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Techniques and practices for the successful, cost effective reconstruction of skeletal elements of the last European elephant of Tilos with LOM and FDM Additive Manufacturing technologies

An interdisciplinary approach of AM for palaeontology

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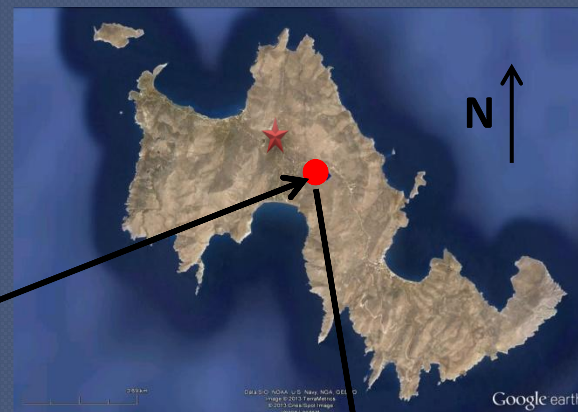
Tilos Island - Charkadio cave

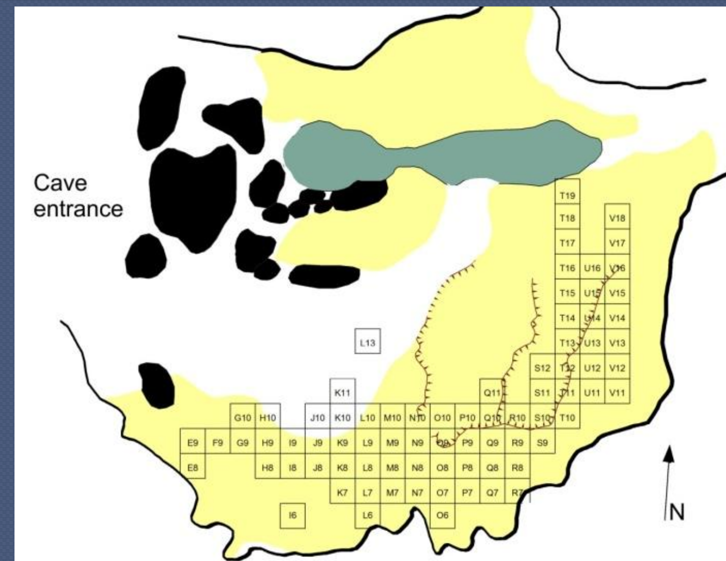
Tilos Island in the Dodecanese complex



Exact location of the Charkadio cave on Tilos island

Excavation periods (1971-2012)

Cave entrance



Cave layout – excavation grids
In Light yellow : Fossiliferous sediment

Palaeontological excavation (2012)
square 07, depth T-3,90 meters.

The *Elephas tiliensis* species

3.500 y BP
Extinction

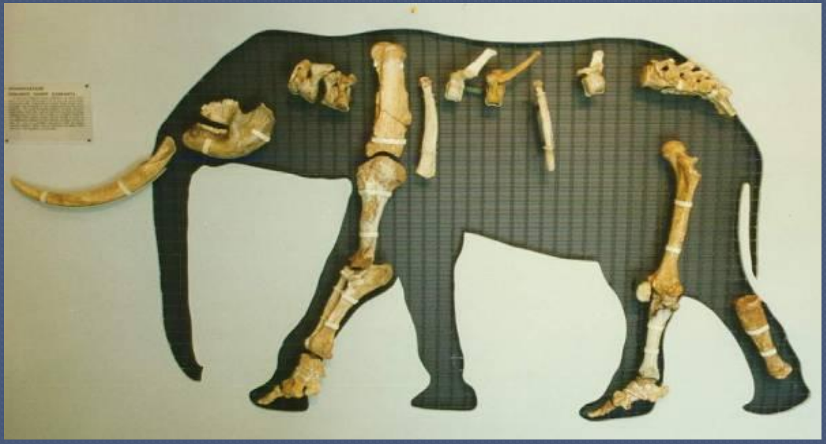
45.000 y BP
Migration to
Tilos

140.000 y BP
end of *Dama* sp.
Deer era

Ecostratigraphy

Main *E. tiliensis* data & problems

- LAST European dwarf elephant (1.4 to 1.7m tall)
- Fossils (>15,000) of approx. 77 individuals identified in Charkadio (of various ages and sex)
- None of the individuals' skeletons is complete more than 20%
- Not all fossils are found in the best condition



E. tiliensis project global goals & challenges

- The full digital and actual 1:1 reconstruction of a typical *E.tiliensis* individual’s skeleton
- Provide a valuable research and education exhibit
- Be as anatomically accurate as possible in the animal’s representation
- Meet the above goals in a streamlined, fast and cost effective manner.
- Provide the palaeontologists of the project and the palaeontological community in general with a reliable and repeatable methodology to use as a toolbox of modern, yet well established, technologies for their future reconstructions.

The Research Group & Program

Palaeontologists & Biologists

NKUA

Mech. Engineers, 3d Modeling and AM specialists

NTUA

Orthopaedics

UoPatras

Recent elephant skeletal parts LONDON - UK

NATURAL HISTORY MUSEUM

Thales - MIS380135 Research Project

European Union
European Social Fund

OPERATIONAL PROGRAMME
EDUCATION AND LIFELONG LEARNING
investing in knowledge society
MINISTRY OF EDUCATION & RELIGIOUS AFFAIRS
MANAGING AUTHORITY

NSRF 2007-2013
programme for development
EUROPEAN SOCIAL FUND

Co-financed by Greece and the European Union

1st Stage of the project

- Digitization and reconstruction of:
  - Animal's hind (back) limbs (Femur, Tibia, Fibula)
  - Selected typical vertebrae (Cervical & Thoracic)
  - Thoracic cavity elements (Ribs)
- Testing and comparison of two different 3d raw data acquisition methods (CT and Laser Scanning)
- Shape & Dimensions specification & finalization (for a typical *E. tiliensis* individual)
- Identification of specific process steps towards 3D digital models, utilizing commercial SW packages available
- Rational distribution of 3D models towards available AM technologies and equipment (LOM, FDM)
- Optimization of AM processes through proper AM-oriented design and techniques

Role of the palaeontologists & biologists during the 1st Stage

- Definition of the reconstruction's strategy (order)
- 1st stage's bone selection for reconstruction
- Definition of measurement/scaling planes and axes
- Definition of final dimensions for <u>all</u> 1st stage skeletal elements prior to their AM fabrication

<u>Methods Used</u>

Taphonomy/
Stratigraphy

1970's Stratigraphic trench

Ontogenic
observations

Allometry & Sexual
Dimorphism theory

(Huxley, 1932)

Bones selected for reconstruction during the 1st Stage

Animal's area	Bone	Type	Quantity	Description
Back Limbs	Astragalus	Left & Right	2	Small bulky part
	Tibia	Left & Right	2	Long bulky part
	Fibula	Left & Right	2	Long thinner part
	Femur	Left & Right	2	Very Long bulky part
Vertebral Column	Cervical	Unique	1	Complex bulky part
	Thoracic	Unique	1	Complex bulky part with elongated protrusion
Thorax	Rib	Left & Right	2	Long thin part

Role of the Engineers during the 1st Stage - Digitization methods used

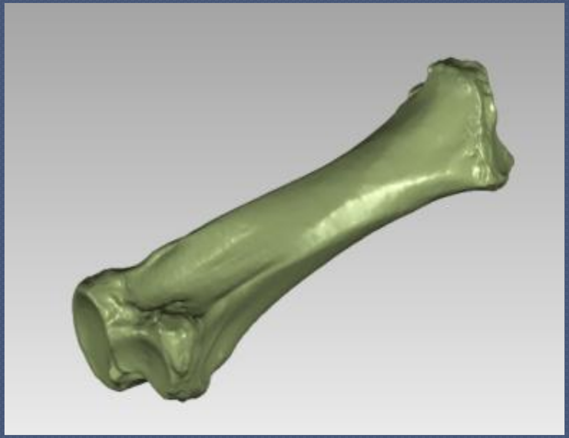
Computer Tomography (CT)

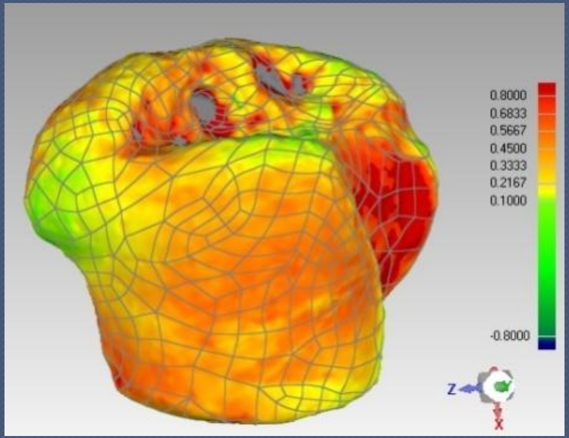
- Philips Brilliance CT 64-slice Tomograph
- DICOM files
- image size 512px × 512px
- pixel size 0.793mm.
- slice increments 0.399mm/0.798

Laser Scanning

- FARO Arm Platinum
- Geomagic Studio Plugin/ WRP files
- Filter angle 75 degrees
- Scan rate 1/1
- Scan density 1/1
- Exposure = 18

Digitization methods evaluated





• CT allows for batch digitizing / Laser Scanning (LS) has to be done individually on every skeletal element
• Pixel size & slice thickness limit the accuracy of CT; interpolation to a certain extent is required for subsequent 3D remodeling / LS exceeds CT clearly in raw data accuracy, but creates vastly big raw data files (Hundreds of MBs to GBs) .
• CT needs slice-by-slice "masking" (image processing) for further 3D point cloud or 3D model generation/ LS directly collects one or more sets of 3D point clouds.
• LS requires point cloud filtering and point cloud reduction for efficient subsequent 3D remodeling
• BOTH TECHNIQUES are well suitable for palaeontological application accuracy

Commercial ME – oriented SW involved in the project's digital 3D remodeling

For the CT-based process

1. Materialise Mimics: Slices into point clouds
2. Raindrop Geomagic Studio: Point Clouds into 3D NURBS surface models
3. 3DS Solidworks: Adjustable, oriented 3D Solid models, suitable for dimensional finalization and AM fabrication

For the LS-based process

1. Raindrop Geomagic Studio: Point Cloud acquisition and conversion to 3D NURBS surface models
2. 3DS Solidworks: Adjustable, oriented 3D Solid models, suitable for dimensional finalization and AM fabrication

Both 3D modeling routes have successfully produced 3d CAD models of the 1st stage's skeletal elements that were easily adjustable to the form and dimensions indicated by the biologists and palaeontologists of the research group for the typical *E. tiliensis* individual under construction. It was decided for these models to be exported in STEP format for their further AM preparation in the AM dedicated Materialise Magics RP SW.

AM fabrication of the 1st Stage skeletal elements – Available equipment

Helisys LOM1015

- Technology: Sheet-based paper lamination
- 1st generation RP machine
- Outdated (almost obsolete) but fully operational
- Max Part Size: *380x250x360mm*
- Min Slice thickness: *0.1mm*
- Does not need supporting structures
- Accuracy: ± 0.3 mm

Stratasys uPrint

- Technology: Extrusion of ABS filament
- 4th generation RP Machine
- Contemporary and fully operational
- Max Part Size: *200x150x150mm*
- Min Slice thickness: *0.254mm*
- Needs supporting structures
- Accuracy: ± 0.25 mm

AM fabrication– Bone Distribution

CRITERIA

- Minimum raw material consumption
- Minimum waste (LOM)
- Minimum support material (uPrint)
- Max parts/machines dimensions (avoid unnecessary splitting)
- Parts' volume/ density/ complexity/ manufacturability
- Minimization of build times and costs

Description	Skeletal Element		
	AM Machine	*Segmented*	*Packed*
Astragalus	uPrint	No	No
Tibia (L&R)	LOM	No	Yes
Fibula (L&R)	LOM	Yes	Yes
Femur (L&R)	LOM	Yes	Yes
Thoracic Vertebra	LOM	Yes	Yes
Rib (L&R)	uPrint	No	No
Cervical Vertebra	uPrint	Yes	Yes

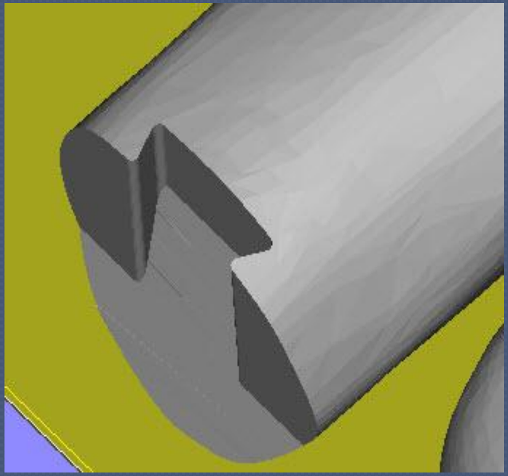
AM fabrication – Operations performed in AM preparation software

Materialise Magics RP was used for the following:

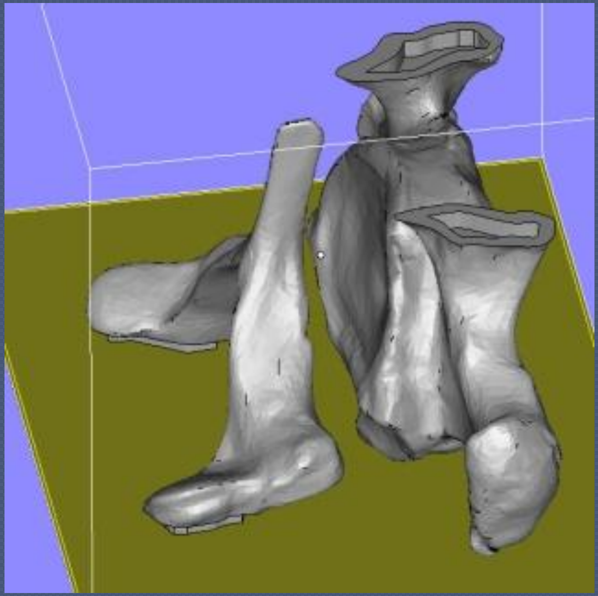
- Incremental triangle reduction of up to 1/20 file size for all the STL files of LOM destined parts, due to PC hardware limitations of the outdated LOM1015 (STEP is imported in full detail).
- File size and quality relaxing also for the uPrint destined parts for more efficient processing.
- Segmentation of STL files (parts) when implied by dimensional limitations of the available AM machines (e.g. long limb bones)
- Minimum Z - maximum Y orientation of the STL files and/or file packs for LOM fabrication
- Minimum support – Maximum quality orientation of the STL files and/or file packs for uPrint-FDM fabrication
- “Tight packing” and proper placement of part packs on the AM machines’ platforms

AM fabrication – Best STL segmentation techniques

All segmentations were performed in **Materialise Magics RP** relatively easily. With some extra effort they are also possible in pure 3D CAD environment.



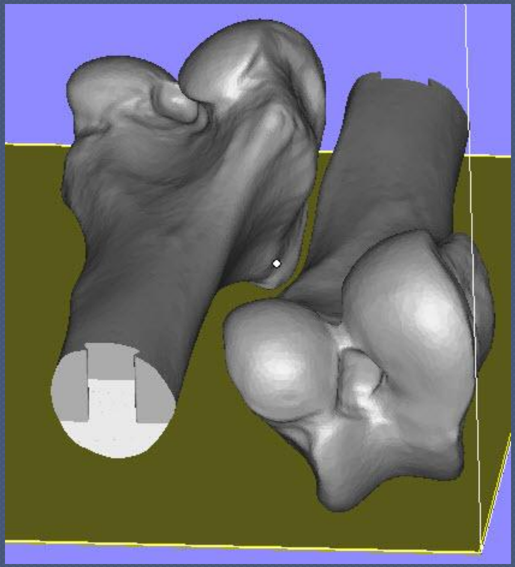
A combination of a “Dove-Tail” slide and an inclined plane was qualified for all LOM segmented parts as it succeeds fast and accurate reassembly and a load bearing capability for the suspended parts (e.g. limbs)

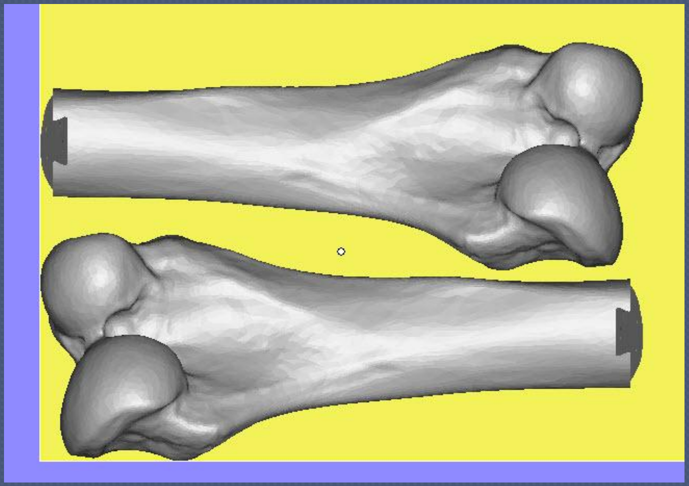


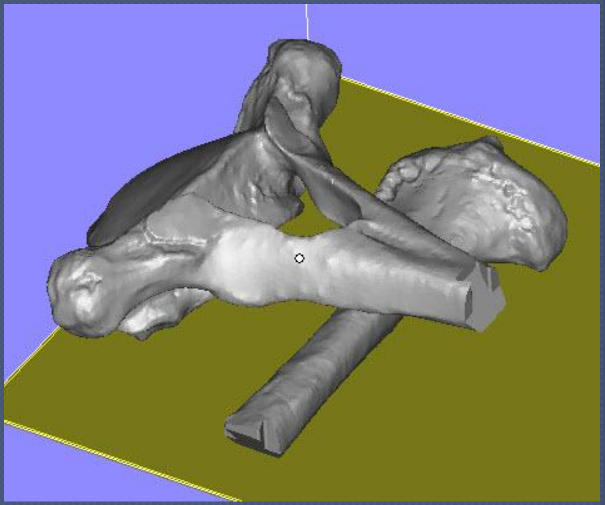
A boss-pocket combination with a 0.3mm clearance was preferred for splitting the FDM-made vertebra, as it is not expected to bear any load and it can be easily get assembled and glued together

AM fabrication – Optimum build platform “packing”

Packing was applied mainly on LOM fabrications for waste minimization and for efficient building & separation (decubing) of the bones







The images illustrate:

(i) the placement selected for the two symmetric lower halves of the Femur on the LOM platform (left & middle) and

(ii) the placement selected for the Thoracic Vertebra (right) also on the LOM platform

AM fabrication – AM Skeletal Elements' Images

Interesting pictures of isolated and assembled skeletal elements of the project's 1st stage are given below:

Hind Limbs Assembly

Fossil vs. LOM

Pair of Ribs

Vertebrae

AM fabrication – Cost and Time data

- Totally 7 LOM and 5 FDM bones were built (12 LOM and 6 FDM separately split parts) for the project's 1st stage
- They were made in 6 runs of the LOM1015 machine and 5 runs of the uPrint machine
- They required:
  - 124 LOM machine operating hours plus 15 hours for pre- and post-processing and part separation and
  - 22 uPrint machine operating hours, plus 7 hours for pre- and post-processing and part separation
- All AM builds of the 1st Stage were done in 15 full working days with an estimated cost of 1,500 €
- The comparison of the above data with similar from any conventional copying/ sculpting techniques followed until now by the palaeontologists is just striking

Planning for the rest of the project

- The project is already on to its next stages
- On Stage 2, remodeling continues, based on already available batch CT data and complementary LS scans of the rest of the limbs, vertebrae, ribs and of smaller foot bones. Fore limbs, pelvis &vertebral column will be ready in digital and AM tangible form by the end of Stage 2.
- On the final 3^d Stage, skull bone raw data of similar animals will be provided by the London National Museum for 3d modeling, form - size adaptation & AM fabrication, as in Charkadio there were no skulls of *E. tiliensis* found.
- By the end of 2015 the MIS380135 project is expected to be concluded with the completely reconstructed *E.tiliensis* skeleton on display in the island of Tilos.

Conclusions

- Results so far from Stage 1 are very encouraging for the rest of the project (Stages 2 & 3) until completion
- The palaeontologists of the research group are stunned by the successful implementation of both 3D digitization/remodeling & AM into their field and amazed by the similarity of the LOM parts to original fossils
- The AM machines used are neither state of the art nor high end/high cost professional systems. Yet they have proven to be reliable, cost effective and highly suitable for the *E. tiliensis* project and for paleontology in general.
- More modern equipment of increased specifications (e.g. colored MCOR A4 AM parts, large uniform FDM parts, direct metal or ceramic AM parts) could literally launch palaeontology onto a whole new level.

Conclusions

- Both the digital 3D modeling, as well as the AM approaches implemented, have already coped with most of the difficulties posed by the nature of the project and can be streamlined for the rest of the stages.
- The benefit of - at some point - having both a complete digital and a complete 1:1 tangible representation of an *E.tiliensis* dwarf elephant it crucial for the NKUA and for all palaeontologists worldwide, as well as for the local community of the island of Tilos.
- Above all, the fully reconstructed *E. tiliensis* skeleton will be a valuable asset for the preservation of the European Natural Heritage.

PUBLICITY OF OUR NATURAL HERITAGE: USE OF STATE OF THE ART TECHNOLOGIES FOR THE DIGITAL IMPRINT AND RECONSTRUCTION OF A 3D SKELETON OF THE LAST EUROPEAN ELEPHANTS (MIS 380135)

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Thank you for your attention!

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Eastern Tilos