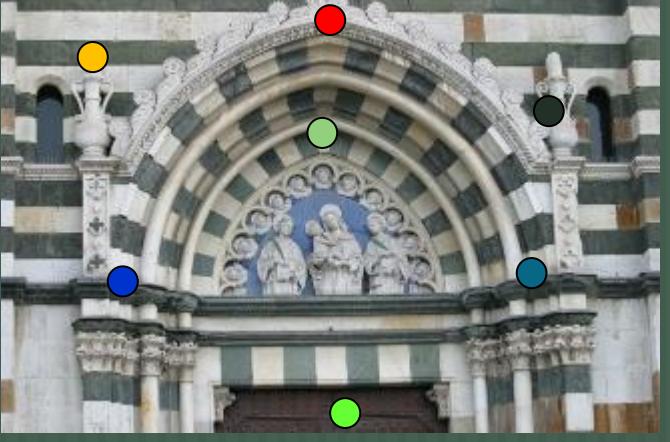
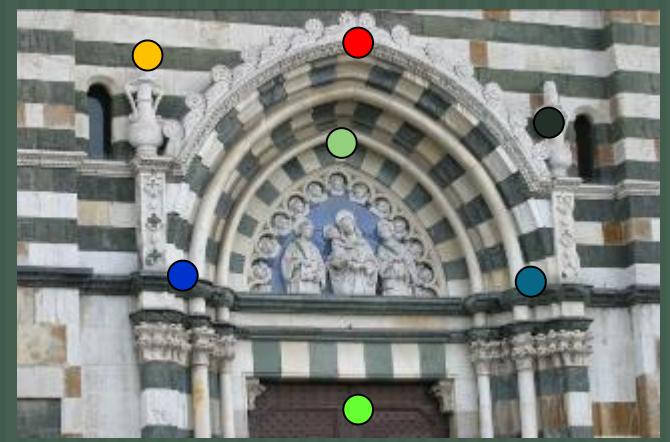
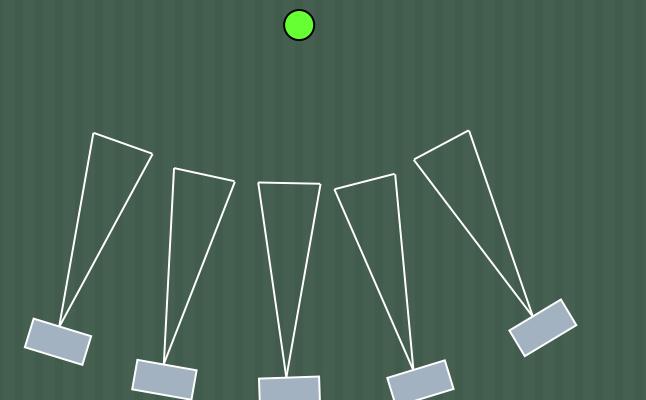
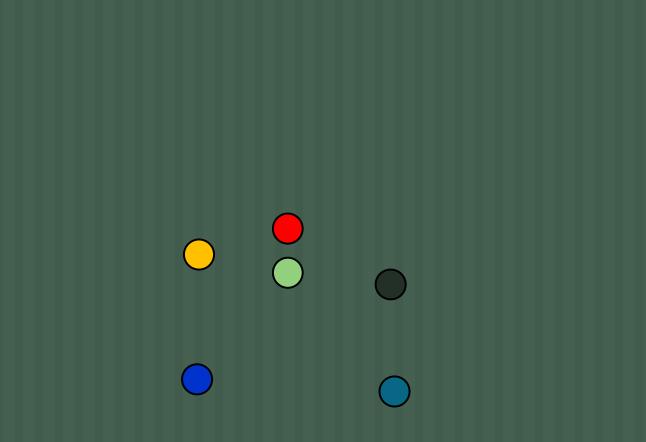
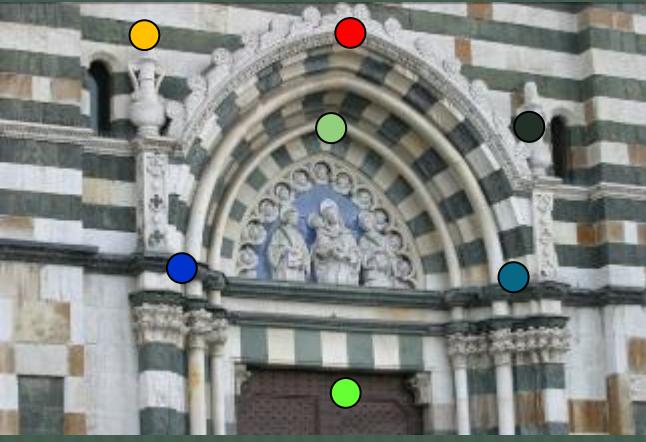
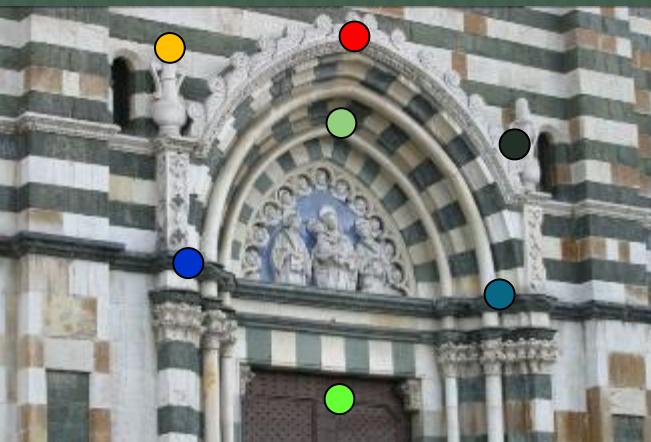
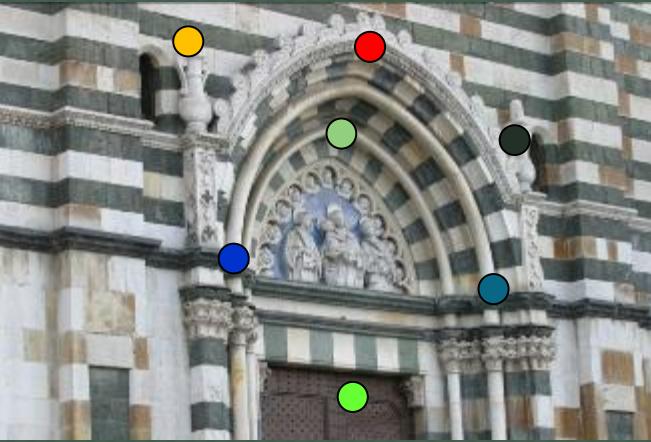
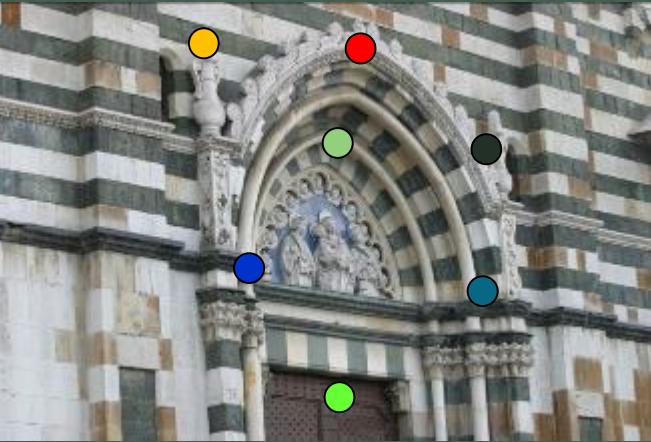
All the existing tools follow the same scheme:

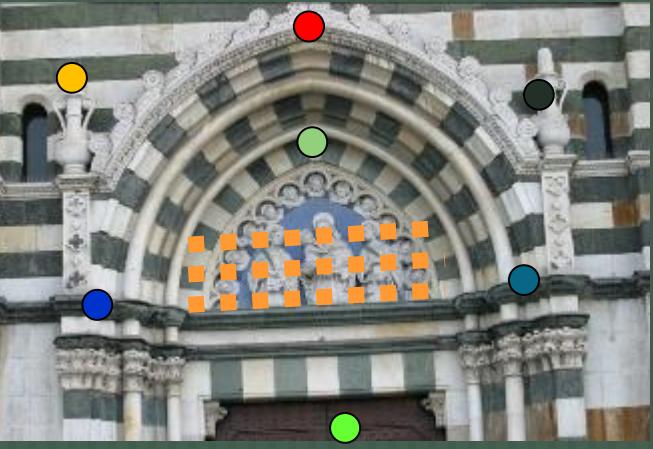
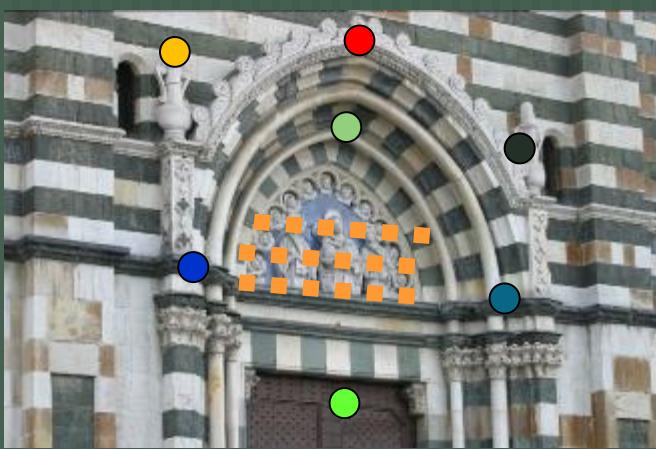
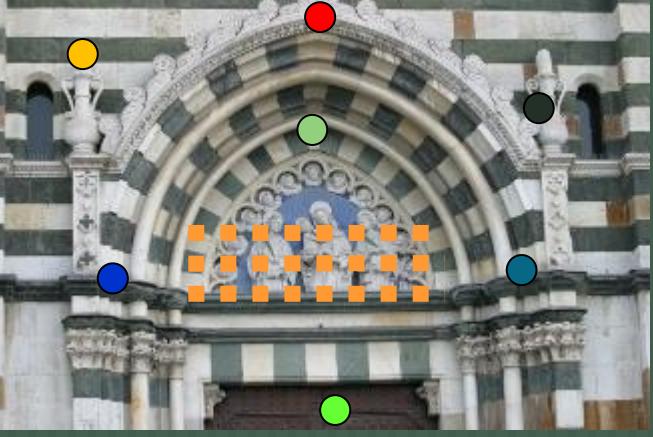
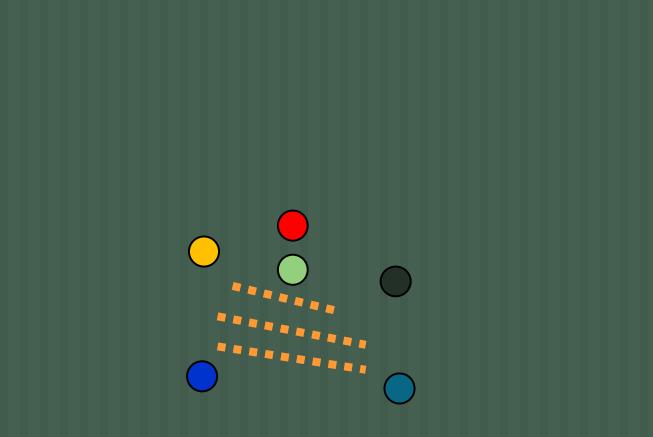
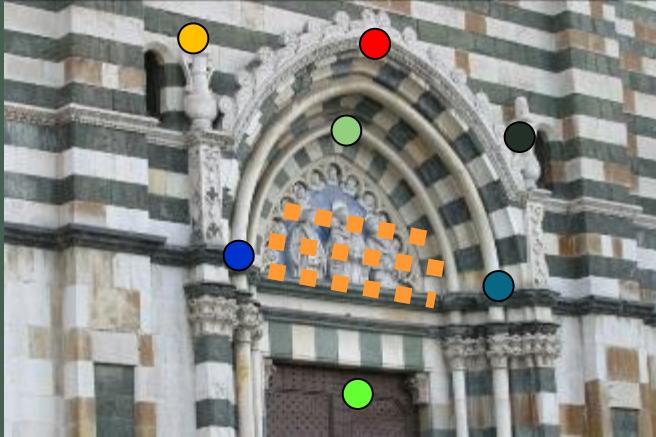
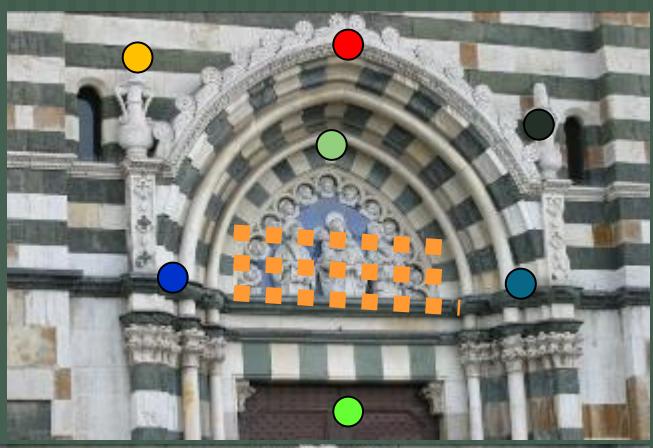
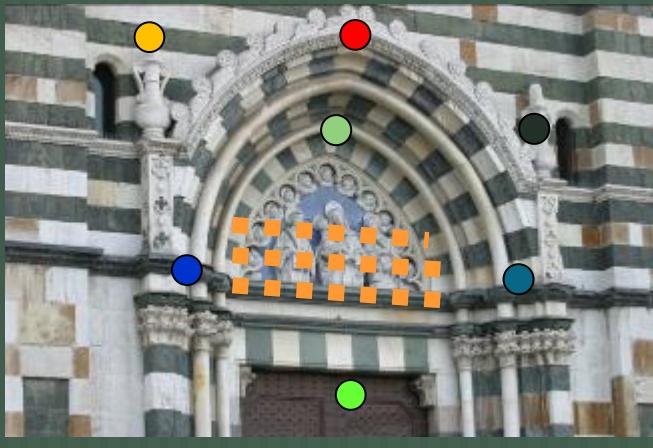
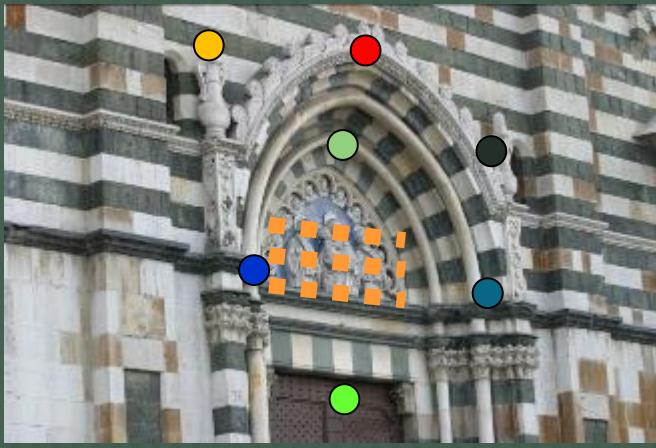
- Using heuristics and local analysis, find some **salient points** in the input images.
- **Match** the salient points across images, determining overlap between images (bag of features).
- From the matched points, determine **calibration+orientation** of the cameras at the time of the shot.
- Using the computed cameras, perform a **dense matching**, trying to determine 3D coordinates for all pixels.











ALL FOR ONE, ONE FOR ALL

Another component used in these tools is:

Bundle Adjustment

Cameras are determined independently, using the detected correspondences, and a global optimization step is often necessary to ensure a good fitting.

Many ready-to-use libraries for bundle adjustment exist...

A PROBLEM OF SCALE

All these tools have a problem in common: the returned geometry is at an unknown scale... every proportion is correct, it is only that the measure unit is unknown. This is because nothing is known about the scene and the camera (you may have been taken a photo of a car or of a car model).

How to solve this? You need a measurement taken on the real object and the corresponding measure from the computed 3D model to calculate the scale factor!

Most tools have a way to calculate/specify this scaling factor at the time of model creation... in any case, it will always be possible to apply a scaling factor to the whole result :).

A PROBLEM OF SCALE

This issue is common also to pure Photogrammetry tools!

Photogrammetry software has inbuilt tools to apply scale, with multiple measurements and residual error calculation.

If you are using markers of known size/pattern size, or some metric details of the scene are known (like the offset of the camera in the MENCI tool), the scale is calculated automatically.

A PLETHORA OF TOOLS

Using 3D from images is easy, you need a camera and one of the many software tools...

A lot of free tools, often a "toolchain" of existing tools.

Some semi-free or very cheap software.

ONLINE - OFFLINE

Computing 3D reconstruction from photos is a cumbersome task, computationally. A reconstruction may take hours, or even more than one day...

For this reason some tools are implemented as web-services.

The data is sent to a remote server, ad you receive the results

- ☺ Good performances, remote code is regularly updated
- ☹ You need network access, you have to send away your data

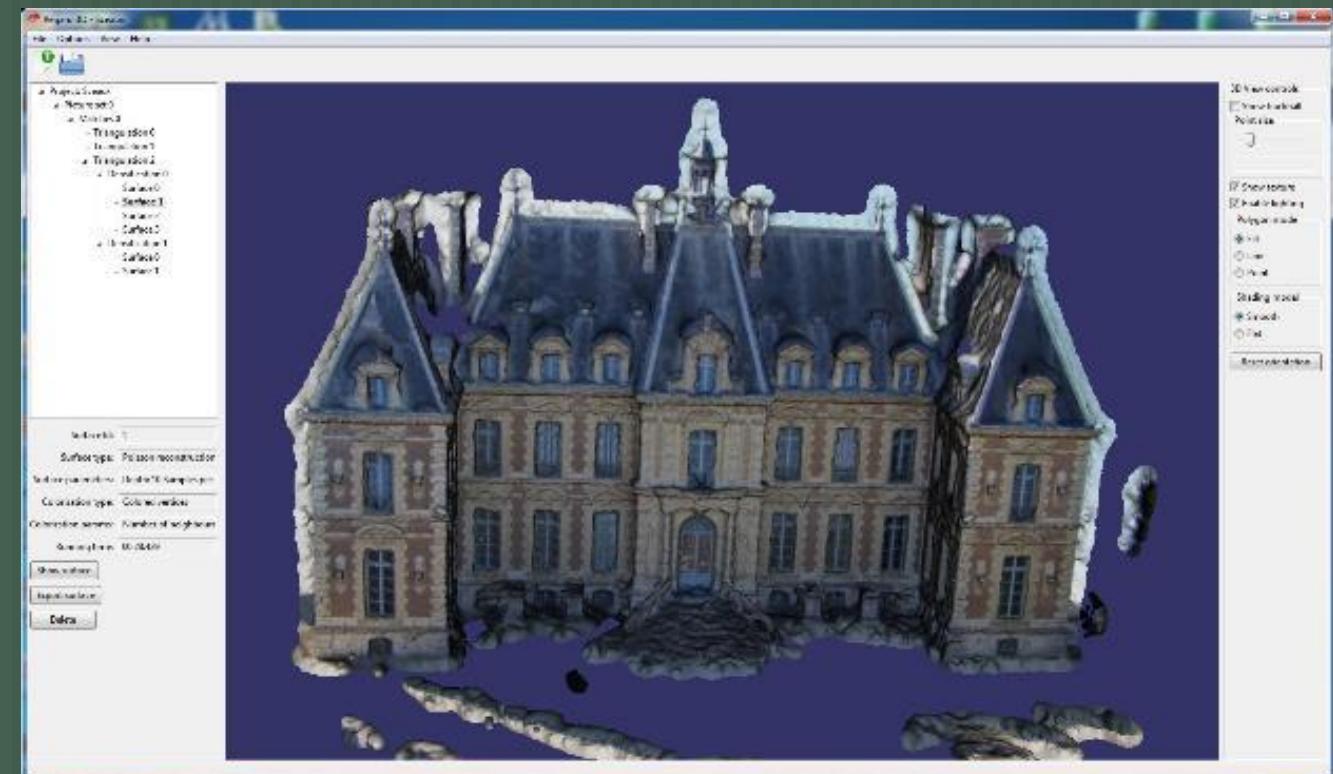
REGARD3D

Open Source tool.

Quite recent, but is becoming widespread.

Completely local. Works on Windows and MacOS

<http://www.regard3d.org/>



VISUALSFM

Free tool (not opesource, but some components are opensource).

Grown a lot in usability and performances...

Completely local. Easy to install (under windows) and use.

Good result at no cost... But has been abandoned

<http://ccwu.me/vsfm/>



PMVS2

Most of the open/free tools, will use for the DENSE step the same tool... PMVS2. This is a research tool made by Yasutaka Furukawa (a major researcher in Computer Vision).

Beware of computation time... if you exaggerate with the extraction parameters, the machine can remain at work for hours (or days). The result is a colored point cloud with normals; with MeshLab it is possible to generate a surface.



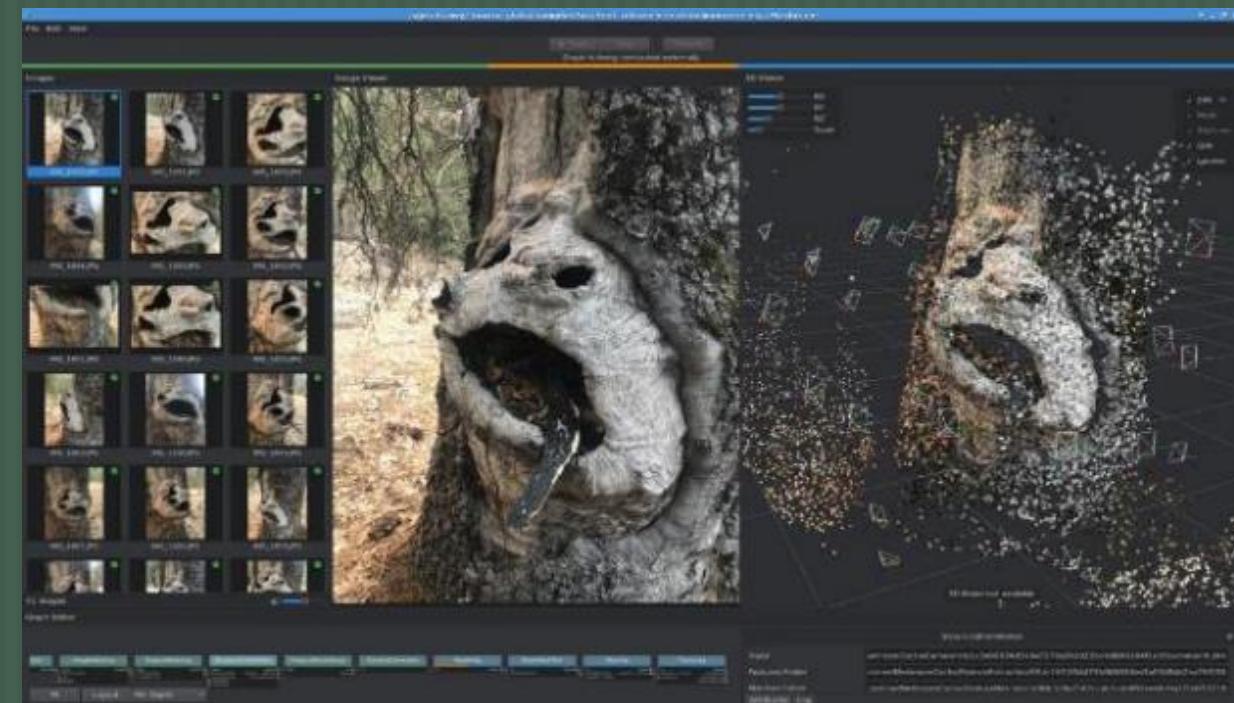
MESHROOM

Another newcomer.

Open-source tool from a commercial company.

Powerful and configurable. A bit more complex to use w.r.t. the other free alternatives.
Difficult to extract intermediate data

<https://alicevision.org/#meshroom>



METASHAPE (WAS: PHOTOSCAN)

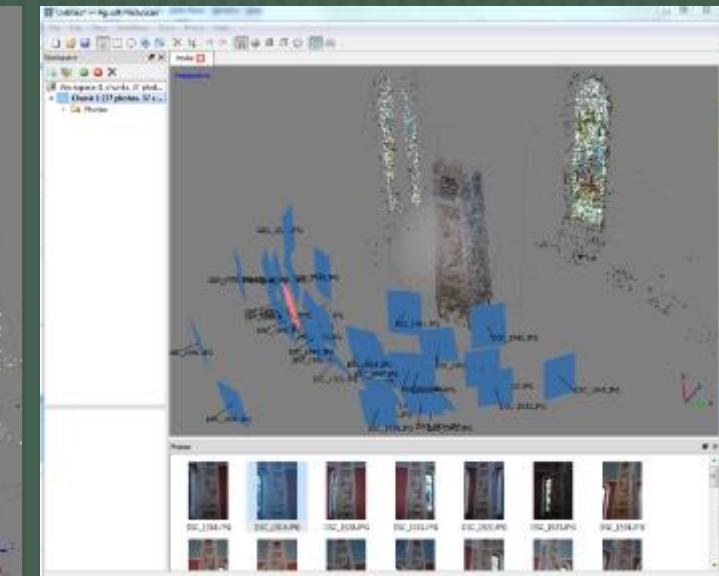
Commercial, low cost tool: 59 € for educational license, 179€ standard license. (win, mac & linux)

Fast, work on **local** machine, directly produce textured model. Very robust and reliable.

We have used it with good results on many diverse datasets.

They also have an integrated tool for camera calibration

<https://www.agisoft.com/>



METASHAPE (WAS: PHOTOSCAN)

Metashape is the **DE FACTO** standard tool in CH...

It's cheap, easy to use, and reliable.

It works incredibly well with DRONES

PRO version has a georeferencing tool, can use markers for automatic scaling, and has a lot of exporting features specific for survey, CAD and GIS tools.

REALITY CAPTURE

Quite recent, but already super-popular...

At the moment, the most compete and powerful tool

Works on really large datasets (1000+ images)

Can integrate photos + 3D scans. Works locally or on their cloud service.

~~:(very high cost...~~

Big news: it was bought by EPIC GAMES

They plan to significantly reduce the price and make it available for educational purposes.

We'll see.



AUTODESK RECAP

Previously known as, 123DCatch, Memento, ...

Very well engineered tool...

Works on a **remote server or locally**

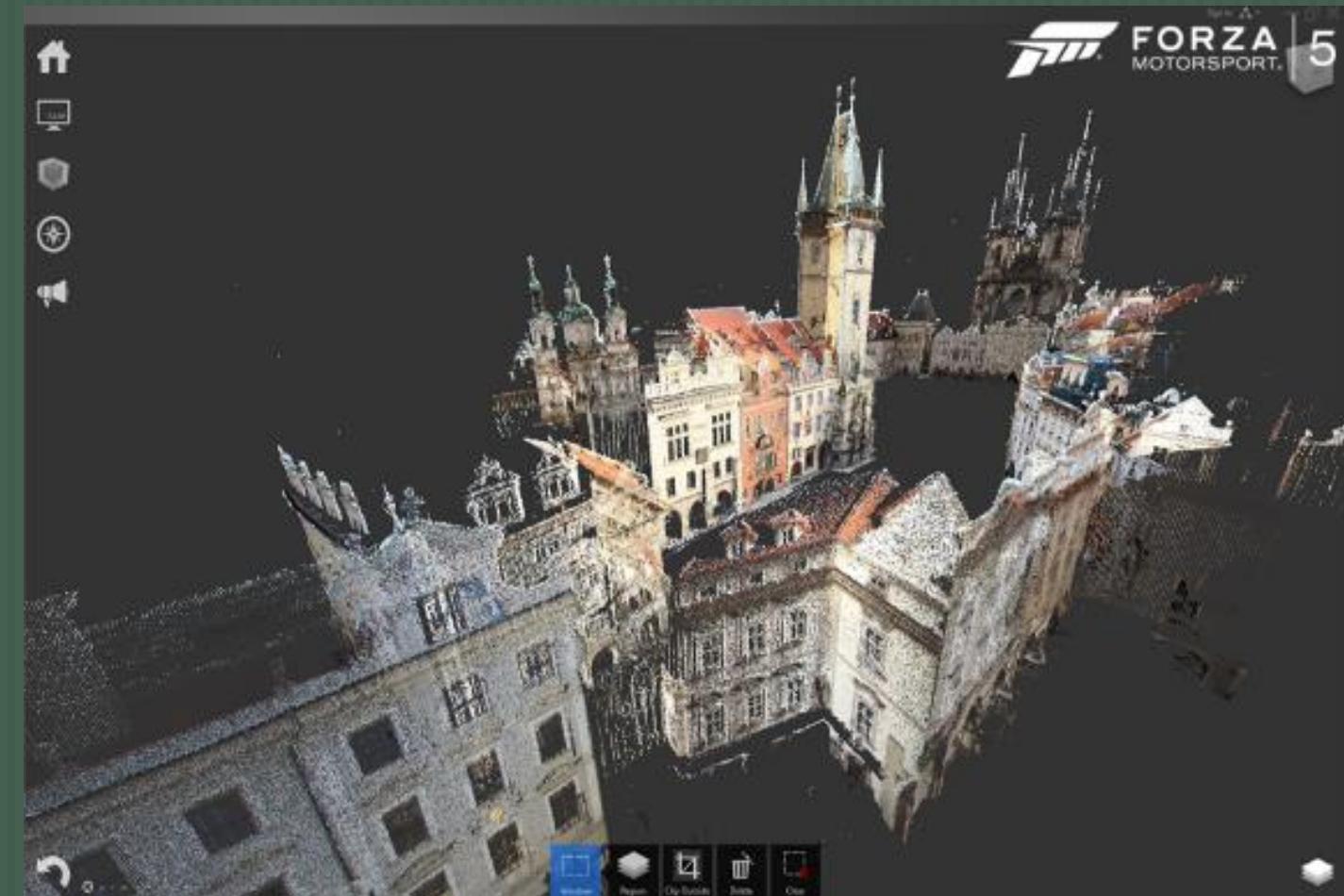
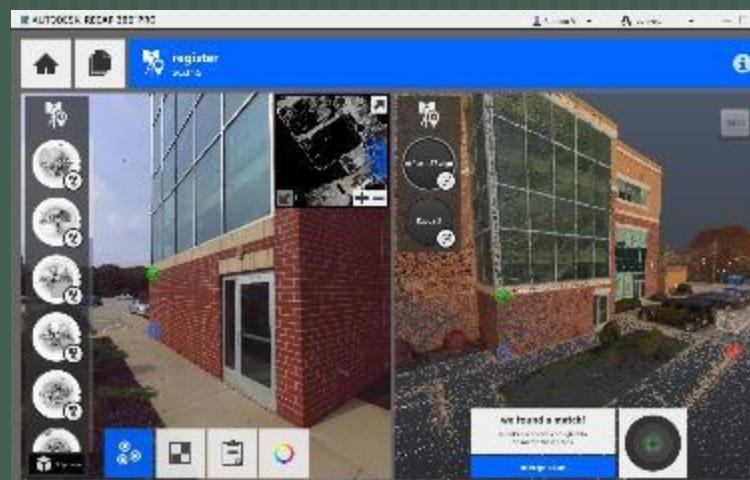
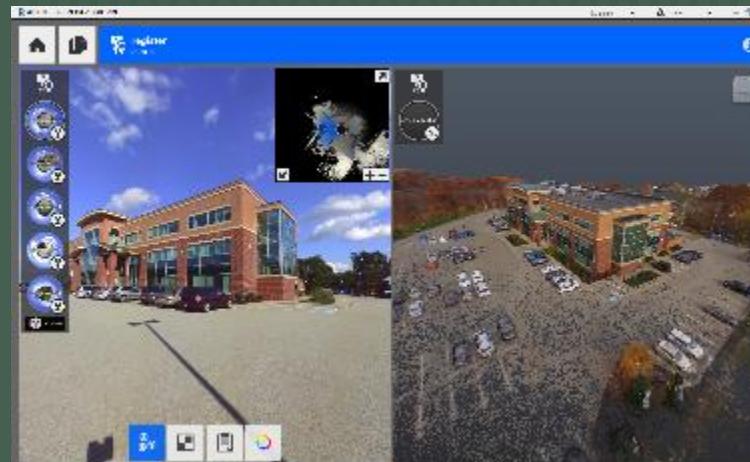
Produces a *complete, textured* model

A full-fledged 3D digitization & processing tool, from scan/photo to CAD and printable models

Has a limited free version...

It is fast, and works very well, is able to reconstruct difficult datasets and the results looks good.

AUTODESK RECAP



OTHERS

- **COLMAP**: free, seems powerful but I have seen many people having problems in running it (I never tried, t.b.h.)
- **3D Zephir**: commercial, but with limited trial, easy to use
- **Pix4D**: commercial, mainly for drones
- **Bentley ContextCapture**: commercial, large scale, for huge projects, super-expensive
- ...

QUESTION TIME

Thanks for your attention

callieri@isti.cnr.it

