Object Complexity vs. Model Complexity

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What is the limiting factor in 3D digitization process today?

Current technology Limits

Available technology	Max. resolution/accuracy
Micro-scanning	1 μm
Photogrammetry	0.5 cm
Laser scanning point cloud	0.5 cm
GNSS topography/surveying	1 cm
UAV imagery	2 cm
Satellite imagery	30 cm

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What is the limiting factor in 3D digitization process today?

Current fit-for-purpose Limits

Possible purpose of use	Max. required resolution/accuracy
3D printing replica 1:1 of small objects. Digital archive at max. resolution	2 µm
3D printing replica 1:1 of large objects. Digital archive at max. resolution	1 cm
Web viewing	200µm (= 0,2 mm at viewing distance)

It is clear that the current technology supports even the most demanding current needs, whereas the mainstream applications needs can be easily met by rather relaxing technology specifications.

ARGUMENT: The focus should be shifted from data acquisition to object modeling.

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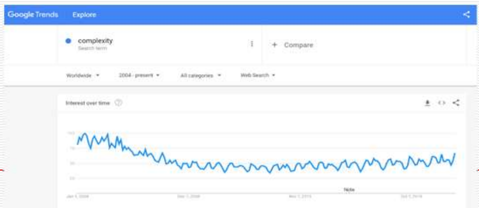
Do we need a definition of "Object Complexity" ?

"Object Complexity" seems to be a trendy term. The number of hits obtained by searching for "complexity in 3D" through Google and Scholar Google are:

- **Google: ≈ 157,000,000** (taken as a proxy of overall diffusion of the concept)
- **Google Scholar: ≈ 2,480,000** (taken as a proxy of academic interest)



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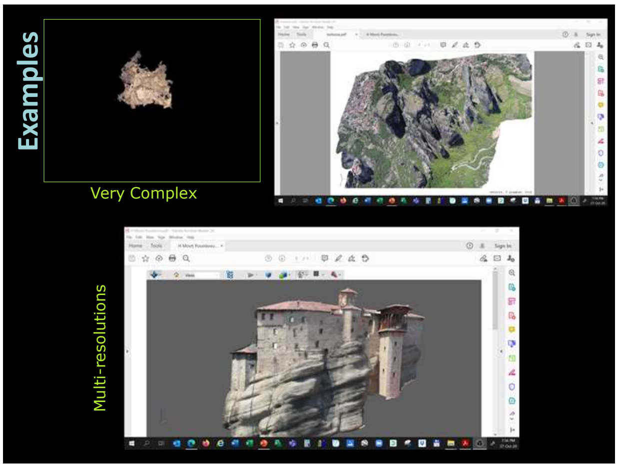

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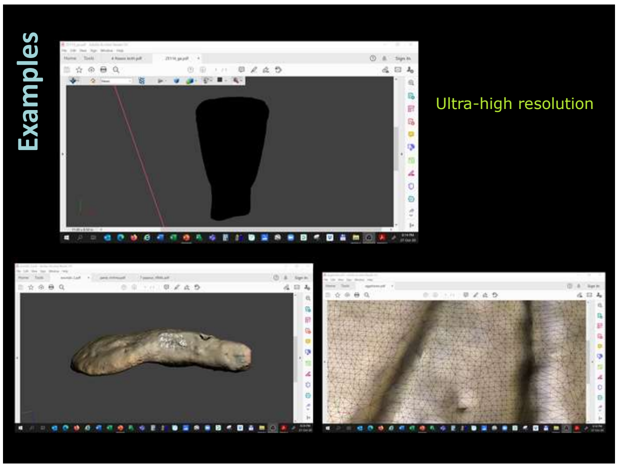

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...and to make things worse....
Cultural Memory includes

- **monuments and archaeological sites**
- **museum objects**

- photographs
- prints (books, journals and newspapers)
- archival documents
- sound and audiovisual material
- intangible heritage

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Do we need a definition of "Object Complexity" ?

- object complexity as a value of its own
- which cannot be estimated subjectively,
- it can be defined only AFTER we make all the measurements on the object (making it useless for 3D digitization planning and decision-making) and
- it is neutral to intended use (making it useless for choosing the best technology)

ARGUMENT:
We need to shift our attention from the "Object complexity" to "Model complexity".

This means that our focus is not the complexity of the real object per se (which is connected to the data capture phase), but the complexity of the produced model (which is connected to the data processing phase).

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… take an example

- Suppose that we have a **3m statue** of a rather complicated marble surface.
- The **purpose** of the 3D digitization is to use it into a **virtual museum** of Roman History.

This means that the produced model will be seen on a computer screen at a max of 3x zoom factor and a max scale of 1:50 of the original statue.

This translates to a model with a dimension of 6cm (=3m x 1:50 scale) which can be zoomed by a factor of 3x (thus the final model should be seen in full detail corresponding to a **virtual object of size 18cm** (= 6cm x 3)).

This should be able to be examined seamlessly at a normal viewing distance, which corresponds to a typical optical resolution of **0,2mm** or 200μm. Dividing the max. dimension of 18cm by this resolution we end up **9,000 surface-defining triangles** of a max dimension 200μm each.

This is the model fidelity as defined by the fit-for-purpose.

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example ….

If we now go back to the original object, and let's assume that the modelling process degrades the fidelity of the original measurements by a relaxation factor of eg. λ = 2. That is, the original measurements are smoothed and generalized through the modelling phase, and so they lose half of their original accuracy of representation. So, in order to make sure that the final model keeps its aimed characteristics, we need to make original measurements twice as accurate than the model specifications, i.e. we need **18,000 triangles** to describe the object surface.

Dividing the object dimension (3m) by the number of triangles (18,000) we end up with a resolution (or max dimension of the triangle side) 1,67cm for the 3D digitization measurements.

Final conclusion: no matter what the complexity of the original object is, we will not be able to see smaller details (or measurement errors) than say **1,5cm** on the object surface. This is the actual complexity that matters to us, and according to this we may plan the use of the optimum technology, and the recording strategy.

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Summarizing : Do we need a definition of "Object Complexity" ?

- Complexity will determine to high degree the **technology** to be used. E.g. it is quite difficult and unproductive to use Photogrammetry to record the complexity of a cave, whereas Laser scanning is the suggested technology in this case.
- Complexity is the missing connection between the **Quality** and the **Purpose-of-use**. E.g. although possible it is useless to use UAV imagery to map a large surrounding landscape of an archaeological site, whereas satellite imagery is much preferable.
- Complexity imposes restrictions on both the technology and intended use. E.g. surface transparency violates basic photogrammetric rules, preventing the use of this technology; also low reflected radiation of certain surface material poses restrictions to laser scanning.
- Complexity connects **Quality, Accuracy and Completeness** as long as it expresses parameters like object size or resolution requirements. E.g. complex interiors call for fusion of technologies, exploiting the merits of each one, while requirements for multiple resolutions/accuracies are often dictated by multiple uses of the same 3D acquired material.

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What should be the characteristics of such a definition?

Complexity as a property is typically defined as (Oehmen et al, 2015):

- Containing multiple parts
- Possessing a number of connections between the parts
- Exhibiting dynamic interactions between the parts; and the behavior produced as a result of those interactions cannot be explained as the simple sum of the parts

In the 3D digitization context, more relevant is the term "**surface complexity**" or "**roughness**".

Roughness metrics either use surface roughness index, or variability in the surface normal vectors. This is quantified by the deviations in the direction of the normal vector of a real surface from an ideal plane and is mainly used in Metrology/Mechanics.

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What should be the characteristics of such a definition?

What is important to note is that the size of the local neighborhood dictates the scale at which surface roughness is characterized. Thus, **roughness or surface complexity is scale-variant, and is assessed at a scale that is meaningful with respect to the specific application**.

…………………

Summing up, the definition of the object complexity should have the following characteristics:

- It refers to both 3D data **capture** and data processing/**modelling**
- It is calculated **subjectively**
- It is estimated **before** the data acquisition phase
- It connects to **Quality, Technology, Purpose** of use
- It provides a meaningful tool for planning both the data **acquisition** and the 3D **modelling**

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How Complexity is defined – How is it measured?

- **Geometric/Structural Complexity** This refers to the resolution, the **degree of detail**, the number of features, the number of surfaces or faces of the object. Given that triangles are the fundamental geometric unit that is used by many graphics systems, the **number of triangles is a key metric for complexity.** Another important aspect of Geometric complexity is its **relationship to the size of the object**. It is clear that the absolute number of triangles does not reflect the object complexity, and only the relative number is useful. We, thus, propose to use the ratio number of triangles per unit surface instead.
- **Surface/Texture Complexity** This refers to RGBA colors as well as multi-textures. RGBA accommodates simple imagery information that captures **Red-Green-Blue-Alpha** values in separate channels where Alpha represents **opacity**
- **Material Complexity** This refers to object complexity originated by the material and its **physical characteristics** (e.g. Reflectance, Transmittance, Absorbance, etc.). which can impose limits or barriers to active or passive data capture technologies.
- **Environment, motion, etc.**

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How Complexity is defined – How is it measured?

Complexity[3]	Immovable				Movable			
Degree of Complexity	Low	Medium	High	Ultra-High	Low	Medium	High	Ultra-High
Geometric/Structural Complexity / Resolution								
Number of triangles per unit surface	<10/m	<100/m	<1,000/m	>1,000/m	<1/cm	<10/cm	<100/cm	>100/cm
Min. triangle dimension	10cm	1cm	1mm	<1mm	1cm	1mm	100μm	<100μm
Surface/Texture Complexity / Resolution								
RGBA texture	•	•	•	•	•	•	•	•
Multi-textured	•	•	•	•	•	•	•	•
Material Complexity								
concrete	•							
brick	•							
metal		•	•			•	•	
ceramic/clay			•				•	
glass				•				•
stone		•					•	

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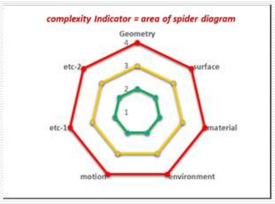
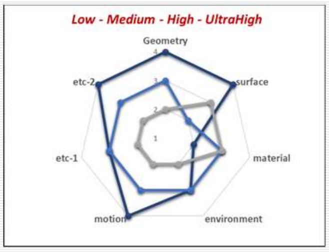
Complexity as a Composite Indicator





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How Complexity is connected to Quality?

Quality	Immovable				Movable			
Degree of Complexity	Low	Medium	High	Ultra-High	Low	Medium	High	Ultra-High
Geometric Accuracy								
Precision								
Accuracy/rms	10cm	1cm	1mm	<1mm	1cm	1mm	100μm	<100μm
Radiometric Accuracy								
Reflectance								
Transmittance								
Absorbance								
Completeness								
% of "blank" pixels	<10%	<10%	<10%	<10%	<10%	<10%	<10%	<10%

Our assumption is that Resolution should not differ from Accuracy since it does not make sense to collect denser points than the accuracy level

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How Complexity is connected to Technology?

Technologies	Immovable				Movable			
Degree of Complexity	Low	Medium	High	Ultra-High	Low	Medium	High	Ultra-High
Tactile								
Hand Survey	*				*			
Architecture	*				*			
Topography								
GNSS		*	*	*				
Traditional topographic survey	*	*	*	*				
Photogrammetry								
Close-range	*	*	*	*	*	*	*	*
Terrestrial	*	*	*	*				
Airborne	*	*	*	*				
UAV	*	*	*	*				
Laser scanning								
Terrestrial Laser Scanner	*	*	*	*	*	*	*	*
Airborne LIDAR	*	*	*	*				
Mobile System	*	*	*	*				
Satellite Remote Sensing								
Low resolution-LR (>5m)	*							
High Resolution-HR (<5m)	*							
Very High Resolution-VHR (<1m)	*	*						
Specialized Technology								
Desktop scanner					*	*	*	*
Hand-held Scanner	*	*	*	*	*	*	*	*
~~Underwater Systems~~	*	*	*	*				
Subsurface Systems	*	*	*	*				
Specialized Hardware (X-Radiography, CT-scan, Stereography)	*	*	*	*	*	*	*	*

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How Complexity is connected to purpose of 3D digitization?

Purpose	Immovable				Movable			
Degree of Complexity	Low	Medium	High	Ultra-High	Low	Medium	High	Ultra-High
Reconnaissance level (accuracy/resolution)								
▪ Condition recording ▪ Initial inventory /planning ▪ Post disaster	= λ_3 x 10cm	= λ_3 x 1cm	= λ_3 x 1mm	= λ_3 x < 1mm	= λ_3 x 1cm	= λ_3 x 1mm	= λ_3 x 100µm	= λ_3 x < 100µm
Preliminary level (accuracy/resolution)								
▪ Initial investigation ▪ Reference data	= λ_2 x 10cm	= λ_2 x 1cm	= λ_2 x 1mm	= λ_2 x < 1mm	= λ_2 x 1cm	= λ_2 x 1mm	= λ_2 x 100µm	= λ_2 x < 100µm
Detailed level (accuracy/resolution)								
▪ As-found condition ▪ Archive ▪ Monitor/maintenance ▪ 3D print/replica	= λ_1 x 10cm	= λ_1 x 1cm	= λ_1 x 1mm	= λ_1 x <1mm	= λ_1 x 1cm	= λ_1 x 1mm	= λ_1 x 100µm	= λ_1 x < 100µm

Relaxation factor (λ): it represents how much degradation of quality we can accept/tolerate between the data capture and data modeling phases. $\lambda_1=1$, $\lambda_2=2$, $\lambda_3=4$.

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Examples - movables

Object type	Movable	Movable	Movable
Degree of Complexity	High	Medium	Low
Size	12 x 10 x 18 cm	12 x 10 x 18 cm	12 x 10 x 18 cm
Number of triangles	**451,284**	**225,642**	**22,5642**
Minimum triangle dimension	**300 µm**	**0.8 mm**	**0.4 cm**
Texture			
Material	Bronze	Bronze	Bronze
Geometric Accuracy	0.05 mm	0.05 mm	0.05 mm
Geometric Precision	0.008 mm	0.008 mm	0.008 mm
Resolution	1.5 mm	1.5 mm	1.5 mm
Radiometric Accuracy			
Completeness	100%	100%	100%
Acquisition Technology	Triangulation laser scanner	Triangulation laser scanner	Triangulation laser scanner
Level of data capture	Detailed level	Preliminary level	Reconnaissance level
Number of points	**666,920**	**125,446**	**12,364**
Application area (Purpose of use)	Detailed level	Preliminary level	Reconnaissance level

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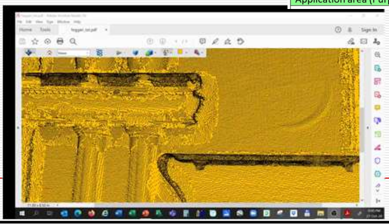
Examples - movables

Object type	Movable
Degree of Complexity	Ultra-High
Size	48 x 48 x 6 cm
Number of triangles	374,919
Minimum triangle dimension	300 µm
Texture	
Material	Wood
Geometric Accuracy	0.05 mm
Geometric Precision	0.008 mm
Resolution	0.1 cm
Radiometric Accuracy	
Completeness	100%
Acquisition Technology	Triangulation laser scanner
Level of data capture	Ultra-High
Number of points	561,908
Application area (Purpose of use)	Detailed level



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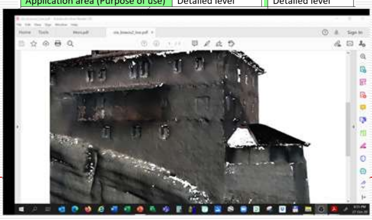
Examples - immovables

Object type	Immovable	Immovable
Degree of Complexity	Medium	Low
Size	32 x 10 x 22 m	32 x 10 x 22 m
Number of triangles	**24,594,111**	**491,881**
Minimum triangle dimension	**1 cm**	**10 cm**
Texture		
Material	Concrete, rock, brick, wood	Concrete, rock, brick, wood
Geometric Accuracy	7 mm	7 mm
Geometric Precision	4 mm	4 mm
Resolution	**1.5 cm**	**10 cm**
Radiometric Accuracy		
Completeness	95 %	95 %
Acquisition Technology	Terrestrial laser scanner	Terrestrial laser scanner
Level of data capture	Detailed level	Detailed level
Number of points	**12,953,956**	**321,518**
Application area (Purpose of use)	Detailed level	Detailed level



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Examples - ultra-high complex objects

Surface complexity due to too fine texture

Surface complexity due to too narrow wires

Material complexity due to opacity

Material complexity due to opacity

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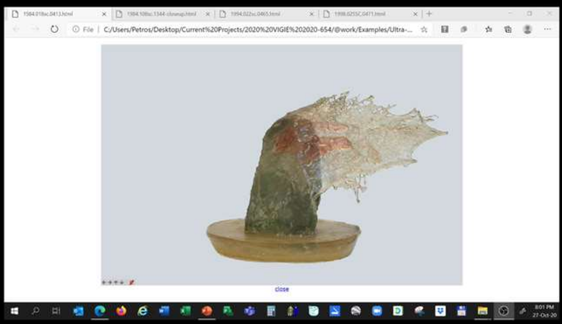
Surface – material complexity



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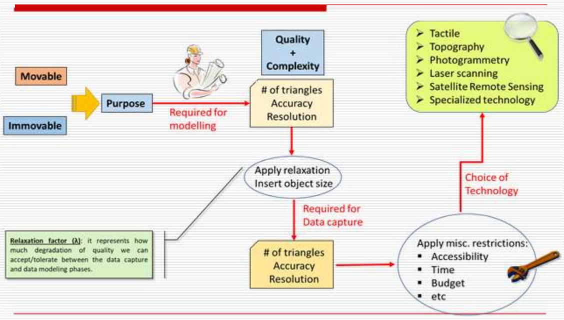
Synthesis – a Decision-making workflow



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… to take home

- current 3D acquisition technology is able to support digital applications beyond the current mainstream applications
- focus should be shifted from data acquisition to object modeling
- the definition of the object complexity should :
  - refer to both 3D data **capture** and data processing/**modelling**
  - be calculated **subjectively**
  - be estimated **before** the data acquisition phase
  - connect to **Quality, Technology, Purpose** of use
  - provide a meaningful tool for planning both the data **acquisition** and the 3D **modelling**
- Complexity can be visualized as a Composite Indicator
- connection to Quality, Technology and purpose of use should be clear and lead to a productive Decision-making workflow

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Thank you for your attention

Glad to hear your thoughts

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