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Innovation and consolidation for large scale digitisation of natural heritage

Rapid 3D Capture Methods in Biological Collections and Related Fields

Deliverable D3.7

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Abstract

This report provides an overview of the status of 3D Digitisation in biological collections and related fields. The report is not intended to provide in depth analysis or description of the 3D digitisation methods as they have been documented in multiple documents referred in the text. The report is designed to identify a) suitable 3D digitisation methods to achieve large scale digitisation and b) the issues which need to be addressed in order to increase 3D digitisation throughput using those methods. Accordingly, the report is divided in six sections: 3D digitisation of NHC, 3D digitisation workflow, 3D Digitisation Methods, Areas of improvement, Ideal 3D digitisation workflow and conclusions. The first section establishes the need for 3D digitisation of Natural History Collections and introduces the different types of 3D products which may be produced for as part of a digital specimen, with some examples. The second section defines a generic workflow for 3D digitisation consisting of tasks which are independent of the specific digitisation methods applied. This section also defines the possible areas of improvement which can support increasing the throughput of digitisation workflows. The third section explores different digitisation methods which have applied to digitise NHC, defining which are the most suitable for mass imaging. The fourth section presents the existing solutions which could help improving the 3D digitisation workflows and practices looking at related fields, particularly cultural heritage. Section five brings together the digitisation methods and improvements to define the ideal 3D digitisation workflow and its prospects for being incorporated into the digitisation plans of natural history institutions in Europe. Finally, section six provides a summary of recommendations and a description of areas which may provide further improvements in 3D digitisation, such as fully integrated systems.

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Summary

This document describes the research into the possibilities of applying 3D digitisation methods to the mass digitisation of natural history collections. The basic premise is that this would require designing and implementing faster 3D digitisation workflows. Following this premise, the partners involved in this task proceeded to analyse several proposals for 3D digitisation methods applied to the digitisation of natural history collections and related areas, such as cultural heritage collections. From this analysis four methods were identified as viable for integration into mass digitisation projects: multi plane photography, photogrammetry, structured light scanning, and laser scanning. This group includes multi plane photography, a method for digitising specimens by creating 2D picture sets, along with methods for creating 3D models. The focus was not to only identify methods for building 3D models, but for methods used for digitising specimens taking into consideration their nature as real life 3D objects. As a result, the outputs of the 3D workflows are denominated 3D products, which is a broader term than 3D models.

In addition to identifying and describing the main characteristics of the viable digitisation methods and workflow tasks, this document identifies two sets of workflow tasks which, if improved, have potential for creating even faster workflows. These task groups as tasks which are dependent of the acquisition method, and common tasks which are independent from the acquisition method.

The knowledge distilled is collated to propose the design of the ideal 3D digitisation workflow which can be integrated with the overall collection digitisation project. The proposal serves as a high-level model for adding 3D digitisation among mainstream methods for NHC ingestion and digitisation processes.

Finally, apart from summarising the findings of the research effort, the report points to emerging techniques which need to be kept in mind and re-evaluated by future projects, either for their potential as methods for 3D digitisation or for the possible alternative uses of 3D technologies in solving existing problems in digitisation in general, such as the visualisation of labels occluded by specimens.

Contents

1. Introduction

The digitisation practices for natural history collections (NHC) are derived from standards initially designed for Libraries and Cultural Heritage Collections. The Federal Agencies Digital Guidelines Initiative (FADGI) [18], METAMORFOZE [32], the US Library of Congress [34], and the UK National Archives [41] are examples of those guidelines. These practices work well for digitisation of 2D artefacts (i.e. books, leaflets, paintings, maps, posters, photos), for the case of NHCs these include collection catalogues, cards, field books, and labels fall in this category. These recommendations extend to some NHC types such as herbarium sheets or microscope slides, which have characteristics similar to those of 2D materials, already covered in well-established digitisation practices. 2D images have an important role in the documentation of NHC, providing additional information to support the electronic catalogue. However, these practices are insufficient for advanced uses of NHC specimens, even when the resulting product of digitisation is a 2D image. There are limits to the usefulness of 2D images when the artefacts being digitised are 3D objects. This means that, for digital specimens to act as surrogates of physical specimens, Natural History Collections require digitisation methods which account for the specimens' 3D nature. An initial solution to this is the production of "Taxonomic Grade" or "Research Quality" digital specimens displaying the main characteristics of the specimens. This requires producing sets of images in different anatomical poses (e.g. ventral, dorsal, cranial, caudal, lateral [7]) at a minimum, or a full 3D model for some cases [4, 8, 9, 48, 61]. In addition to pose, colour is highly relevant for the correct identification of some traits [48], which requires special illumination. Taxonomic Grade digital specimens should be created to support the detection of morphological consistencies among specimens of one group, and consistent differences between different groups [4]. For this, identifying and highlighting landmark positions as accurately as possible is required. Measurements taken on 3D models of specimens provide distinct advantages over physical measurements, such as repeatability and reduced risk of damage to the specimen [4, 29].

Natural history collections contain specimens which are real life 3D objects, and therefore limiting digitisation to 2D would result in a loss of potentially valuable information [4]. The diversity in the types of specimens in natural history museum collections prevent the use of a single 3D digitisation technique, as a result, a range of 3D digitisation techniques have been tried with different types of specimens. However, many technologies are still expensive, under development or require implementing specialised processes and training. The need for 3D digitisation has spurred the development of different custom solutions for capturing and publishing 3D specimen models. The current consensus is to perform 3D digitisation at limited scale for specimens identified as having specific characteristics (e.g. scientific value, preservation state, uniqueness) that justify the cost of 3D digitisation. The quality criteria for 3D digitisation aligns with the intended use of the digitised specimens. The greatest potential of 3D digitisation is to support scientific research, especially when the features of the specimen that need to be illustrated cannot be faithfully reproduced in 2D images [2]. Advanced digital techniques such as 3D geometric morphometric analysis and finite element analysis for biomechanical research also depend on 3D models of adequate quality.

1.1 3D Imaging Methods applied to NHC

The methods applied to NHC for imaging three dimensional specimens (3D Specimens) ranges from creating 2D photos for cataloguing to creating full 3D models for research. In between these two extremes other forms of imaging such as views of anatomical planes [4], 360° photo sets [8, 9, 89]

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Grant Agreement No 777483

and 360° views [60] have also been explored as mediums for representing 3D specimens. This report categorises 3D products in two types: Two-dimensional key view (2D+) image sets and 3D models. A 2D+ image set is defined as a set of photos of a specimen which are taken from different angles for displaying specimen features which would not visible on a single 2D photo[1]. 2D+ image sets encompass any representation of a specimen which is based on multiple 2D images (two or more), including anatomical multi plane sets, 360° photo sets and 360° view. A 3D model is a dataset of coordinates defining vertices, edges, and/or planes which are designed to represent the surface of a real-life object in a computer model of a 3D space. 3D models can also include colour and/or texture information. 3D models include point cloud, polygon mesh, and wireframe and models. Table 1 illustrates these types of 3D products with a brief definition and some sample uses.

Table 1 Types of 3D products used in digitisation of NHC

Type	Product	Description	Sample Uses[1]				
			Documenting	Web Publishing	Anatomical Measures	Trait Identification	3D Printing
2D+	Multi Plane Set	Set of two or more images from different perspectives	X	X	X	X	
	360° Photo Set	Set of images showing different views from the three-dimensional planes		X	X	X	
	360° Virtual Videos	Cursor controlled composition of pictures or video frames allowing different views of specimen	X	X	X		
3D Model	Point Cloud	3D model defined by a collection of coordinates in a 3D space. The coordinates represent points on the surface of the modelled object.	X	X	X	X	X
	Polygon Mesh	3D model defined by a collection of coordinates, edges, and planes in a 3D space. The mesh represents the surface of the 3D object as a collection of polygons.	X	X	X	X	X
	Wireframe	3D model defined by a collection of edges in a 3D space. The edges represent the intersections of the planes which cover the surface of a 3D Object	X	X	X	X	X

1) The uses displayed are those likely to overlap between 2D+ and 3D models. However, uses go beyond these, including for instance printing image catalogues (2D), immersive environments or virtual reality. On the other hand, using 3D models to document the collection may seem overkill.

There are various methods for obtaining the 3D products defined above, and several of them have been tested and applied in digitisation of natural history collections [8, 9, 14], for instance: Multi plane photography (with or without focus stacking) (2D+), Photogrammetry (with or without focus stacking – 2D+ and 3D), Structured Light Scanning (3D) , Infrared Scanning (3D), Laser Scanning

[1] Other types of 2D image sets exist, such set may include specimen images, label images and/or catalogue images. However, if the additional images do not show different specimen views, they are not 2D+.

(3D), and Micro-CT (3D). Table 2 shows the institutions and the types of collections to which these methods have been applied and the 3D products which have been produced. The quality of the 3D products will vary depending of the acquisition and processing applied. Consequently, 3D quality attributes are relevant factors to consider when evaluating the type of acquisition method to implement. Optical methods based on 2D imaging are placed first, then the methods combining 2D and projection, and finalises with different projection methods (infrared, laser, and Micro-CT)

Table 2 Examples of Acquisition Methods by Collection and Institution

Method	Institution[1,3]	Collection[2,3]	Type of 3D Product(s)
Multi Plane Photography (with and without focus stacking)	FinBIF[4], MfN, MNHN, NHM, Naturalis, RBINS, RMCA	Vertebrates, Skins, and Invertebrates (dry and wet preserved), Entomology, Invertebrates, Vertebrates, Anthropology and Prehistory, Palaeontology	2D+
Photogrammetry (with and without focus stacking)	MfN, RBINS, RMCA	Zoology, Geology, Palaeontology (dry specimens) Entomology, Invertebrates, Vertebrates, Anthropology and Prehistory, Palaeontology, and Geology	2D+ and 3D Models
Structured Light Scanner	RBINS, RMCA	Zoology, Geology, Palaeontology (dry specimens)	3D Models
Infrared Scanner	RBINS, RMCA	Entomology, Invertebrates, Vertebrates, Anthropology and Prehistory, Palaeontology, and Geology	3D Models
Laser Scanner	MNHN, NHM	Zoology, Geology, Palaeontology (dry specimens)	3D Models
Micro-CT	HCMR, MfN, RBINS, RMCA	Marine invertebrate specimens, Vertebrates, Botany, Entomology, Zoology, Geology, Palaeontology (dry and wet specimens)	3D Models

1) The institutions listed have examples of published specimens which are produced with one of the methods listed.
2) The collections included are intended to illustrate the types of collections which have been digitised using the method specified.
3) The primary source of the institution and item lists are the Synthesis reports [8, 9] and it is complemented with examples found on the public data portals of ICEDIG partners [19, 40, 42, 44].
4) FinBIF is not a single institution, it is a national infrastructure publishing specimen data for several institutions including LUOMUS, the Finnish Museum of Natural History (University of Helsinki).

1.2 Examples of 3D Imaging for NHC

The images in Figure 1, are screenshots of a 3D model of a 25.5-meter long Blue Whale from the Natural History Museum London (NHM) produced by laser scanning [43]. The published model consists of 247,170 triangles and 123,633 vertices[2]. The smallest part of the model is the mid-section of the skull (Figure 2b) which consists of 3,936 triangles and 1,970 vertices.

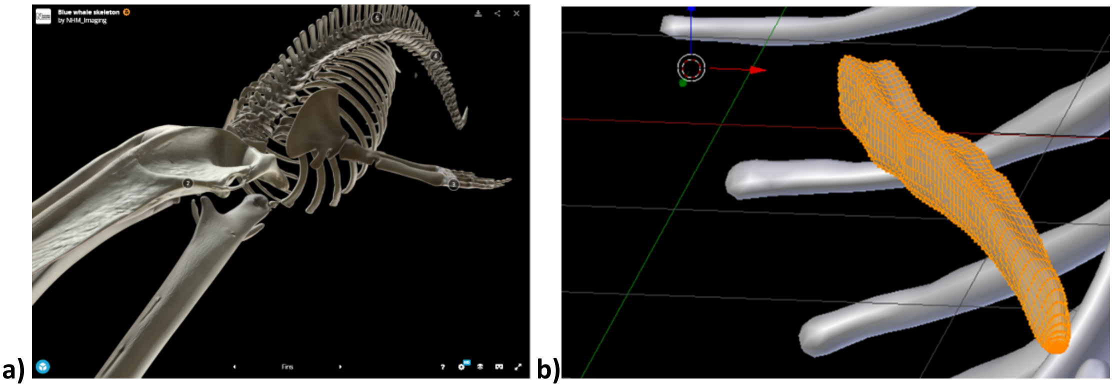

Figure 1 3D Model of a Blue Whale Published by the Natural History Museum[3]. Image 'a': left view of full skeleton. Image 'b': mid-section of the skull highlighted as a mesh. This is the smallest independent component of the model consisting of 3,936 triangles and 1,970 vertices[4]

The images in Figure 2 are part of a 360° video of a pigeon (MPEG4). The video is composed of 35 frames, at a 10 frame per second rate (3.5 seconds playtime) produced with an automated photogrammetry software package. Each frame has a width of 464 pixels and a height of 728 pixels. The nominal resolution of each frame is 300 DPI. Using this nominal resolution of 300 DPI as a reference, the size of the actual specimen is calculated as 2.55cm width by 3.40 cm height (calculated from Figure 2b). In this case, the published 360° video is optimised for online viewing.

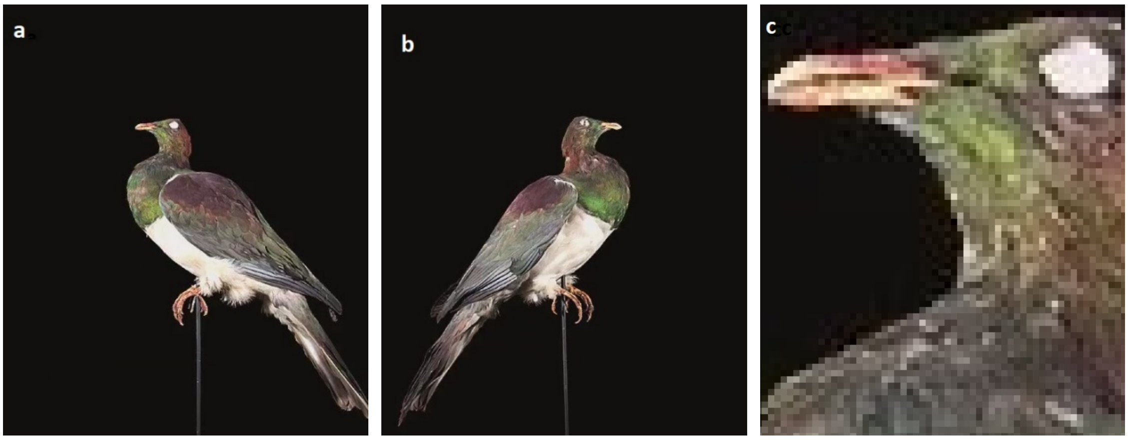

Figure 2 Images 'a' and 'b' show two frames of the 360° video of the Extinct Norfolk Pigeon (or Norfolk Island Pigeon – Hemiphaga novaeseelandiae spadicea), Published by Naturalis[5]. Image 'c' shows a 8X magnification of the specimen's head (from 'a') .

The images shown in Figure 3a to Figure 3i show part of the images from a 360° sequence of a beetle, consisting of 120 images produced by focus stacking (2D+) . The images are (nominally) stored at 300 PPI, however, using the scale bar on the ZooSphere website as a reference, the resolution of the image is estimated to be 3,856PPI, or 152 pixels per mm. At this pixel resolution

[2] NHM model available at: https://sketchfab.com/models/8502dbef80ed4aa688c13c90cb14de73
[3] Produced by [43]. url: http://www.nhm.ac.uk/discover/blue-whale-skeleton-3d.html, https://sketchfab.com/models/8502dbef80ed4aa688c13c90cb14de73
[4] NHM [43] model available at: https://sketchfab.com/models/8502dbef80ed4aa688c13c90cb14de73
[5] Naturalis BioPortal [44], URL: http://data.biodiversitydata.nl/naturalis/specimen/RMNH.AVES.110112

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the actual magnification is close to 40X. The close-up image shown as Figure 3j is a 3mm section with a magnification of 20X (half the maximum possible from of the original image).

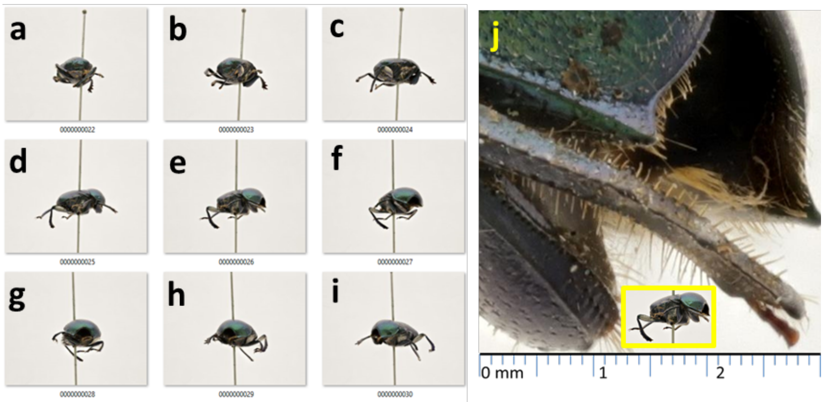

Figure 3 ZooSphere project at Berlin MfN[6]. Images 'a' to 'i' : part of the image sequence of a 360° Specimen View of Beetle (Gymnopleurus virens). Image 'j': 20 X magnigification of 3mm section from 'e'. Inset above scale bar: specimen at 1 to 1 size (proportional to scale bar).

Of the seven types of 3D digitisation techniques, photogrammetry is applicable to the widest range of collections and specimen sizes [15, 21, 47, 57]. Additionally, photogrammetry is most future-proof, as long as the raw data is saved (for instance as DNG), the 3D geometry and colour info can always be recreated [15, 21, 47]. Existing workflows, such as the one from ZooSphere at the Berlin museum of Natural History (MfN Berlin), make possible the construction of 3D models using photogrammetry (Figure 4) [54, 89]. Further, since the sequences are preserved as stable sources, multiple photogrammetry techniques can be applied and compared.

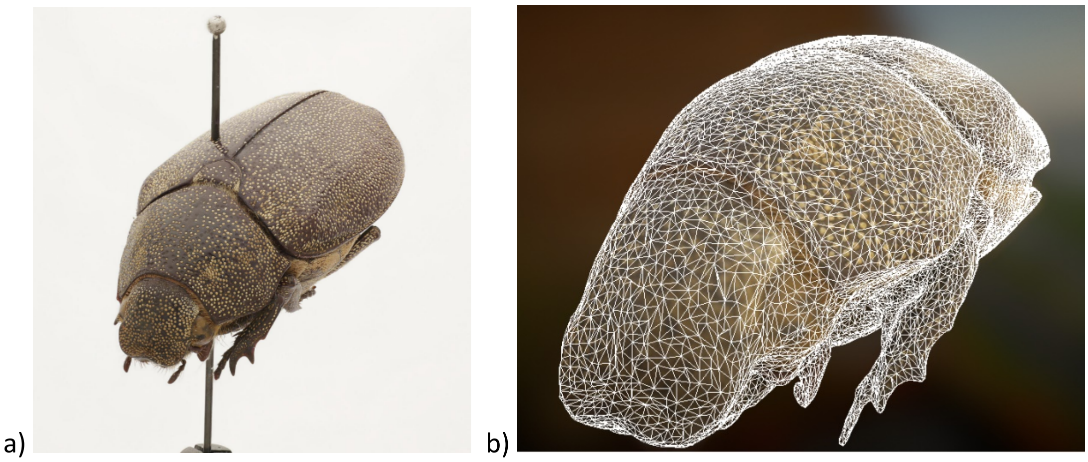

Figure 4 The image shows: (a) one of the photos in a sequence published by ZooSphere and (b) a 3D model created using images from the same sequence[7]

1.3 Report Structure

The reminder of this report will present a generic view of the 3D digitisation, abstracted as at the level of workflow tasks (Section 2); an analysis of 3D digitisation techniques applied in NHC digitisation projects and determine the ones amenable for optimisation(Section 3); afterward

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[6] ZooSphere MfN [89], URL: http://www.zoosphere.net/sequence/143/Gymnopleurus/virens
[7] ZooSphere MfN [89], http://www.zoosphere.net/sequence/76/Leucopholis/irrorata

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H2020-INFRADEV-2016-2017
Grant Agreement No 777483

existing proposals for improving 3D digitisation workflows are presented (Section 4); and conclude with a description of the ideal of 3D digitisation Workflow (Section 5).

2. 3D Digitisation Workflow

The Synthesys3 project documented 12 different digitisation workflows from pilots performed at four European NHC intuitions (HCMR, MfN, RBINS, and RMCA) [8, 9, 48]. 3D digitisation workflows are slower and more complex than other digitisation workflows [48]. 3D digitisation workflows throughput is affected directly by the 3D data acquisition process, the varied type of specimens, the number of collections which contain specimens suitable for 3D modelling, the level of documentation of the collection, and the expected 3D product(s) to be obtained. Moreover, in several cases the 3D digitisation workflows hardware and software have been developed and integrated in-house, with resources available at each institution (especially in the case of photogrammetry) [8, 9, 31, 45, 48].

2.1 3D Imaging Workflow Tasks

Table 3 provides a brief description of the 3D workflow tasks derived from the digitisation tasks documented by iDigBio, and Synthesys3 [8, 9, 31, 45, 48]. Most of the tasks in the table coincide with those defined by iDigBio [31, 45]. The tasks shown Table 3 are not all compulsory or strictly sequenced, the order of tasks can vary, and some tasks can be excluded. For instance, the ZooSphere project focuses mainly on “imaging” and “processing” (acquiring and composing stacked images) without building the 3D models [89]. Similarly, it is likely that specimen data capture has already been done separately, so that the “pre-digitisation curation” and “data entry and correction” tasks can be omitted or significantly reduced [48].

Table 3 Description of 3D workflow tasks, derived from iDigBio recommendation [31].

Workflow Task	Description/Subtasks	Influence Model Quality
Pre-digitisation Curation	Selection of specimens to digitise; retrieval from storage; identification of specimens (barcoding); identification of Specimens requiring high-definition digitisation; defining safeguards for identifying and handling specimens treated with hazardous materials (e.g. mercury); transfer to digitisation station; and creation of skeletal metadata record.	Specimens should be selected and prioritised for digitisation by the collection curators. .
Imaging Station Setup	Digitisation equipment selection, acquisition, and set up; equipment testing/calibration; and training of digitisation technicians.	Equipment should be calibrated to minimise image post-processing.
Conservation	Required conservation/restoration of specimens selected for digitisation.	Some specimens may be damaged, fragile, or require to be re-mounted to display all relevant traits.
Specimen Scanning	Data capture; identification (barcoding); mounting for scanning (may require different mounts for different poses, darkening); scanning of specimen (varies depending on the capture technique); creation of master file (raw); temporary storage of master file; and unmounting and return of specimen.	Identification, digitisation and [meta] data capture, so that images are correctly linked to the corresponding specimen records.

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H2020-INFRADEV-2016-2017
Grant Agreement No 777483

Table 3 Description of 3D workflow tasks, derived from iDigBio recommendation [31].

Workflow Task	Description/Subtasks	Influence Model Quality
Scanned Data Processing	Creation of master files for archiving; Image adjustment (using colour charts); creation of stacked images; creation of derivatives for OCR and data transcription; verification of naming and linking of files to digital specimen. Extraction of colour information for texturing and illumination of 3D model.	Verification of master image resolution and verification that derivatives adhere to quality standards.
Build 3D Model	The building process depends of the method for acquisition and raw data produced. For instance, photogrammetry processes specimen images for building the 3D Model. Other methods may not require images to be processed, instead delivering 3D models formats directly (e.g. point cloud, mesh).	3D model detail will vary according to the type of images and building process used. Images can be used for creating textures for the final model. The acquisition method influences the quality of the models produced
Build Model Derivatives	Several derivatives can be produced, including images for information extraction, models of lower resolution for publishing, animation, or display.	The expected use of the derivatives will determine the quality required.
Asset Identification	Assigning identifiers to the digital assets generated while building the 3D products. This includes raw data, intermediate data products and derivatives.	Recovery, and reproduction of the model require proper identification of assets.
Image and Model Storage and Archiving	Transfer of master and derived files to archive servers, image servers, and public servers in preparation for publishing.	Verify that master and derived files are not corrupted in transfer to storage.
Optical Character Recognition	Automated extraction of data from images, for populating/complementing specimen record.	Verify suitability of derived image for OCR.
Data Entry and Correction	Manual extraction of data from images, for populating/complementing specimen record. Data capture and correction of digital specimen record before publishing.	Verification against reference image and recorded data before publishing.
3D Model Publishing	Providing access and long-time preservation of 3D models, and to its sources	Access to the model and its related digital assets allows verification, preservation and reproduction
3D Model Display	Rendering/accessing 3D models	Rendering of the model, generation of previews or snapshots supports further uses of the model.

The sequencing of tasks and the alternative paths vary between workflows, as shown in the Synthesys 3 examples [8, 9, 48]. An approach to making sense of the variety of possible 3D imaging workflows is to look at the general tasks which are common regardless of the collection, imaging technique, and planed outputs. Figure 5 presents a simplified view of the generic digitisation workflow divided in four tasks. These tasks can be broken down as demonstrated in the following examples to illustrate possible task sequences.

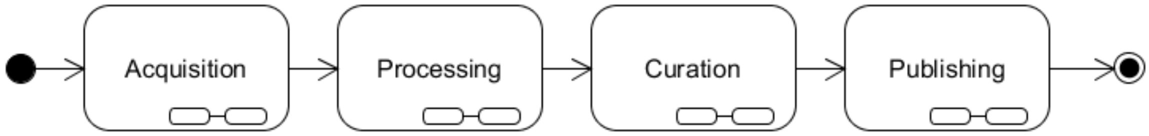

Figure 5 A high-level view of the generic 3D imaging workflow.

Acquisition encompasses the tasks that are required for acquiring the data for creating the 3D product (2D+ or 3D model). This includes pre-digitisation curation, image station setup, and specimen scanning.

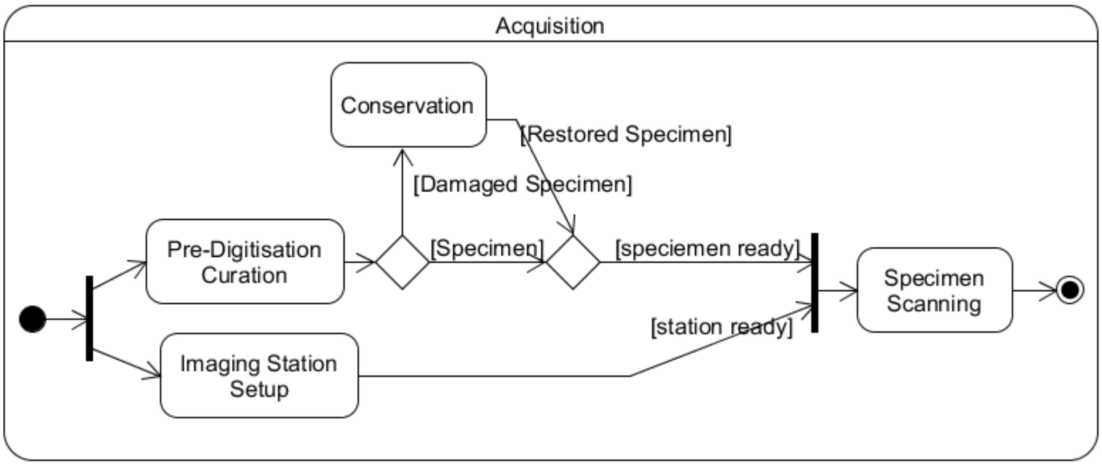

Figure 6 Fine-grained view of the acquisition tasks for a generic 3D digitisation workflow.

Processing includes the processing of raw data, building 3D model and building derivatives. This includes extraction of derivate images for information extraction, and extraction information for model texturing and colouring.

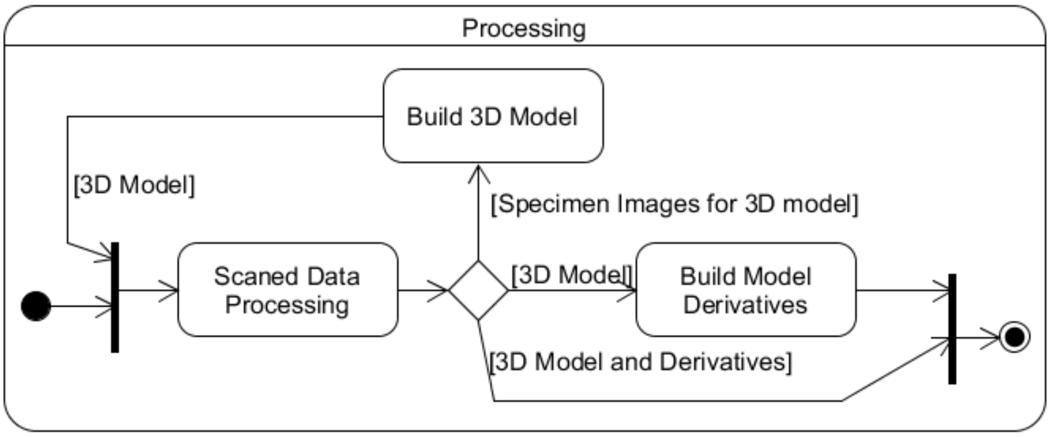

Figure 7 Fine-grained view of the processing tasks for a generic 3D digitisation workflow.

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Grant Agreement No 777483

Curation encompasses the tasks for preserving raw data, 3D products and associated data and metadata. This may also require further processing for information extraction (OCR, or manual), annotation, and data validation.

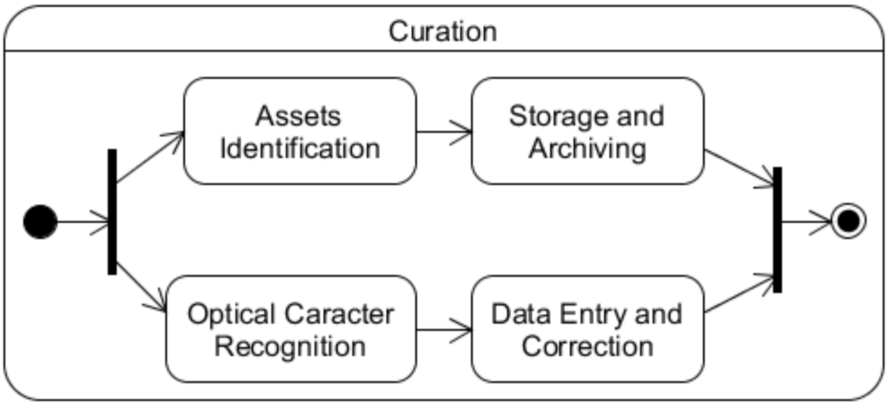

Figure 8 Fine-grained view of the curation tasks for a generic 3D digitisation workflow.

Publishing covers the tasks which are needed for making the 3D products available for the target audience.

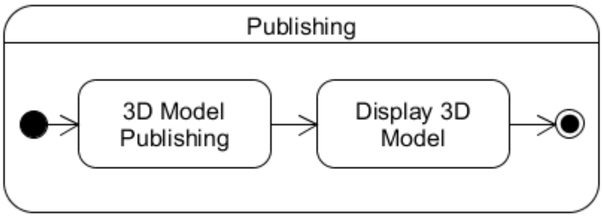

Figure 9 Fine-grained view of the publishing tasks for a generic 3D digitisation workflow.

2.2 Areas of Improvements for 3D Imaging Workflow

Imagine station set up and processing tasks are closely linked requiring fine tuning, and expertise for achieving rapid model turn out, which impacts directly in the cost and suitability for NHC digitisation. Optimising imaging stations and processing tasks requires advanced imaging research. Other tasks of the 3D digitisation are independent of the processing methods of the 3D digitisation workflows can be optimised to achieve greater 3D digitisation throughput of NHC: specimen handling and mounting, curation, 3D model publishing, and 3D model display. Table 4 describes the tasks of the generic 3D workflow which are have the most potential for increasing the throughput, moving closer towards mass digitisation for NHCs.

Table 4 3D Digitisation Tasks that can help achieving higher throughput

Workflow Step	Workflow Task	Improvement Areas	Improvement Opportunities
Acquisition	Specimen Handling	Techniques and devices for specimen handling before and after image acquisition.	Specimen handling and mounting is required for creating faster end-to-end digitisation workflows.
	Specimen Mounting	Techniques and devices used for specimen handling during image acquisition.	
	Imaging station setup	Techniques and devices for specimen scanning (rigs, platforms, lighting).	Digitisation stations can be implemented with consumer off-the-

Processing	Scanned data processing	Integrate and verify raw data sets. Prepare of data sets for building 3D models (e.g. removing outliers and duplicates).	shelf equipment (e.g. photogrammetry), acquired from vendors or combine different techniques (e.g. using images for colour texture acquisition). Optimise number of passes, determine best angles and appropriate lighting. Map the type of primary models to be created and the associated types of derivatives which can be obtained.
	Build 3D Model	Models with higher quality increase the number and types of derivatives which can be created.	
	Build model derivatives	Derivatives clearly defined beforehand can streamline the curation and publishing tasks.	
Curation	Model Identification	Identification of 3D models	Curation tasks add information for digital specimens, this can include adding data about the physical specimen, the digitisation process, and the 3D reconstruction process.
	Information extraction	Extraction of metadata from digitised specimen (from tags, barcodes, etc.)	
	Specimen annotation	Annotation of digitals specimens, including model metadata and specimen data (from catalogues)	
Publishing	3D model Publishing	Providing access and long-time preservation of 3D models	The publishing processes for digitised materials needs to follow FAIR principles[8].
	3D model Display	Rendering/accessing 3D models	Supporting preview of the models and their associated metadata is among the goals of digitisation.

3. 3D Digitisation Methods Applied to Natural History Collections

This section describes the 3D methods which have been applied for creating 3D products as part of the outputs of the digitisation of NHC specimens.

3.1 Overview of 3D digitisation methods

The 3D methods for NHC of collections from which some results have been published by either documenting the workflow, publishing the models, or both are presented in Table 5. The main objective is to identify the most suitable methods for rapid 3D digitisation. 2D+ (with and without focus stacking), Photogrammetry, Structured Light Scanning, and Micro CT were the main 3D digitisation techniques analysed by the Synthesys 3 project [9]. In addition to these, Table 5 also includes laser scanning from examples provided by MNHN and NHM.

Table 5 Summary of 3D Methods applied to NHC

Method and Institution(s)	Tasks	Status
Multi Plane Photography (with and without focus stacking) RBINS, RMCA, and MfN [9]	handling and mounting	All manual
	acquisition	Some automation in the control of stack, shutter, and image storage Specimen posing,
	processing	Images need to be validated and processed to ensure consistent quality of the image set (focus, sharpness, colour). Focus stacking requires extra processing to build the final images.
	curation	Some image stored automatically. Data on magnification, step size, number of views needs to be manually recorded. Linking to catalogue data is manual

[8] https://www.force11.org/group/fairgroup/fairprinciples

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Grant Agreement No 777483

Table 5 Summary of 3D Methods applied to NHC

Method and Institution(s)	Tasks	Status
	publishing	RBINS 2D+ specimens published on own website[9] RMCA 1,842 2D+ specimens published online on own website[10] MfN Specimens published on own website[11]. Some 3D models linked on Sketchfab (17 models available produced by third parties using ZooSphere sequences[12])
	display	RBINS and RMCA: local storage and display of 2D+. MfN: Local storage and display of 2D+, Remote storage and display of 3D models.
	collections	Entomology (pinned insects, some amber encased insects), Invertebrates, Vertebrates, Anthropology and Prehistory, Palaeontology, and Geology
	outputs	2D+ sequences (small image sets < 10 images) and 3D models
	time/cost	RBINS/RMCA 1 to 10 minutes /1€-5€ per specimen MfN 1 to 6+ hours /NA
Photogrammetry (with and without photo-stacking), MfN, RBINS, RMCA [9]	handling and mounting	All manual
	acquisition	Automated, including rotation of specimen, camera positioning, and lighting
	processing	Images need to be validated and processed to ensure consistent quality of the image set (focus, sharpness, colour). Focus stacking requires extra processing to build the final images. The 3D model is built from the resulting 2D+ dataset. Model building can take places with or without focus stacking.
	curation	Some images stored automatically. Data on magnification, step size, number of views needs to be manually recorded. Linking to catalogue data is manual.
	publishing	3D specimens published on own web within six collections: Entomology, Invertebrates, Vertebrates, Anthropology and Prehistory, Palaeontology and Geology on linked from RBINS and RMCA websites[13] [14] to Sketchfab MfN: NA
	display	Rendering is provided by Sketchfab. RBINS has 44 models publicly accessible the rest are linked through RBINS website[15]. RMCA has 425 3D specimen models published on Sketchfab[16]. MfN: NA. Some examples on authors' websites[17]
	collections	Entomology, Invertebrates, Vertebrates, Anthropology and Prehistory, Palaeontology, and Geology
	outputs	3D models
	time/cost	1 to 6 hours/10€-100€ per specimen
Structured Light Scanner RBINS-RMCA [9]	handling and mounting	All manual
	acquisition	Manual
	processing	Building of the model is supported by software licensed by the scanner provider. The amount of user interaction required varies depending of the type of scanner used.
	curation	Imaging data and sources stored automatically. Additional data on preparation, mounting, operator, identifiers and linking to catalogue data is manual.
	publishing	NA
	display	NA. Some examples on authors publications[18]
	collections	Zoology, Geology, Palaeontology (dry specimens)

[9] http://virtualcollections.naturalsciences.be/
[10] http://digit03.africamuseum.be/allspecimens
[11] http://www.zoosphere.net/
[12] Examples: https://sketchfab.com/search?q=zoosphere&sort_by=-pertinence&type=models
[13] http://digit03.africamuseum.be/allspecimens
[14] http://virtualcollections.naturalsciences.be/
[15] https://sketchfab.com/naturalsciences
[16] https://sketchfab.com/africamuseum
[17] https://peterfalkingham.com/blog/ and https://dinosaurpalaeo.wordpress.com/
[18] http://biowikifarm.net/v-mfn/3d-handbook/Structured_Light_Scanning_RBINS_%26_RMCA#tab=Links

Table 5 Summary of 3D Methods applied to NHC

Method and Institution(s)	Tasks	Status
	outputs	3D models
	time/cost	10 min to 1+ hours/10€-50€
Infrared Scanner RBINS, RMCA [9]	handling and mounting	All manual
	acquisition	Manual manipulation of scanner, including rotation of specimen, camera positioning, and lighting
	processing	Building of the model is supported by software licensed by the scanner provider. The amount of user interaction required varies depending of the type of scanner used.
	curation	Imaging data and source files stored automatically. Linking to catalogue data is manual.
	publishing	3D specimens published on own web within six collections: Entomology, Invertebrates, Vertebrates, Anthropology and Prehistory, Palaeontology and Geology on linked from RBINS and RMCA websites[19] [20] to Sketchfab
	display	Rendering and hosting are provided by Sketchfab. RBINS has 44 models publicly accessible the rest are linked through RBINS website[21]. RMCA has 425 3D specimen models published on Sketchfab[22].
	collections	Entomology, Invertebrates, Vertebrates, Anthropology and Prehistory, Palaeontology, and Geology
	outputs	3D models
	time/cost	1 to 30 minutes/5€-50€ per specimen
Laser Scanner MNHN [14], NHM [43]	handling and mounting	Manual. Mounting replaced by staging to enable in situ acquisition.
	acquisition	Semiautomated, required repositioning the equipment rather than the specimens
	processing	Building of the model is supported by software licensed by the scanner provider. The amount of user interaction required varies depending of the type of scanner used.
	curation	Imaging data and sources stored automatically. Additional data on preparation, staging, operator, identifiers and linking to catalogue data is manual.
	publishing	MNHN: NA NHM: has 69 models published on Sketchfab[23].
	display	MNHN: NA. Some examples on museum site[24] NHM: examples hosted on Sketchfab and embedded remotely on from museum pages using Sketchfab plugins.
	collections	Zoology, Geology, Palaeontology (dry specimens)
	outputs	3D models
	time/cost	10 min to 1+ hours/10€-50€
Micro-CT HCMR, MfN RBINS and RMCA [9]	handling and mounting	All manual
	acquisition	Automated
	processing	Building of the model is supported by software licensed by the scanner provider. Most of the time this is automated and only minor corrections can be made by user (surface model, volumetric model).
	curation	Imaging data and sources stored automatically. Additional data on preparation, mounting, operator, identifiers and linking to catalogue data is manual.

[19] http://digit03.africamuseum.be/allspecimens
[20] http://virtualcollections.naturalsciences.be/
[21] https://sketchfab.com/naturalsciences
[22] https://sketchfab.com/africamuseum
[23] https://sketchfab.com/NHM_Imaging
[24] https://www.mnhn.fr/fr/collections/actualites/galerie-anatomie-comparee-paleontologie-3d

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H2020-INFRADEV-2016-2017
Grant Agreement No 777483

Table 5 Summary of 3D Methods applied to NHC

Method and Institution(s)	Tasks	Status
	publishing	HCMR [9] Mentions three possible sites for publishing (GigaDB, Digital Morphology, Dryad). The only example found was one Dryad data package with 11 Micro-CT models linked to an article[25]. MfN has some snapshots of examples published on their Micro CT homepage[26] RBINS and RMCA 3D models hosted and rendered through Sketchfab and embedded in their own webpage
	display	Rendering is not always provided (HCMR and MfN). Mentions some software for rendering online. Examples published online are published on Sketchfab
	collections	Marine invertebrate specimens
	outputs	3D models
	time/cost	1 to 6+ hours/50€-500€ per specimen

3.2 Rapid 3D digitisation candidates

The 3D digitisation methods shown in Table 5have been applied in other institutions, such as Naturalis, NHM and MNHN as part of their digitisation programs. However, only MfN, Naturalis, RBINS, and RMCA, have published 3D specimens as part of their digital collections. This illustrates that 3D data is not yet integrated in curation and collection workflows, rather often it is done for specific research or outreach purposes. From the six methods analysed, micro CT is the least likely candidate given that it is potentially destructive, requires the costliest equipment, on site and there are hard limitations for the sizes of specimens (in addition to requiring expert operators). In contrast several low-cost off-the-shelf and custom-made stations for 2D+, photogrammetry, and structured light scanning exist. The second costliest method is laser scanning, because of the type of equipment required and the amount of training required to become a proficient digitisation operator, moreover most examples tend to be outsourced to expert providers. However, laser scanning can also be a valid candidate because the upfront investment can be offset by the precision and speed for large scale scanning of large specimens. These four methods have been used for different types of specimens, pointing to them as the most likely to succeed in bringing 3D scanning closer to the needs for mass 3D digitisation.

The instances in which 3D digitisation have been undertaken in different institutions show some common approaches, such as the prevalence of manual tasks in specimen handling and mounting, curation, publishing and display. Acquisition and processing are the workflow tasks which show different degrees of automation. This is common with 2D digitisation workflows [29], for instance digitisation of herbarium sheets has been automated to a point where acquisition time is not as important as the curation, publishing and use of digitised outputs. Existing alternatives in these areas are the subject of the next section.

4. Proposals for Improving 3D Digitisation

The analysis of the tasks of the 3D digitisation workflows identified six areas in which can potentially help achieving greater throughput and reducing digitisation costs. The tasks are further explored in the following sections two main areas: method depended and method independent

[25] https://datadryad.org/resource/doi:10.5061/dryad.84m54
[26] https://www.kristin-mahlow.de/en/mico-ct-labor/aktuelle-projekte-im-%C2%B5ct-labor/

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Grant Agreement No 777483

tasks. Method dependent tasks encompass Acquisition and Processing tasks which have directed dependencies with the digitisation method selected. Method independent tasks outline some recent findings in the areas of specimen handling, curation, publishing, and display of 3D specimens, which are more independent of the acquisition method.

4.1 Method dependent tasks

There are two groups of method dependent tasks which can support the improvement of 3D imaging workflows: acquisition tasks and processing tasks. In these two areas, the key element is the automation of the processes to minimise the participation of human actors in the workflow.

4.1.1 Acquisition

The automation of acquisition task depends greatly on the type of digitisation station and the method for digitisation to be applied. In this case, imaging stations can range from manual stations to fully automated. With this perspective, digitisation stations can be classified according to their degree of automation in three broad groups: manual, semiautomated, and fully automated. Manual stations are those which require significant intervention by the digitisation technician for posing the specimen and acquiring the imaging data. Semiautomated stations require less intervention from the digitisation technicians, in this case either the posing or the acquisition is assisted, but not both. Fully automated stations require no intervention from the digitisation technicians, apart from mounting and retiring the specimens as they are being digitised.

Multi plane photography and Photogrammetry can be used to illustrate all levels of automation, with examples of custom-built stations by institutional digitisation teams to fully integrated stations developed by several vendors. Structured light scanning and laser scanning on the other hand are either semiautomated or fully automated. For instance, scanners allow for manual handling of the scanner while data is being acquired, but apart from initial calibration and specimen mounting the rest of the acquisition is managed by the scanner hardware and software.

4.1.2 Processing of captured data

The automation of processing tasks depends is linked to the type of digitisation method. There are several examples of software which can be finetuned to support greater automation of the processing of captured data. However, the refinement of 3D products still requires the manual modification by experienced technicians.

Table 6 Summary of automation perspectives for acquisition and processing tasks

Method	**2D data processing**	**3D Model Building**	**3D Model Refinement**	**Main Output**
Multi Plane Photography	Required Several applications have been developed for automation.	Optional Some of the processes for 3D models building have been automated.	Optional Most of the processes are performed by technician manually	2D image sets

Table 6 Summary of automation perspectives for acquisition and processing tasks

Method	2D data processing	3D Model Building	3D Model Refinement	Main Output
Photogrammetry	Required Several applications have been developed for automation.	Required 3D models building can be automated to some degree	Optional Most of the processes are performed by technician manually	3D model Coloured or Textured
Structured Light Scanning	Not required	Required 3D models building is automated.	Optional Most of the processes are performed by technician manually	3D model Coloured or Textured
Laser Scanning	Not required	Required 3D models building is automated.	Optional Most of the processes are performed by technician manually	3D model Coloured or Textured

The processing tasks for multiplane photography include photo-stacking, masking, colour correction, sharpening, quality control, verification of image sets, identification, linking to corresponding data, and organisation of images for presentation (gallery, image cube, or 360° compositions). Several of these tasks have been automated both in open source and proprietary software.

The processing tasks of photogrammetry data includes those for multi plane photography and additional tasks for building 3D models such as calculation of sparse and dense cloud, building of mesh, using targets and markers to align the images and multiple positions and to scale the object. Additionally, after the model has been built further processing may be required such as hole filling, noise reduction, UV unwrapping, and texture/colour per vertex calculation. Manual editing of texture may be needed to create a nice display derivative. Retopology and/or decimation, especially to create an extra derivative for web viewing. Online viewing may also require producing normal (and bump or displacement). In this case, there are examples of open source and proprietary software packages for editing 3D models, however the best results are still achieved by manual edition.

The data produced from structured light scanning takes the form of 3D models, which may require further processing to obtain the best results. This can include tasks such as cleaning of scans, aligning of scans, meshing, mesh editing, UV unwrapping, texture/colour per vertex calculation. Manual editing of texture may be needed to create a nice display derivative. Retopology and/or decimation, especially to create an extra derivative for web viewing. Online viewing may also require producing normal (and bump or displacement). In this case there are examples of open source and proprietary software packages for editing 3D models, however the best results are still achieved by manual edition.

The data produced by laser scanning are 3D models which can also require further processing like those applied to structured light scanning. The main difference can is that, in general, laser scanning does not include capture of colour information[27]. The software for processing 3D models is mainly manual with both open source and proprietary offerings.

Each cluster of steps can be done in separate software packages. Sometimes the proprietary software that comes with structured light scanners or the various photogrammetry solutions have mesh editing options, but sometimes it is better to this in specialised software. Good UV unwrapping, retopology and normal map extraction can be done in more artistic types of software (ZBrush/Cinema4D/Blender/3DS Max/Maya/3D Coat) as used by game studios and VFX studios. This is important when the goal is to also create a derivative that can be viewed on low-end and portable devices and used in AR/VR.

The objective of processing is to create high quality models through processing the data, however, the trade of to consider is that this means greater manual interaction. Photogrammetry, laser scanning and structured light capture software often offer (semi-)automated processing, but they do not always guarantee reaching the best results. In fact, human operation and steep learning curves are limiting factors in capturing as clean data as possible unless done by dedicated expert technical staff. Proper automation of capturing setups (such as is mostly possible through photogrammetry, e.g. CultLab3D [21]) results in neater data that can be processed cleanly through the auto-processing options.

4.1.3 Examples and Providers

This section presents three examples of how acquisition and processing methods with different types of automation which have been shown to work in institutional settings. The selected examples are the British Library, and Fraunhofer Institute. The techniques shown in these examples can be integrated into existing workflows and combine the automation of positioning of specimen and acquisition equipment.

British library

The British Library in partnership with CYREAL[28] installed and customised a multicamera scanning station [13]. The station consists of a robotic turntable, illumination equipment and five DSLR cameras. The modular design of the station means that it can be customised to include more cameras to increase the quality of the models produced and speed up the acquisition process.

This station can produce images for either 360° views or 3D models. CYREAL can deliver the station and control software. The interesting part of this approach proposal is the decoupling of acquisition

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[27] There are examples of new laser scanners which can capture also colour information, for instance Faro Quantum ScanArm with Prizm Laser Line Probe. https://www.faro.com/en-gb/products/3d-manufacturing/faro-scanarm/

[28] https://www.cyreal.com/

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Grant Agreement No 777483

from model building, acquisition is done onsite, and the 3D models are built afterwards by CYREAL, after the library sends the acquired datasets.

The cost of the digitisation station is 6,000.00 € (at 2018 prices) and CYREAL charges an extra fee of 22.00 € for each model created. This can offset the need for hiring and training a digitisation expert, while achieving high quality results from the beginning of operation.

Figure 10 A view of the BL digitisation station developed by CYREAL. The image on the right shows the robocase system and the workstation controlling the image capture software, and the image on the left shows a close up of the turntable with the artefact being digitised[29].

Fraunhofer Institute for Computer Graphics Research

The Fraunhofer Institute for Computer Graphics Research (Fraunhofer IGD) has developed five types of digitisation stations for the cultural heritage: CultLab3D, CultArc3D, CultArm3D, CultArc3D mini, Real Time Structured Light Scanner (RTSLS). Meso-Scanner V1, Meso-Scanner V2, and HDR-ABTF-Scanner [21, 50]. CultLab3D is a complex digitisation station which integrates CultArc3D and CultArm3D (optional) connected by a tray conveyor system (Figure 11). According to their specifications, the fully automated acquisition process for geometry and texture of an object takes less than ten minutes, on average, at a resolution in the sub-millimetre range (up to 200 μm). The station can be customised as required.

The CultArc3D scanner captures geometry, texture, and material properties at high resolution. It consists of two arcs equipped with cameras and ring lights for digitisation of objects from all sides and combinations of camera perspectives and light directions. The bottom of an object is acquired through a transparent carrier disk. Capture time for geometry and texture is approximately three minutes per object at up to 200 μm resolution [21]. The CultArm3D scanner consists of a camera, laser scanner or a structured light scanner, mounted on a lightweight robotic arm. The geometry and texture of the objects placed on a turntable are digitised automatically. This scanning station can capture geometry and texture at resolutions of up to 200 μm (photogrammetry) or 50 μm (structured light and laser) [21].

[29] https://www.bruns.nl/en/news/robocase-nominated-for-the-heritage-in-motion-award-2018

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Grant Agreement No 777483

Figure 11 A view of the CultureLab3D digitisation station developed by Fraunhofer IGD. Image 'a': compelete set up of CultureLab3D. Image 'b:' CultureArc3D. Image 'c': CultureArm3D with a RTSLS mounted[30].

CultArc3D mini station is a tabletop version of CultArc3D. It is a photogrammetry 3D scanner that captures an image set for building 3D models with geometry and texture reconstruction coupled with a conveyor system for automatic object feed-in and -out. Model building is handled by software that handles every single process step of the complex sequence from image acquisition, sensor-based object transportation, and 3D reconstruction involving different kinds of calibrations. Positioning and pickup of objects is automatically registered, the only thing left for the operator to do is placing an object at the entry and retrieving it from the exit after scanning [50].

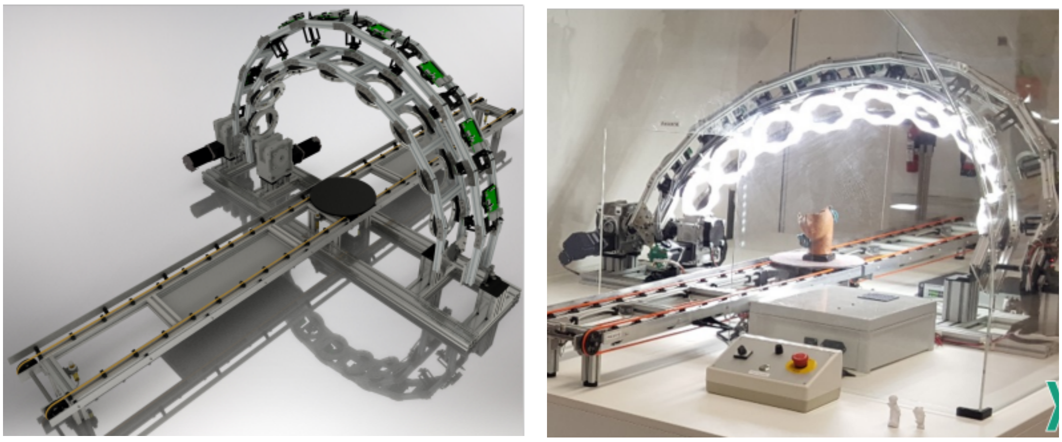

Figure 12 A view of the CultArc3D mini digitisation station developed by Fraunhofer IGD.[31].

Meso-Scanner V1, and Meso-Scanner V2 are desktop structured light scanners designed for the scanning of small artefacts, such as coins and seals. The resolution of these scanners is of 55 µm lateral and 20 µm depth (for V1), and 32 µm lateral 15 µm depth (V2). With average scan speed of five minutes (V2) [21]. The HDR-ABTF-Scanner is designed to capture the optical behaviour of objects with surfaces that respond differently to (e.g. textiles and leather). The scanner illuminates the surfaces from different directions and captures texture and light-surface interaction of materials using an Approximate Bidirectional Texturing Function (ABTF). This type of digitisation

[30] Images taken from [21]
[31] Images taken from [21]

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Grant Agreement No 777483

station could be useful for scanning and creating textures for true-to-life 3D visualizations and specimens with iridescence and other special optical properties.

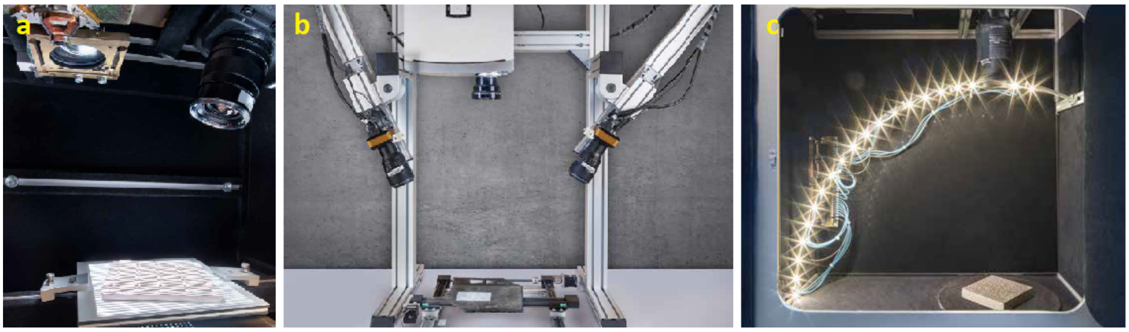

Figure 13 3 specialised desktop scanners developed by Fraunhofer IGD. Image 'a': Meso-Scanner V1. Image 'b:' Meso-Scanner V1. Image 'c': HDR-ABTF-Scanner [32].

The speed and accuracy of the scanners developed by Fraunhofer IGD could address most of the requirements for 3D digitisation of NHC specimens. The most relevant ones are the desktop scanners (Figure 13) as they could target collections with smaller specimens such as entomology.

In terms of cost, there are various prices for the different configurations, however in a recent paper, they claim that the CultArc3D mini system, complete with a 3D printer for replicating the models can cost less than 5,000.00 € (2018 price at time of publishing) [50].

Other providers

There are few providers of multi plane photography stations, however, there are examples of adaptations which can create multiplane digitisation stations from existing stations such as Sertifer[33], that provides a conveyor-based digitisation station for pinned insects [27]. The station can be fitted with multiple cameras for taking different planes of each specimen. This system has already been tested at the MfN Berlin, which used the stations for taking dorsal and lateral view images of pinned insects[34].

The University of Helsinki is currently performing research to further use of 3D digitisation and its integration into a conveyor belt digitisation system. The aim is to minimise the amount of work required for extracting label information from pinned insects [27]. In their experiment, the images from nine angles are cropped vertically from the 3D model, removing the specimens to expose label information, this is being carried out in collaboration with LUOMUS, Setifier[35] and NampaWorks Ltd. Figure 14 shows the sequence of images required to produce the 3D model and Figure 15 shows the results obtained. This proposal from the University of Helsinki is similar to the work produced by NHM [1, 49] and Hereld [25], and it is critical because speeding up information extraction is likely to speed up the digitisation process and an outstanding problem in drawer level digitisation of pinned insect collections.

[32] Images taken from [50]
[33] http://www.sertifer.fi/eng/digitointipalvelut.html
[34] https://www.uef.fi/en/-/digitariumin-toiminta-joensuussa-loppui-mutta-tyo-jatkuu
[35] http://www.sertifer.fi/eng/digitointipalvelut.html

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Grant Agreement No 777483

Figure 14 Example of 3D digitisation for extracting information from pinned insects [27]. The images captured from nine angles can be used to create a 3D model. The model can be vertically cropped to extract label information which is occluded by the specimens.

Figure 15 Results of 3D digitisation for extracting information from pinned insects [27]. In the images above, data acquired as shown in Figure 14 is used to create a 3D model. The image on the left shows the view of the model showing the specimens and the image on the right shows the vertical crop which allows viewing label information which was occluded by the specimens.

The combination of focus stacking and photogrammetry is mentioned as a viable alternative for the 3D digitisation of small specimens [8, 9]. ZooSphere has reported that some of their digitised specimens have been used to experiment with this possibility, which has also been explored by others [37, 46, 47, 88].

The main bottleneck on this process is the acquisition of images at different focus distances. In this area, the use of light field cameras that simultaneously capture multiple focal planes (e.g. Raytrix[36]) could yield significant improvements in acquisition time and accuracy [10, 25].

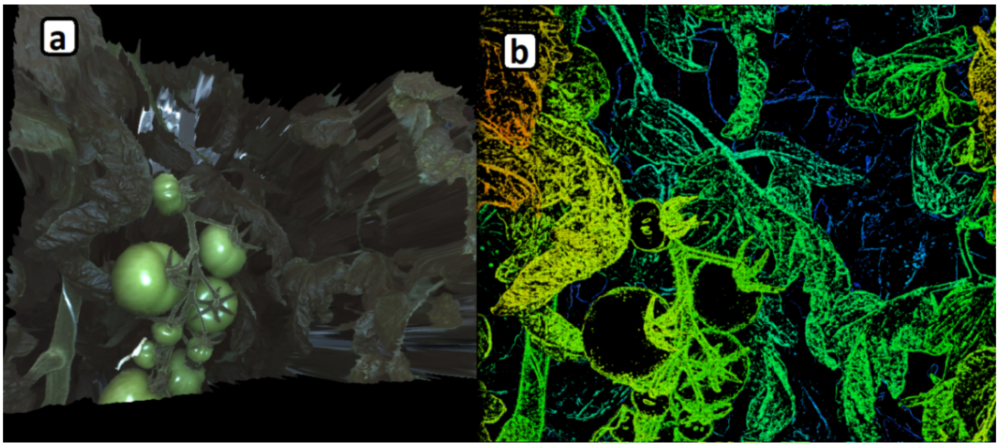

Figure 16 Example of an image from a live plant specimen acquired with a Raytrix R29 camera. Image 'a': shows the specimen. Image 'b:' shows the colour mapped depth information of from 'a'[37].

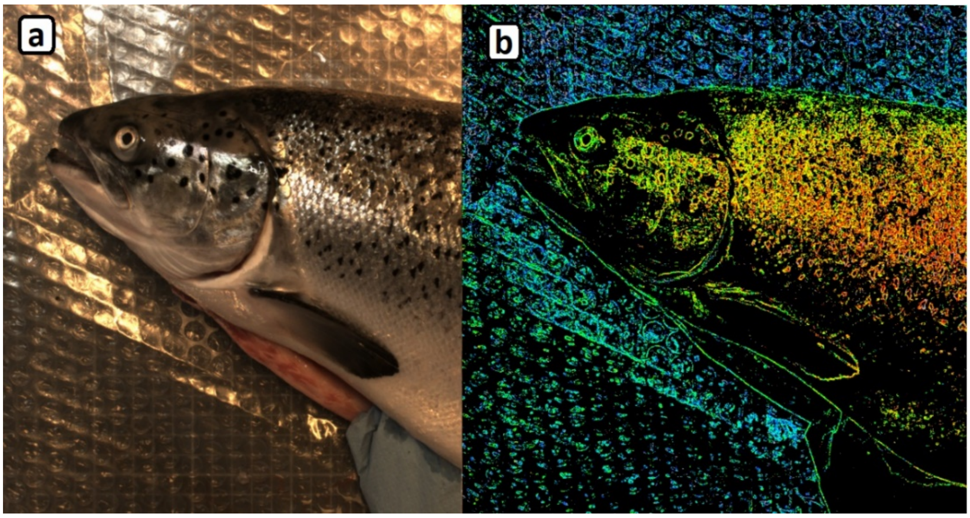

Figure 17 Example of an image from a wet specimen acquired with a Raytrix R42 camera. Image 'a': shows the specimen. Image 'b:' shows the colour mapped depth information of from 'a'[38].

As shown in the examples from Figure 16 and Figure 17, the depth information stored in light field images facilitates the identification of features, borders and background, which are areas that have been addressed by various proposals in 3D modelling.

The increasing popularity of 3D modelling in different domains has created a thriving market with several providers of low cost 3D digitisation equipment such as SHINING 3D [55, 56], Artec (very

[36] https://raytrix.de/products/
[37] Images taken from https://raytrix.de/products/
[38] Images taken from https://raytrix.de/products/

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Grant Agreement No 777483

commonly used in museums)[39], HP 3D scan[40], Breuckman[41], Aicon[42], and many others. However, this is also young market in which companies open, but there is no guarantee of long-term sustainability, such as the example of the Zeiss 3D scanner, which has been earmarked for withdrawal from the market by Zeiss little over a year after its official launch[43].

Finally, museums have also demonstrated the use of laser scanning for quick digitisation of large collections, such as the experiment by CVAST and MNHN. The experiment combined laser scanning and 2D photography to digitise the Galerie de Paléontologie et D'anatomie Comparée (Paleontology and Comparative Anatomy Gallery) on site, without moving the specimens and little disruption for the daily operation of the museum [14].

4.2 Method Independent Tasks

There are four groups of method independent tasks which can support the improvement of 3D imaging workflows: handling and mounting, curation, publishing, and display tasks. In these areas, the key element is the automation of the processes to minimise the participation of human actors in the workflow.

4.2.1 Specimen Handling and Mounting

Streamlining of specimen handling processes have already been tested in the mass digitisation workflows of herbarium specimens and pinned insects. These solutions use conveyor belts and trays which help positioning the specimens for image acquisition. Human operators load the preselected and labelled specimens in the trays and the system then can position and scan the specimen automatically. After acquisition, human operators offload the specimens and get them ready for return to storage.

The automation of 3D imaging for NHC spans different requirements due to differences in size, preservation type, fragility and potential hazards [28]. The ideal model for automation of specimen handling would require modifications to the way specimens are catalogued, stored and handled. The research on robotics and warehousing performed by ICEDIG [28] proposed the model shown in Figure 18, which lists the tasks

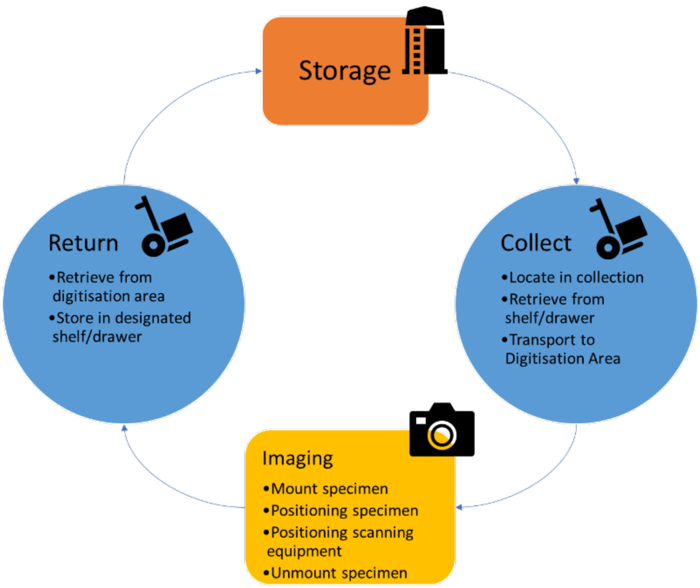

Figure 18 End to end process of storing, transporting, and imaging natural history artefacts (adapted from [28])

[39] https://www.artec3d.com/portable-3d-scanners/artec-spider
[40] https://www8.hp.com/us/en/campaign/3Dscanner/overview.html
[41] https://www.aniwaa.com/product/3d-scanners/aicon-3d-systems-breuckmann-smartscan/
[42] https://www.hexagonmi.com/products/white-light-scanner-systems/aicon-smartscan
[43] https://www.zeiss.com/corporate/int/newsroom/press-releases/2018/zeiss-realscan.html

which could be partially or completely automated. The transport tasks (collect and return) as well as storage are the ones requiring greater changes in physical collections management. The handling during imaging tasks are part of the design of digitisation stations and have less impact on the physical collection management.

There are no examples of these type of automation solution for NHC management and imaging. However, the British Library (BL) and Bruns[44] (innovative exhibition design company) demonstrated two cases which could be adapted to NHC [3]. The BL demonstrated the warehousing solutions developed for their collections in Boston Spa. At the site they have two fully automated warehouses, in which the books are stored and retrieved automatically, minimising the required human interaction (Figure 19). The system was designed to minimise time required for locating and retrieving books and newspapers. The storage buildings incorporate automated storage and retrieval systems, optimum environmental controls and low oxygen fire prevention technology [3].

Figure 19 A view of the additional storage building (ASB) of the British Library, at Boston Spa. The image on the left shows the building and the image on the right a section of the automated storage system[45].

The BL example is interesting because of the similarities with NHC: improve object-based research, large volume of specimens in storage which need to be accessible and searchable, requirement of controlled climate for preservation (temperature, humidity, oxygen levels and pest control). Many of these requirements have been addressed by the system implemented by the BL.

Bruns is the provider of Robocase, a robotic exhibition display system which enables the easy operation of a robotic arm for retrieving and displaying museum artefacts. The idea is to allow the user to come close to a display cabinet and use a touch screen to select an item in the cabinet. After selection, the robotic arm will retrieve the item and place it on turntable closer to the user. In this way, the objects can be closely inspected. According to Bruns, the operation of the arm is calibrated to enable safely retrieving, transporting, and returning items as fragile as a house of cards [3].

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[44] https://heritageinmotion.eu/himentry/slug-6d216b455dc490141c7f1792a7c9ccba
[45] https://www.bl.uk/press-releases/2015/january/british-library-opens-national-newspaper-building

Figure 20 A view of the Robocase exibition system developed by Bruns. The image on the left shows the robocase system and a user interacting with it, and the image on the right a close up of the robot arm returning an artefact[46].

The Robocase example is interesting because of the fine control of the robot arm for handling fragile specimens. The equipment could be costly for exhibition use, but it could be adapted for retrieving individual specimens and positioning them in a digitisation station.

4.2.2 Curation

Curation of digitised specimens includes tasks which extract information from the specimens. This can include retrieving and linking metadata about the original specimen, the digitisation process, and the 3D reconstruction process. The data required for management of 3D specimens must address the needs for identifying, storing, retrieving and displaying such specimens.

The most advanced example on the curation of 3D digital specimens is the one developed by the Smithsonian Institution (SI). The SI 3D digitisation strategy encompasses specimen selection, development of a custom digitisation station, development of digitisation software, selection of processing software, publishing of imaged specimens, and encouraging use an exploitation of 3D digital resources [58]. Figure 21 shows the Smithsonian Institution metadata model [57]. The metadata model attempts to encompass all the metadata needed to fully document a 3D capture event. The model is initially focused on photogrammetry capture, because photogrammetry is accessible, and non-proprietary. Additionally, 'raw' data image files can be stored in open formats such as DNG and have existing best practices for preservation. The complexity of photogrammetry projects is comparable to that of projects using 3D capture methods. The Smithsonian approach is to address photogrammetry first, accounting for many "edge cases" in capture techniques and will be straightforward to extend to other capture types (laser, micro CT, structured light scanning).

[46] https://www.bruns.nl/en/news/robocase-nominated-for-the-heritage-in-motion-award-2018

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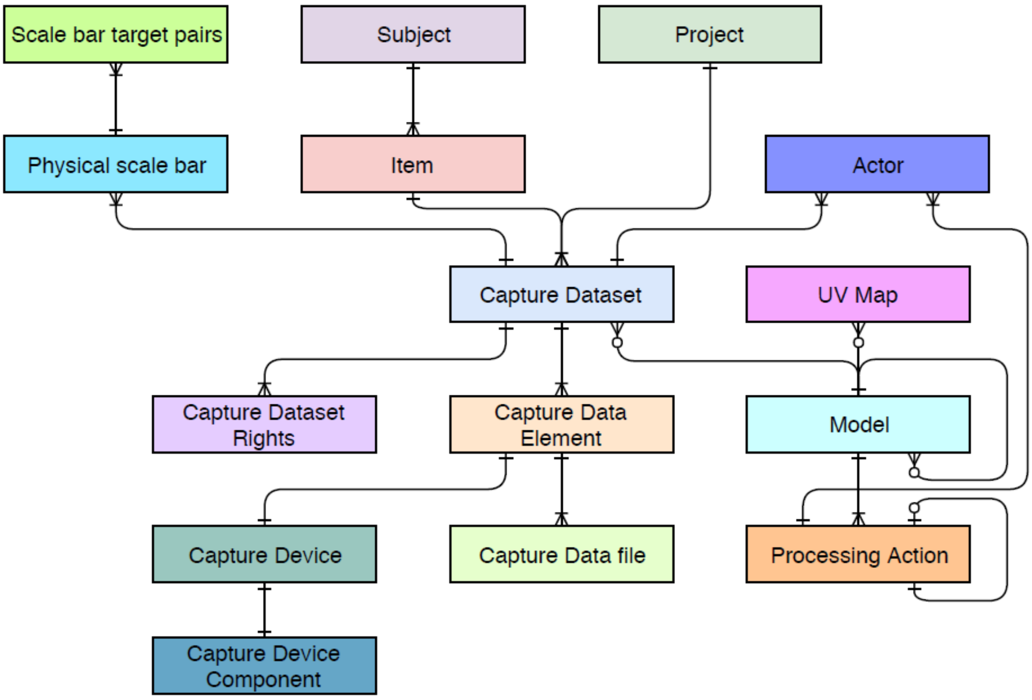

Figure 21 The image shows the common metadata model for 3D assets [57]. This model is adjusted to the definition of a generic common workflow for 3D digitisation which can be adapted to the requirements of any item in any collection.

The Smithsonian 3D digitisation strategy presents an adaptable plan for 3D digitisation of collections containing specimens of different sizes, by considering a generic workflow and data model which can be adapted to different 3D digitisation technologies.

4.2.3 Publishing 3D Specimens

The publishing processes for digitised materials needs to follow FAIR principles[47]. This will require determining if the formats currently being employed by different museums follow these recommendations and what impact, if any, does this have on the whole digitisation workflow. Publishing of digital specimens to facilitate and increase access to specimens is one of the main goals of natural history collection digitisation. Adherence to FAIR data principles (Findability, Accessibility, Interoperability, and Reusability) is intended to guide digitisation efforts to ensure that the data produced adheres to contemporary FAIR publishing requirements [87]. The efforts of defining a minimal metadata model for publishing digital specimens pursued in ICEDIG is a step in this direction [30]. The derived recommendations should be integrated as part of the metadata produced during curation (see Subsection 4.2.2 above).

The International Image Interoperability Framework (IIIF)[48] is an example of a coordinated effort for the development of standardised formats and application program interfaces for exchange and integration of digitised image collections [52]. ICEDIG could reuse some of the existing API definitions for the display of 2D digital collections and contribute to the development of similar standards and APIs for publishing and sharing 3D models. Cultural heritage institutions such as the BL are active members in IIIF [13] and there is interest from various ICEDIG partners, such as RBGM.

[47] https://www.force11.org/group/fairgroup/fairprinciples
[48] http://iiif.io/

Acquisition metadata for various 3D scanning techniques need to be recorded during acquisition. These settings are not saved (such as spacing for laser scanners and quality settings for some types of structured light scanners). The difficulty is that multiple settings may be used for a single object capture. Even if this capture metadata is stored in the raw data, this is not transferred to the output (mesh). This is not a problem for natural history to solve: there needs to be a wider discussion about this with manufacturers, software makers, industry and cultural heritage users.

There needs to be a clear difference between making research-quality models available and models for display on the web (especially keeping in mind that these are often viewed on low-end and mobile devices). Research quality models should not be retopologised and (heavily) decimated. Textures should not be sharpened, or missing colour data painted in. Extensive hole filling and reconstruction (especially on complex inter-connecting models such as skulls with foramens) should not be done. This is all interpretation, a clean model for research should always be preserved. Even meshing is technically interpretation. Even better it is to preserve the original scan data as well (or photos in case of photogrammetry), so that any researcher may go back to check the unprocessed data. In practice, this is blocked by several issues. Firstly, the original scan data can be as large as several gigabytes, ramping up the required storage drastically. Secondly, the raw scan data from most laser scanners and structured light scanners are saved in proprietary formats which may not be accessible to all or be obsolete in a few years. Some raw scans can also be exported in various point cloud formats, but often this does mean loss of some information.

4.2.4 Display of 3D Specimens

Currently the most widespread platform for hosting, publishing and displaying 3D models is Sketchfab which supports several 3D formats[49]. It is widespread among cultural and natural history institutions; however, the main use base is the Computer Graphic Art community. While Sketchfab only works through hosting on their side, the models can be embedded on any website or even social media platforms. Exporters are being made available to upload to Sketchfab from specific software packages and there is also an API available. Licensing and location of collections may be an issue since use of Sketchfab has restrictive terms of use and privacy policies which transfer the model's rights, i.e. the user gives a royalty free perpetual license to Sketchfab[50]. For the moment, it may be viable to use the platform for display. However, this type of commercial repository is not reliable or compatible with cultural heritage preservation of digitised specimens[51] or FAIR principles.

Publishing does not inherently require providing a tool for previewing or manipulating the 3D digitised specimens. However, supporting preview of the models and their associated metadata is among the main goals of digitisation. One of the greatest barriers to the acceptance of 3D digitisation is the lack of examples of use (success stories), of the products of 3D digitisation.

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[49] https://help.sketchfab.com/hc/en-us/articles/202508396-3D-File-Formats
[50] https://sketchfab.com/terms#user-content
[51] A similar problem occurred for users of google code, in that case, the company decided to close the service, and users who wanted to preserve their code or keep it available had to migrate to other hosting platforms (see examples below).

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The quality of the 3D models is closely related to the intended uses of those models. For instance, the criteria for a model to be published and inspected on the web will be different from the criteria for a model that is intended for 3D printing or research [29]. There are examples of use of 3D models for research [4], for documenting (e.g. label information from pinned insects [25, 27, 49]), and for general use by the public [23, 39], and open use for any purpose [58, 89]. In the case of open use, the higher quality models are the ones with more versatile application, since different types of derivatives can be produced to cover wider ranges of use.

The Smithsonian Institution 3D digitisation programme [58] actively promotes the use of the 3D digital specimens in different ways (as shown in Figure 22).

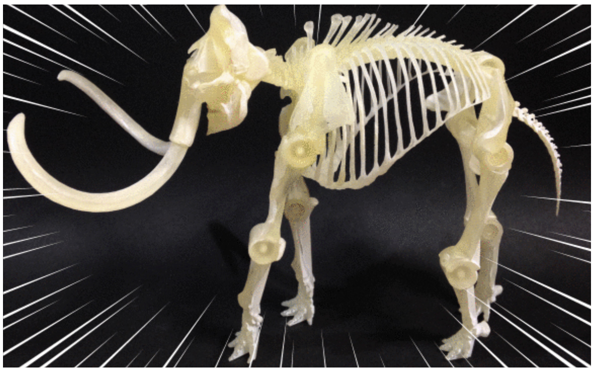
a)  b) 

Figure 22 The Smithsonian Institution digitisation project actively encourages the use of digitisation products. For instance, the images above show a published 3D specimen (a) which has been reused to produce a 3D printable articulated model (b) [23]

The Cabinet of Virtual Reality Cabinet (Cabinet de Réalité Virtuelle) is a project at the MNHN France. It offers an alternative learning experience using Virtual Reality (VR) headsets to allow visitors explore the tree of life and play interactive games. In this case, the 3D models are used side by side within the museum exhibition (see Figure 23).

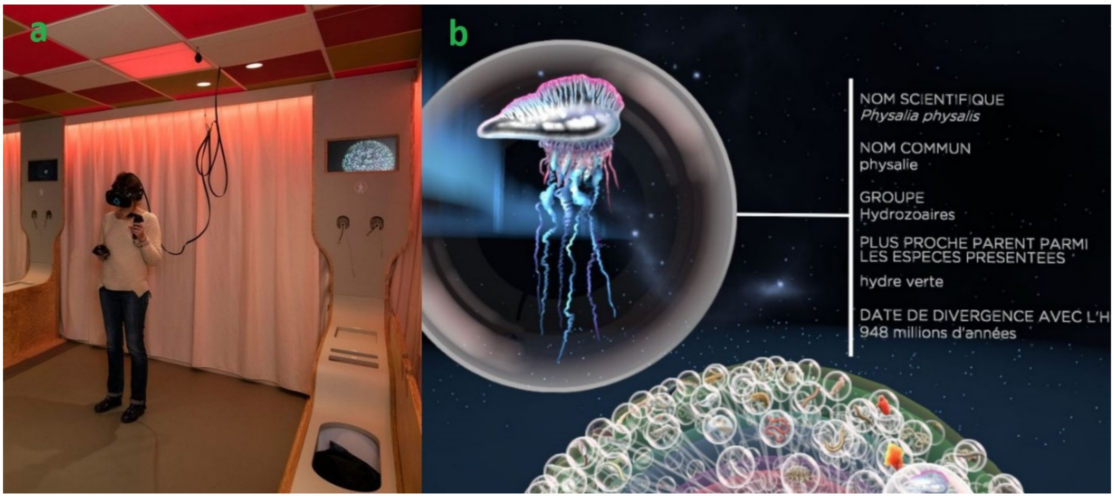


Figure 23 The Cabinet of Virtual Reality at the MNHN Paris. Image 'a': a visitor at one of the VR stations. Image b: screenshot of the information available through the VR system [23]

However, more research is needed into the case studies related to the use of 3D models. There are indications that the technologies have potential and are accepted by the public, however some researchers argue that the acceptance is not guaranteed [6]. For instance, unless there are installations where the equipment and interfaces are provided (e.g. the Cabinet of VR at MNHN

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Grant Agreement No 777483

above), museum visitors were reluctant to download an app on the spot during their visit for looking at 3D models [6].

Besides hosting through a third-party service such as Sketchfab, there is a concern in the wider community about safety of the data and usage rights. When 3D models are made available for download, watermarking of textures or embossing of logos in the mesh can be done but also easily removed. Structural watermarking is also possible, but not completely secure[52]. Even when the 3D model is not made available for download, it can be recreated from the renders of the web viewer through the exact same photogrammetry process, which will eliminate most casual users because some skill is needed. This is a concern in the creative community because it often concerns professional portfolios that are being ripped off. In scientific communities, it should be considered that no legitimate researcher would use 3D models that the provenance cannot be explained of. In the community of public users of the natural and cultural history models, piracy of these models can be prevented by making it available through some form of Creative Commons license, even if only for the lower resolution models. This type of licensing is often already used by institutions for their 2D images.

5. The Ideal 3D Digitisation Workflow

The use of 3D digitisation in NHC is accepted practice and several digitisation methods have been successfully tried, producing multiple 3D products. However, moving 3D digitisation forward into mainstream mass digitisation projects of Natural History institutions requires strategic planning. Having that in mind, with current resources, mass 3D digitisation is not feasible. A viable alternative to include 3D digitisation would be to design a rapid 2D digitisation pipeline and a procedure to identify suitable specimens for 3D digitisation. Once identified, the specimens would be handed to a parallel 3D digitisation workflow. This is similar to the way some digitisation workflows operate, for instance the microscopic slides workflow from NHM [35], the Item Drive Image Fidelity (IDIF) approach at the Smithsonian [2], and the Herbarium digitisation workflow from RBGE [24], and the workflow established at MfN for the ZooSphere project.

5.1 Working example

The ZooSphere project from MfN is an ongoing digitisation program targeting 3D digitisation end-to-end. The project includes a strategy for specimen selection, development of a custom digitisation station, development of digitisation software, selection of processing software, and publishing of imaged specimens [89]. Figure 24 presents the ZooSphere workflow and digitisation station.

The ZooSphere approach presents a viable solution for digitisation of large collections. The digitisation project prioritises type specimens and digitisation on demand. The digitisation of type specimens is programmed and prioritised by the collection curators who are responsible for selecting and retrieving the specimens as well as for curating the published image sequences. For digitisation on demand, the digitisation team and curators may select specimens have been

[52] https://www.watermark3d.com/ versus https://www.youtube.com/watch?v=wpGeSKHetfA

requested by scientists in other institutions. Moreover, the 3D digitisation of specimens is part of a wider strategy which also includes drawer level and individual level fast 2D digitisation.

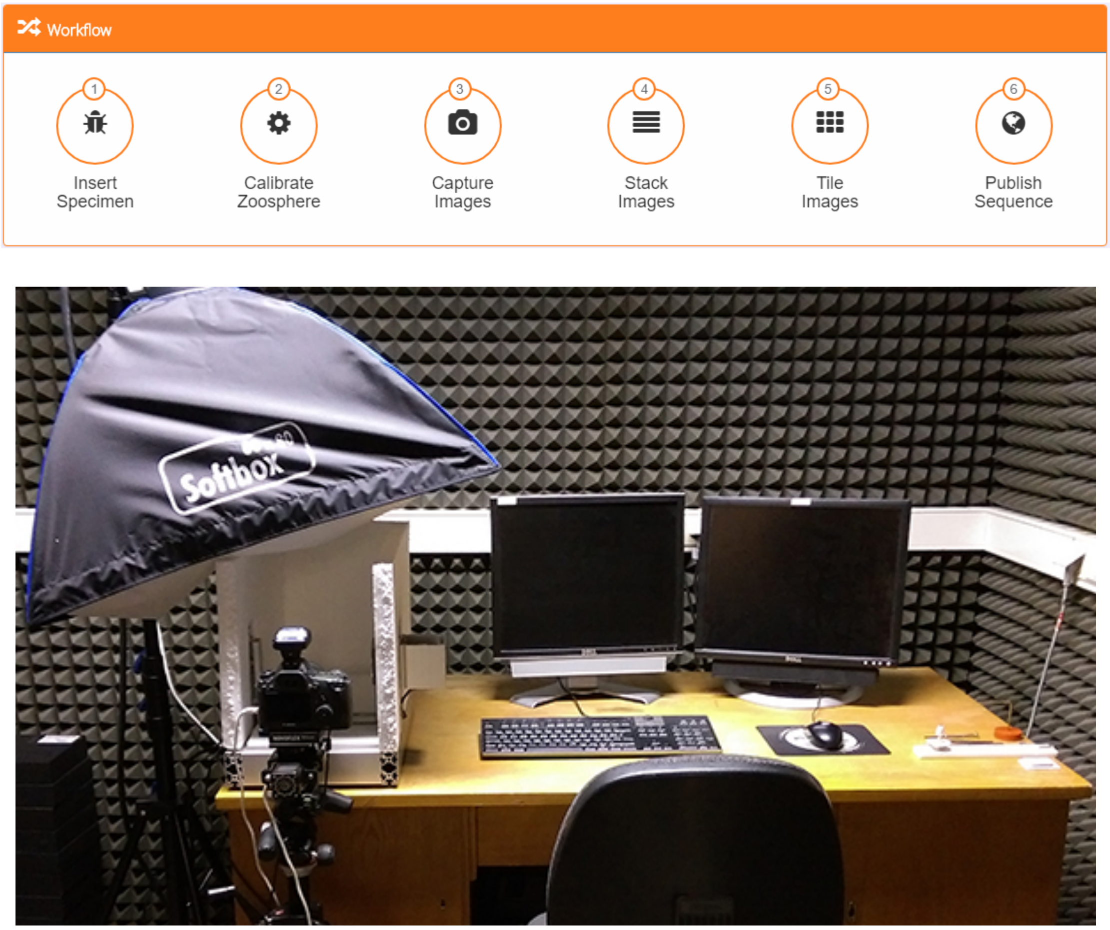

Figure 24 Schematic overview of the ZooSphere Workflow (top) and the custom-built digitisation station (bottom) [89]

The focus of ZooSphere is on producing multi plane photography image sets. However, the quality of the images makes possible the construction of 3D models from those sequences (see Figure 25). Additionally, image sequences are stable sources, that enable applying and comparing multiple 3D model building techniques.

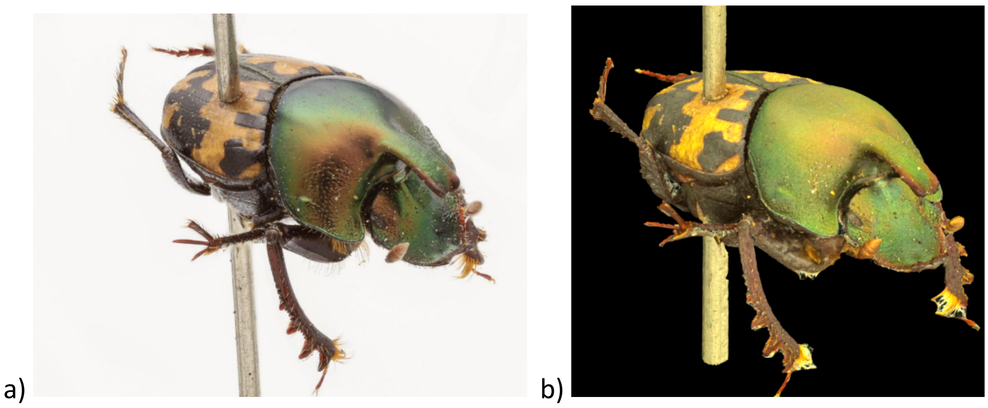

Figure 25 Example of a 3D digital specimen from ZooSphere: (a) one of the photos in the sequence and (b) a 3D model created by a third party using the same sequence[53]

[53] ZooSphere MfN [89], http://www.zoosphere.net/sequence/63/Onthophagus/elegans

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6. Conclusions

This report provides an overview of the main technologies for 3D digitisation and their potentials for becoming common practice as part of NHC digitisation projects.

The research effort has identified four candidate techniques for implementing 3D digitisation of NHC specimens. Additionally, the report has defined six workflow task groups which can be further improved to achieve greater throughput. Three of the groups considered, namely Curation, Publishing and Display of 3D products were identified as areas which are really underdeveloped, and often overlooked when designing the digitisation campaigns.

The guidance provided by this report can help in different areas such as:

- identifying the appropriate 3D digitisation technologies which may be applicable for each type of specimen,
- determine the attributes of physical specimens which make them candidates for 3D digitisation,
- describe the ways in which the current rates of 3D digitisation have been achieved and possible areas of improvement, and
- a call for action on establishing metadata guidelines with manufacturers, industry and cultural heritage.

These guidelines could influence and inform areas of research and development for larger digitisation projects in the context of DiSSCo.

Achieving this will require to work with the different teams researching the digitisation workflows (Tasks 3.1 and 3.4) within ICEDIG to validate the basic expectations about the requirements and prospects of the use of 3D digitisation.

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Acronyms

APM Agentschap Plantentuin Meise (Botanic Gardens Meise) https://www.plantentuinmeise.be/en/home/

BL The British Library http://www.bl.uk

CU Cardiff University https://www.cardiff.ac.uk/

DiSSCo Distributed Systems of Scientific Collections https://www.dissco.eu/

DNG Digital Negative

FADGI The Federal Agencies Digital Guidelines Initiative http://www.digitizationguidelines.gov/

FinBIF Finnish Biodiversity Information Facility https://laji.fi/en

Fraunhofer IGD Fraunhofer Institute for Computer Graphics Research https://www.igd.fraunhofer.de/en

HCMR Hellenic Centre for Marine Research https://www.hcmr.gr/

iDigBio Integrated Digitized Biocollections https://www.idigbio.org/

ICEDIG innovation and consolidation for large scale digitisation of natural heritage https://icedig.eu/

LUOMUS The Finnish Museum of Natural History https://www.luomus.fi/en

Micro-CT micro computed tomography

MfN Museum für Naturkunde Berlin (Berlin Museum of Natural History) https://www.museumfuernaturkunde.berlin/en

MNHN Muséum National d'Histoire Naturelle (National Museum of Natural History) https://www.mnhn.fr/

Naturalis Naturalis Biodiversity Center https://www.naturalis.nl/en

NHM The Natural History Museum London https://www.nhm.ac.uk/

NHC Natural History collection(s)

RBGE Royal Botanic Gardens Edinburgh https://www.rbge.org.uk/

RBINS Royal Belgian Institute of Natural Sciences https://www.naturalsciences.be/

RMCA Royal Museum of Central Africa https://www.africamuseum.be/en/home

OCR Optical Character Recognition

SI Smithsonian Institution https://www.si.edu/

Synthesys 3 Syntesis of Systematic Resources https://cordis.europa.eu/project/rcn/108204/factsheet/en

UH University of Helsinki https://www.helsinki.fi/en

2D+ Two-dimensional key view set

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3D Three Dimensional

Glossary

Anatomical Plane: An anatomical plane is a hypothetical plane used to transect the body, in order to describe the location of structures or the direction of movements [62].

Bump mapping: Bump mapping is a technique in computer graphics for simulating bumps and wrinkles on the surface of an object. This is achieved by perturbing the surface normals of the object and using the perturbed normal during lighting calculations. The result is an apparently bumpy surface rather than a smooth surface although the surface of the underlying object is not changed. Bump mapping was introduced by James Blinn in 1978. [63]

Camera rig: is a modular piece of equipment used to extend the usefulness of a camera, whether through accommodating additional shooting styles, allowing for additional gear to be mounted safely, or for smoothing out the motion of the shot [59].

Colour chart (colour reference card): it is a flat, physical object that has many different colour samples present. They can be available as a one-page chart, or in the form of swatch-books or colour-matching fans [64].

Colour reference charts is a type of colour char intended for colour comparisons and measurements. Typical tasks for such charts are checking the colour reproduction of an imaging system, aiding in colour management or visually determining the hue of colour. Examples are the IT8 and ColorChecker charts [64].

Colour selection chart is a type of colour chart presented as a palette of available colours to aid the selection of spot colours, process colours, paints, pens, crayons, and so on – usually the colours are from a manufacturer’s product range. Examples are the Pantone and RAL systems [64].

Colour Depth or colour depth (see spelling differences), also known as bit depth, is either the number of bits used to indicate the colour of a single pixel, in a bitmapped image or video frame buffer, or the number of bits used for each colour component of a single pixel [65].

Colour per vertex: assigning a colour to each vertex associated with a polygon face. Colour per vertex data (CPV) is commonly applied to 3D models that are created for interactive video games to more efficiently simulate shading and pre-lighting effects [5].

Delta E (ΔE, δE, dE) is a metric for understanding how the human eye perceives colour difference. The term delta comes from mathematics, meaning change in a variable or function. The suffix E references the German word Empfindung, which broadly means sensation [53].

Digital Negative (DNG) is a patented, open, lossless raw image format written by Adobe used for digital photography. Adobe's license allows use without cost on the condition that the licensee prominently displays text saying it is licensed from Adobe in source and documentation, and that the license may be revoked if the licensee brings any patent action against Adobe or its affiliates related to the reading or writing of files that comply with the DNG Specification [66].

Displacement mapping: using a (procedural-) texture- or height map to cause an effect where the actual geometric position of points over the textured surface are displaced, often along the local surface normal, according to the value the texture function evaluates to at each point on the surface. It gives surfaces a great sense of depth and detail, permitting in particular self-occlusion, self-shadowing and silhouettes; on the other hand, it is the costliest of texturing techniques owing to the large amount of additional geometry [].

Dots per inch (DPI, or dpi) is a measure of spatial printing or video or image scanner dot density, in particular the number of individual dots that can be placed in a line within the span of 1 inch (2.54 cm) [68]. Monitors do not have dots, they have pixels; the closely related concept for monitors and images is pixels per inch (or PPI). Many resources use the terms DPI and PPI interchangeably.

Focus stacking (also known as focal plane merging, z-stacking, focus blending, 2D+) is a digital image processing technique which combines multiple images taken at different focus distances to give a resulting image with a greater depth of field (DOF) than any of the individual source images. Focus stacking can be used in any situation where individual images have a very shallow depth of field; macro photography and optical microscopy are two typical examples. Focus stacking can also be useful in landscape photography [69].

Image resolution is the detail an image holds. The term applies to raster digital images, film images, and other types of images. Higher resolution means more image detail [70].

Infrared Scanning is a variant of structured light scanning in which infrared light is used to prevent interference with other computer vision tasks for which the projected pattern would be confusing (e.g. texture acquisition) [22].

Laser Scanning (3D laser scanning) describes the three-dimensional measurement of the surface of an object through the analysis of the reflected light from a laser beam which is scanned over the object surface [36].

Light field 3D imaging: Light field imaging is a technique that simultaneously record the position and direction of light rays in a single shot. The recording of light field data allows the estimation of scene depth through two techniques: disparity and blur. Disparity and blur are regarded as two dimensions of performance on the scene depth variation [10].

Micro-computed tomography (X-ray micro-tomography, micro-CT) is a non-destructive three-dimensional imaging technique based on mapping X-ray attenuation in the scanned object [17]. Micro-CT is a 3D imaging technique utilizing X-rays to see inside an object, slice by slice. Micro-CT, also called microtomography or micro computed tomography, is similar to hospital CT or “CAT” scan imaging but on a small scale with greatly increased resolution.

Normal mapping (Dot3 bump mapping) is a technique used for faking the lighting of bumps and dents – an implementation of bump mapping. It is used to add details without using more polygons. A common use of this technique is to greatly enhance the appearance and details of a low polygon model by generating a normal map from a high polygon model or height map [75].

Parallax Mapping: Parallax mapping (also called offset mapping or virtual displacement mapping) is an enhancement of the bump mapping or normal mapping techniques applied to textures in 3D

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rendering applications. Parallax mapping is implemented by displacing the texture coordinates at a point on the rendered polygon by a function of the view angle in tangent space (the angle relative to the surface normal) and the value of the height map at that point. At steeper view-angles, the texture coordinates are displaced more, giving the illusion of depth due to parallax effects as the view changes [76].

Photogrammetry encompasses methods of image measurement and interpretation to derive the shape and location of an object from one or more photographs of that object [36].

Pixels per inch (PPI, or ppi) is a measurement of the pixel density (resolution) of an electronic image device, such as a computer monitor or television display, or image digitizing device such as a camera or image scanner. PPI can also describe the resolution, in pixels, of an image file [77].

Point cloud: a point cloud is a set of data points in space. Point clouds are generally produced by 3D scanners, which measure a large number of points on the external surfaces of objects around them [78].

Polygon mesh (mesh): A polygon mesh is a collection of vertices, edges and faces that defines the shape of a polyhedral object in 3D computer graphics and solid modelling. The faces usually consist of triangles (triangle mesh), quadrilaterals, or other simple convex polygons, since this simplifies rendering, but may also be composed of more general concave polygons, or polygons with holes [79].

Quality assurance (QA) is a way of preventing mistakes and defects in manufactured products and avoiding problems when delivering solutions or services to customers. ISO 9000 defines as "part of quality management focused on providing confidence that quality requirements will be fulfilled"[80].

Quality control (QC) is a process by which entities review the quality of all factors involved in production. ISO 9000 defines quality control as "A part of quality management focused on fulfilling quality requirements"[81].

Radiometric resolution determines how finely a system can represent or distinguish differences of intensity and is usually expressed as a number of levels or a number of bits, for example 8 bits or 256 levels that is typical of computer image files. The higher the radiometric resolution, the better subtle differences of intensity or reflectivity can be represented, at least in theory. In practice, the effective radiometric resolution is typically limited by the noise level, rather than by the number of bits of representation [71].

Retopology: Retopology is the act of recreating an existing surface with more optimal geometry. A common use-case is creating a clean, quad-based mesh for animation, but it's also used for final objects that need to be textured, animated, or otherwise manipulated in a way that sculpted meshes are not conducive to [11].

Scale refers to apparatuses or systems used for measuring: the graduated marks on a line or rule used to measure distances and ascertain relative dimensions; the equally divided grid-lines on the surface of a map, chart or plan that enable ratios of area and distance to be established; the ratio pertaining between a model and the reality it represents or projects [20].

Spatial Resolution The measure of how closely lines can be resolved in an image. Spatial resolution depends on properties of the system creating the image, not just the pixel resolution in pixels per inch (PPI). For practical purposes, the clarity of the image is decided by its spatial resolution, not the number of pixels in an image. In effect, spatial resolution refers to the number of independent pixel values per unit length [72].

Spectral Resolution is the ability to resolve spectral features and bands into their separate components. Colour images distinguish light of different spectra. Multispectral images can resolve even finer differences of spectrum or wavelength by measuring and storing more than the traditional three of common RGB colour images [73].

Structured Light Scanning encompasses the methods of stationary fringe projection based on a fixed grid of fringes generated by a projector and observed by one camera. The grid has a periodical structure, normally with a square or sine-wave intensity distribution with constant wavelength. LCD fringe projectors are used for the projection of line patterns and subsequent surface measurement by structured light methods [36].

Temporal resolution refers to the precision of a measurement with respect to time. Movie cameras and high-speed cameras can resolve events at different points in time. The time resolution used for movies is usually 24 to 48 frames per second (frames/s), whereas high-speed cameras may resolve 50 to 300 frames/s, or even more. Many cameras and displays offset the colour components relative to each other or mix up temporal with spatial resolution [74].

Texture map: is an image applied (mapped) to the surface of a shape or polygon. This may be a bitmap image or a procedural texture. They may be stored in common image file formats, referenced by 3d model formats or material definitions, and assembled into resource bundles [82].

Texture Mapping: is a method for defining high frequency detail, surface texture, or colour information on a computer-generated graphic or 3D model. Its application to 3D graphics was pioneered by Edwin Catmull in 1974 [82].

Three-Dimensional Model (3D Model): Three-dimensional (3D) models represent a physical body using a collection of points in 3D space, connected by various geometric entities such as triangles, lines, curved surfaces, etc. Being a collection of data (points and other information), 3D models can be created by hand, algorithmically (procedural modelling), or scanned. Their surfaces may be further defined with texture mapping [83].

Two Dimensional Key Views (2D+): a technique for imaging specimens which relies in the presentation of a base two-dimensional image and additional images from viewpoints that match anatomical plane perspectives or predefined view angles [38].

UV mapping: UV mapping is the 3D modelling process of projecting a 2D image to a 3D model's surface for texture mapping. The letters "U" and "V" denote the axes of the 2D texture because "X", "Y" and "Z" are already used to denote the axes of the 3D object in model space. The UV mapping process at its simplest requires three steps: unwrapping the mesh, creating the texture, and applying the texture [84].

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UV unwrapping: UV unwrapping is the generation of UV coordinates (also known as texture coordinates for the vertices in a 3D model [84].

Wireframe (wire-frame model) A wireframe model is a visual presentation of a 3-dimensional (3D), or physical object used in 3D computer graphics. It is created by specifying each edge of the physical object where two mathematically continuous smooth surfaces meet, or by connecting an object's constituent vertices using straight lines or curves [86].

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