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Scan4Reco

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Deliverable

D2.1. Technology Exploration Report

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Authors List

Leading Author (Editor)			
Surname	Initials	Beneficiary Name	Contact email
Krukowski	A K	RFSAT	Artur.Krukowski@rfsat.com

Co-authors (in alphabetic order)				
#	Surname	Initials	Beneficiary Name	Contact email
1	Vogiatzaki	E V	RFSAT	Emmanouela@rfsat.com
2	Dalezios	N D	RFSAT	dalezios@rfsat.com
3	Krukowski	P K	RFSAT	pavlos@rfsat.com
4	Dimitriou	N D	CERTH	nikdim@iti.gr
5	Gobbetti	E G	CRS4	Enrico.Gobbetti@crs4.it
6	Pintus	R P	CRS4	Ruggero.Pintus@crs4.it
7	Ciortan	I C	UNIVR	Irina.Ciortan@univr.it
8	Giachetti	A G	UNIVR	Andrea.Giachetti@univr.it
9	Daffara	C D	UNIVR	Claudia.daffara@univr.it
10	Marchioro	G M	UNIVR	Giacomo.marchioro@univr.it
11	Salonikios	V S	OF-ADC	vsalonik@auth.gr
12	Apostolidis	G A	OF-ADC	giorgos.apostolidis@hotmail.com
13	Karagiannis	G K	OF-ADC	g.karagiannis@artdiagnosis.gr
14	Galeotti	M G	OPIFICIO (OPD)	monica.galeotti@beniculturali.it
15	Markus	G M	AVASHA	m.george@avasha.com
16	Urban	P U	Fraunhofer	philipp.urban@igd.fraunhofer.de
17	Barchewitz	D B	BWTek	danielb@bwtek.com

Reviewers List

List of Reviewers (in alphabetic order)				
#	Surname	Initials	Beneficiary Name	Contact email
1	Gobbetti	E G	CRS4	gobbetti@crs4.it
2	Giachetti	A G	UNIVR	andrea.giachetti@univr.it

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Executive Summary

This document reports on the technology inspection carried out in Task 2.2, aimed to provide continuous awareness of the continuously evolving the state-of-the-art in the fields related to activities within the project. Each of the participating technology partners has performed a detailed state of the art analysis of the scientific areas he/she is involved within the framework of the project and thus allowing for the analysis of pathways towards innovation and beyond state-of-the-art success.

The range of technologies investigated in this deliverable has been identified based on the user needs and expectations expressed and summarised in deliverable D1.2 "*Scientific end-user and public requirements*". As a result, deliverable D2.1 includes the investigation and technical evaluation of various relevant hardware (HW) and software (SW) in each technical area relevant to the subsequent design of the overall Scan4Reco system. Results of those experimentation will allow for the selection of the most applicable 3D scanning sensors, modelling and reconstruction algorithms and SW, for the development of the realistic overall system architecture in task T2.3 and the definition of necessary interfaces among sub-systems and modules, both HW and SW ones, in respective task T2.1.

Finally, results of D2.1 will allow also for the data fusion of requirements of the modules to be utilized and be selected in task T2.1, preparing grounds for overall integration in follow up tasks T5.1 and T6.3.

The structure of the deliverable D2.1 is as follows:

Section 2: provides an overview of multi-sensory and multi-spectral scanning technologies, focussing on technologies allowing for determining the internal structure of the object and the composition of the materials used.

Section 3: describes technologies for high resolution surface microprofilometry.

Section 4: discusses methods for acquisition and extraction of object feature with reflectance transformation imaging.

Section 5: follows with an overview of existing techniques for 3D scanning and modelling of the object surfaces with the highest accuracy, including also cost-performance compromise.

Section 6: describes current commercial approaches to the design of mechatronic systems, aimed specifically for sensor probe positioning and scanning using "mechanical arms".

Section 7: outlines approaches used for artificial ageing for paintings and metals used in CH objects

Section 8: talks about spatiotemporal simulation and reconstruction in the context of performing simulated ageing, detection of degradations towards user-friendly object presentation.

Section 9: outlines current 3D printing technologies and discusses future trends to achieving the most realistic reproductions of CH objects.

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1. Introduction

1.1 Purpose of the Deliverable

The purpose of this deliverable is to report on the activities in Task 2.2 where an up-to-date analysis of the State of the Art and investigation of technologies and products available on the market, which may be of use and relevant to the focus of the project. has been performed. The aim is to avoid repetitions, performing similar research and/or developing same or similar technologies that are already (or close to be) commercially available. Despite the deliverable D2.1 being submitted on M12, the process shall continue throughout the project and results will be directly introduced into research and development of sub-systems contributed by each partner. Therefore, each section starts with the definition of the State of the Art, following with the evaluation of most promising existing solutions. Subject to identification of any shortcomings in those, the areas for advanced applied research are determined that would be pursued in the frame of the SCAN4RECO project. Each research and development partner has been expected to contribute to this deliverable with respect to the areas of its competence and expertise. Furthermore, deliverable D2.1 shall provide supporting information to Task T2.3 for the definition of the system requirements and finalisation of the architecture specification. It will also support Task 5.1 in combining 2D and 3D information into 3D models, as well as Task 6.3 in overall system integration.

1.2 Relation with other WPs and deliverables

This deliverable D2.1 is a direct outcome of task T2.2 on "*Technology Exploration and S/W fusion requirements*", whereby the scope of investigations and the range of technologies considered therein originates from task T2.4 and specifically from deliverables D2.3 related to "*User Needs and Requirements*" as well as D2.4 reporting on *System Specification*s. It has dependencies with the other tasks in the WP2 either done or ongoing. The main scope of D2.1 is to review the State of the Art in all areas related to the project, evaluate the relevant technologies thus leading to the selection of most promising ones as well as directions for further research wherever any features or capabilities are missing. Figure 1 illustrates more elaborately the dependencies between the current task/deliverable and its related deliverables/task/WPs.

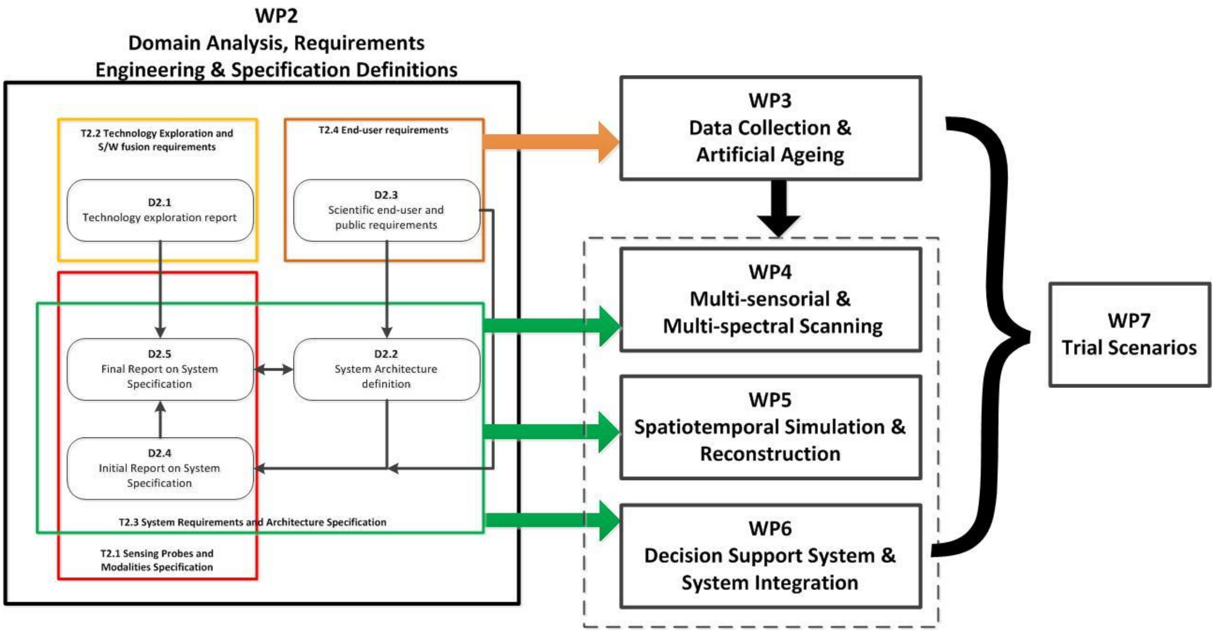

Figure 1: Relations among WPs, tasks and deliverables in Scan4Reco project (WP2-centric).

2. Multi-Sensory and Multi-Spectral Scanning Technologies

The scientific field of conservation and analysis of Cultural Heritage objects consists of a wide array of methods and techniques offering complementary information. The use of spectroscopic scanning is particularly important for the determination of material properties, while ultrasonic microscopy is utilized to obtain structural information of the art object. Combing these methods with imaging produces an information-wise rich map, where every pixel contains various spectra, image and stratigraphy information. The existing scientific literature is rich with examples of multi-sensorial investigations of art objects [138][[142].

2.1 State of the Art

2.1.1 Spectroscopies

Spectroscopy and spectrometry refer to a class of methods comprising of quantitative observation of the interaction of electromagnetic radiation and matter. These methods are distinguished by the spectral range in which they operate as well as the principal under which they operate. In this context, the list of types of spectroscopy, classified with regard to the spectral range, are shown in Table 1.

Table 1: Examples of UV-Vis spectrophotometers available in the market

	Frequency	***Wavelength***
Far Infrared	*0.3THz to 20THz*	*15μm to 1000 μm*
Long wavelength Infrared	*20THz to 37THz*	*8μm to 15 μm*
Mid-wavelength Infrared	*37THz to 100THz*	*3μm to 8 μm*
Short *wavelength* Infrared	*100THz to 214THz*	*1.4μm to 3 μm*
Near *Infrared*	*214THz to 400THz*	*0.75μm to 1.4μm*
Ultraviolet – Visible Spectroscopy	-	*10nm to 700nm*
X-ray Spectroscopy	-	*0.01nm to 10nm*

Every spectroscopic method quantifies the interaction of matter and incident radiation by measuring the intensity of the reflected or transmitted radiation as a function of wavelength, frequency or wavenumber. Different characteristics of matter affect the reflected or transmitted response in different spectral regions and in turn these are manifestation of different physical phenomena. Other technologies are based on nonlinear phenomena such as **Raman Spectroscopies** and **Laser-induced breakdown Spectroscopy**. This implies that better understanding of an art object's material synthesis can come from its examination under different spectroscopic methods. Some of the most widely used spectroscopic methods are described next.

2.1.2 UV-VIS Spectroscopy

UV-Vis Spectroscopy is a dispersive spectroscopic method for the measurement of absorption or reflectance spectra in the ultra violet-visible region. The sample under investigation is illuminated with use of fiber optics by a light source in the UV-Vis spectral range; the resulting partially absorbed light beam is dispersed to the corresponding set of wavelengths by a reflection grating and then collected from a charge coupled device (CCD) or a photodiode. Depending on the diffraction grating and the detector used, the UV-Vis spectrophotometers can be divided into two categories. In the case of single photodiode detector, the diffraction device is a scanning monochromator, which moves the diffraction grating so that only a single wavelength reaches the detector at one time. In the case of a

CCD or photodiode array detector, fixed gratings are used light of different wavelengths is collected on different pixels of the detector simultaneously. The resulting absorption or reflectance spectra have a direct relation to the perceived colour of the sample.

Spectrophotometers are further classified into three types: Single Beam, Double beam and Split beam. Their difference lies into the way they perform corrections for the loss of light intensity as the beam passes through the sample. In every case, the resulting measurement is compared to a reference measurement, which is the base for every measurement, to produce a reflectance or absorbance spectrum. Single beam spectrophotometers use only one light path and as a result require frequent manual calibration with a reference sample. In comparison, double beam spectrophotometers use two beams, thus two light paths, and perform the required calibration automatically. Split beam spectrophotometers are a variation of the double beam spectrophotometers, where a single beam is rapidly alternated between the sample light path and reference light path. Double beam spectrophotometers operate faster and provide better reproducibility. As with all spectrometers employing a CCD detector, detector cooling is of great importance as it directly affects the detector's sensitivity. Available choices can be Peltier thermoelectric cooling and even liquid nitrogen cooling among others. Examples of some UV-Vis spectrometers available in the market are compared in Table 2.

Table 2: Examples of UV-Vis spectrophotometers available in the market

	Spectral Range	Spectral Resolution	Type
Avantes AvaSpec-HS1024x58/122Tec	200-1160nm	1.2-20nm	Single Beam
Perkin Elmer LAMDA 1050	175-3300 nm	<=0.05 nm (UV-Vis) <=0.20 nm (nIR)	Double Beam
Shimadzu UV-1800	190-1100 nm	1nm	Double Beam
ThermoFisher Evolution 201/220	190 -1100nm	0.8nm	Double Beam
BWTek i-Spec	900-1700nm 1100-2200nm	3nm	Single Beam

2.1.3 Fourier Transform Infrared Spectroscopy

Fourier-transform infrared (FT-IR) spectroscopy is a useful tool for identifying a variety of inorganic and organic compounds, based on their selective absorption of radiation in the mid-infrared region of electromagnetic spectrum. The characteristic band parameters measured in FTIR spectroscopy are frequency (energy), intensity (polar character), band shape (environment of bonds) and the polarization of various modes, that is, transition-moment directions in the molecular framework. Because the vibrational energy levels are distinctive for each molecule (and its isomers), the IR spectrum has often been called the *fingerprint* of a molecule, in the sense that it registers the most specific information concerning the molecule. FTIR spectroscopy is a rapid and sensitive method with instrumentation that allows for numerous sampling techniques. A variety of digital signal processing techniques may be applied for the evaluation and quantification of spectral features. FTIR can be used in all applications where a dispersive spectrometer was used in the past. In addition, the improved sensitivity and speed have opened up new areas of application.

Although IR spectroscopy has long been a workhorse technique in analytical laboratories, many improvements, regarding new sources improved computing, detectors and optics, have been made in the past years. As a result, commercially available FT-IR spectrometers can offer spectral ranges covering from the far Infrared (25,000cm^{-1}) to the Visible spectrum (80 cm^{-1}), spectral resolution of down to 0.001 cm^{-1} and scan rates that can exceed 50 spectra a second. Furthermore, *in situ* measurements are possible as there is a number of portable FT-IR spectrometers available in the market. There is also the option of FT-IR imaging and single point spectroscopy in FT-IR microscopes, with spatial resolution of down to 1.1 μm. Examples of commercially available FT-IR spectrometers are compared in Table 3.

Table 3: Examples of Fourier Transform Infrared spectrometers available in the market

	Spectral Range	Spectral Resolution	Type
Bruker Alpha	375 - 7,500 cm^{-1}	0.8cm^{-1} to 256 cm^{-1}	Bench Top
Bruker Tensor	370-7500 cm^{-1} 200-5000 cm^{-1}	1 cm^{-1} 0.5 cm^{-1} (option)	Bench Top
ThermoFisher Nicolet iS 5N	3800-11000 cm^{-1}	< 4 cm^{-1}	Bench Top
Agilent 4300 (DTGS Detector)	650-4500 cm^{-1}	4–16 cm^{-1}	Handheld
Agilent Cary 630	350-6300 cm^{-1}	< 2 cm^{-1}	Bench Top
PerkinElmer Frontier	350-8300 cm^{-1}	0.4 cm^{-1} for the 3028 cm^{-1} band in Methane	Bench Top

2.1.4 Inelastic Scattering Spectroscopy (Raman Spectroscopy)

Raman spectroscopy gives important information about a molecule's structure that can be used for the identification of a wide range of organic and inorganic materials. Typically, the sample under investigation is illuminated with a laser beam. The elastic scattered radiation at the wavelength corresponding to the laser line is filtered out, while the radiation corresponding to changes in the induced dipole moment –Raman scattering- is measured to produce a Raman spectrum. The resulting frequency distribution is characteristic of the sample's structure and composition; therefore, is unique to this particular material. Raman spectroscopy allows for the examination of a sample of any size or shape without modification and with use of fibre optics there is remote sampling capability.

Raman spectrometers can be classified into two basic instrument designs: dispersive Raman and Fourier Transform Raman (FT-Raman). The resulting spectral information is essentially the same for both techniques. As a general rule, the major advantage of FT-Raman is its absence of fluorescence interference, which simplifies and hastens the acquisition of a measurement. However, dispersive Raman is more sensitive and offers higher spatial resolution.

Several different variations of Raman spectroscopy have been developed over time with effort focusing on improving sensitivity, spatial resolution or to acquire specific information as Raman Resonance.

- Raman spectroscopy with improved sensitivity:
  - Surface-enhanced Raman spectroscopy (SERS)

    SERS can be used to overcome the sensitivity limitation to the detection of trace amounts of material. Typical signal enhancement with SERS may be in the range of 10^5 to 10^6.
  - Surface enhanced resonance Raman spectroscopy (SERRS)

    Combination of SERS and resonance Raman. Enhancements of the order of 10^{13}.
  - Coherent anti-Stokes Raman spectroscopy (CARS)

    CARS requires generally the use of two pulsed laser sources and the total Raman signal collected from a sample is the incoherent addition of the signal from individual molecules.
- Raman spectroscopy with improved spatial resolution:
  - Surface Plasmon Polariton Raman spectroscopy

    Raman microscopy that probes a dielectric layer located directly below a thin metal film with lateral spatial resolution near the diffraction limit.
  - Tip enhanced Raman Spectroscopy(TERS)

Combines the sensitivity of SERS with high spatial resolution of scanning probe microscopy. 0.5 – 1 µm diffraction limited laser spot

The selection of the excitation laser wavelength of a Raman spectrometer is particularly important in the selection of the appropriate instrument, as Raman excitation efficiency, fluorescence and the sample's heat absorption are directly related to it. The sensitivity of Raman spectroscopy to a chromophore, the part of the molecule that is responsible for its colour, can be significantly enhanced by tuning the excitation Raman laser wavelength to be in coincidence (or near so) to the absorption wavelength maximum of the chromophore in its electronic (visible or UV) spectrum. Although different options are available, the most widely used laser wavelengths are 532nm, 785nm and 1064nm. Table 4 summarizes the performance parameters of these lasers.

Table 4: Performance of Raman system regarding the wavelength of their excitation source

	532nm	785nm	1064nm
Excitation efficiency	high	medium	low
Fluorescence	high	medium	low
Heat absorption	low	medium	high

Another very important part of a Raman spectrometer is its detector. Most of the commercially available Raman spectrometers employ CCD (charge coupled device) detectors. In general, the dark noise of the CCD is reduced by 50% with every 5 degree drop in operating temperature. Most research-grade spectrographs employ vacuum-sealed arrays operating between -50 and -90C for highest sensitivity. Examples of some Raman spectrometers available in the market are compared in Table 5.

Table 5: Examples of Raman spectrometers available in the market

	Excitation Laser (Available Power)	Spectral Range	Spectral Resolution
BWTek i-Raman Plus	532nm (<50mW) 785nm (<300mW)	$175cm^{-1}$-$4000cm^{-1}$ $175cm^{-1}$-$3200cm^{-1}$	~$4cm^{-1}$@614nm ~$3.5cm^{-1}$@912nm
BWTek i-Raman Pro	785nm (<420mW)	$65cm^{-1}$-$3200cm^{-1}$	~$4.5cm^{-1}$@912nm
ThermoFisher DXR 2 SmartRaman	455nm 532nm 633nm 785nm	$50cm^{-1}$-$3500cm^{-1}$ (Full Range Grating) $50cm^{-1}$-$1800cm^{-1}$ (HighResolution Grating)	$5cm^{-1}$ $2cm^{-1}$
Renishaw RA100 Raman Analyser	488nm 514.5nm 632.8nm 785nm	457-830 nm	*Not Available*
Horiba T64000	Multi-laser bench with motorized laser selection	Depending on the gratings	0.15cm-1

2.1.5 Fluorescence Spectroscopy (XRF Spectroscopy)

X-ray fluorescence (XRF) spectrometry involves the detection and measurement of the energy of characteristic x-rays produced by inner-shell ionization. This technique can be used to determine elemental composition. The rays directed at a sample may be absorbed by the material's atoms, giving up their energy to a tightly bound inner-shell electron that escapes from its orbital, leaving a vacancy in the shell and the atom in an unstable (excited) state. To regain atomic stability, an electron from an outer shell drops into the inner shell vacancy, emitting energy at the same time. The atom is then said to be in a stable (ground) state. The energy emitted in the x-ray region by this procedure, describes actually the energy difference between the excited and ground states of an atom. These are referred to as transitions. Each element has a limited number of allowed transitions, referred to as spectral lines or family of x-rays. These result in the generation of transition lines that are observed as peaks on the x-ray spectra. The energies of the electron transitions are characteristic of the elements present and can be detected and recorded as a series of peaks in a spectrum.

XRF spectrometers can be classified into two categories: energy-dispersive (ED) and wavelength-dispersive (WD) spectrometers. Both setups use an X-ray source to excite the sample. In the case of WD XRF spectrometers, the emitted from the sample X-ray beam is diffracted from a crystal or some other diffraction device and detected from an X ray detector in position. Depending on the characteristics of the diffraction device and the relative angle between the sample and the detector, specific emitted wavelengths can be detected, while changing the angle can produce a sequential detection of elements. The WD-XRF spectrometers offer also the capability to use multiple diffraction devices and detector for the simultaneous detection of elements. In the case of ED XRF spectrometers, the entire polychromatic spectrum from the sample is incident upon a detector that is capable of registering the energy of each photon that strikes it. The detector electronics and data system then build the X-ray spectrum as a histogram, with number of counts versus energy. WD XRF spectrometers offer better resolution, up to 5 eV, however they are costly, large and slow for full elemental analysis. In contrast, ED XRF systems offer lower resolution, up to 150eV or less for liquid nitrogen cooled Si (Li) detectors, but can be portable, more affordable and faster than the WD counterpart.

Regarding the integration of an XRF spectrometer to a multi-sensorial platform, the size of the sample area under examination is considered quite important. The use of micro-focusing optics has been employed already in commercial available XRF spectrometers and can offer a sampling area in the size of a spot of 70μm. Indicative examples of commercial ED X-ray fluorescence spectrometers are:

- **ThermoFisher** Nitton XL3t XRF
- **Bruker** Tracer Si
- **Bruker** Titan Si
- **Olympus** Vanta

2.1.6 Laser-induced breakdown spectroscopy

Laser-induced breakdown spectroscopy (LIBS), a rapid elemental analysis technique, which is applicable *in-situ* and is nearly non-destructive, offers a potential alternative for other optical spectroscopic, mass spectrometric, or X-ray techniques used in art conservation and documentation-related applications. Indeed, in recent literature, several examples of the use of LIBS in the analysis of pigments in easel paintings, icons, and wood polychromes have been reported [155], demonstrating the prospects of the technique for becoming a useful analytical tool in art and archaeology. Laser-induced breakdown spectroscopy is a well-known atomic emission spectroscopic technique for elemental analysis of materials, which provides qualitative and, in some cases, quantitative information. The analytical information in a LIBS experiment derives from time and spectrally resolving the radiation emitted from excited atoms and ions produced within a transient micro-plasma, which is formed as a result of focusing an intense nanosecond laser pulse on the surface of the material/object that is analysed. Characteristic peaks in the emission spectrum lead to the determination of the elements contained in the minute amount of material ablated, providing the local elemental composition of the sample. Commercial products of LIBS systems are:

- **Applied PHOTONICS** LIBSCAN Series
- **AVANTES** AvaLIBS

- **BWTek** Handheld LIBS
- **Bruker** EOS500

2.1.7 Ultrasound Systems

Spectroscopic spectra contain information about the chemical composition and physical properties of the objects under in investigation. However, there is not information about other important properties of art objects as the thickness of varnish and paint layers in paintings or the subsurface structure of three-dimensional art objects. Acoustic imaging and microscopy allows for the determination of these stratigraphic properties.

In acoustic microscopy, the thickness of layers or subsurface structures are determined by the returning echoes of a partially reflected at discontinuities sound wave. Higher acoustic frequencies permit detection of thinner layers and finer discontinuities, but sound energy will not penetrate as deep as lower frequencies. Lower acoustic frequencies have a better penetration depth, especially for materials like metals, but are less sensitive to finer details. As a result, the use of acoustic microscopy in art conservation is focused on Ultrasound frequencies (>50MHz) and the resulting method is referred to as Ultrasound microscopy.

The current knowledge and scientific background in the field of medical diagnosis is very important with respect to the goals of the proposed venture. The progress and development of acoustic microscopy systems is briefly shown in references [156]-[162].

The complete structure of an acoustic microscope consists of a pulse-receiver system and a transducer. Past advancements in the field of electronics have pushed the technology of pulse-receiver systems to a very satisfactory state and as a result, improved performance of acoustic microscopes relies mainly on the quality of the transducer.

Manufacturing of high-frequency piezoelectric transducers and acoustic microscopes is presented in [165] and [166], some of which operate at frequencies as high as 200MHz. These can provide axial resolution of approximately 12μm (order of magnitude) and axial resolution of 14μm, for analysing tissues with characteristic sound propagation velocity of 1540m/sec.

In the context of the proposed venture, sound velocities for different materials vary around an average value of 1660m/sec, as tested and verified in laboratory experiments. Reference [165] states that PZT and PVDF materials are showing reduced efficiency at frequencies well above 100MHz. In the same reference, $LiNbO_3$ has been used for manufacturing a high-efficiency focused transducer at 200MHz with a focal length of 4mm. Using $LiNbO_3$ is advantageous due to its mono-crystal nature (hence efficiency problems are avoided because of the material's granules [166]. The image quality acquired by such a transducer (in range of 200MHz) depends on the beam distribution of the wave "transmitted" by the transducer, as well as on the pulse bandwidth.

Commercial products of acoustic microscopes systems are used mostly in medical application; the most indicative ones include:

- **VisualSonics** Vevo Series (resolution 30μm)
- **Atys medical** DERMCUP
- **Toshiba** Applio 500/400/300 Platinum Series
- **Siemens** ACUSON Series
- **Supersonic imagine** Aixplorer

High frequency ultrasonic transducers for prototype system are mainly produced by Olympus [169].

2.1.8 Multispectral Imaging

Multispectral imaging can be used to enrich the available information content for a given art object. Multispectral imaging from the visible spectrum up to near infrared provides surface information as well as information from under-layers. Longer wavelengths of infrared radiation penetrate beneath the surface, while upper layers remain transparent. The degree of penetration is multi-parametric and depends on the thickness of the layers, the type of material and the wavelength of the incident radiation. As a result, safe assumptions about the exact layer from which information originated cannot be made. The image that is produced is cumulative and can only lead to qualitative conclusions. Multispectral imaging requires no contact with the art object. Numerous techniques have already been applied in the field of infrared reflectography and multispectral imaging [163].They can be divided mainly in two different categories:

1. The object is illuminated using an infrared power-source in a specific region-of-interest (ROI) or in its whole, while using an infrared camera with an appropriate detector for the reflection to be acquired (with interference filters). These filters have a bandwidth of 90-100nm.
2. An infrared source is used again but the radiation is guided in a monochromator system which provides radiation with a bandwidth of 5-20nm to the ROI of the artwork. The monochromatic reflected power from the artwork is collected by an appropriate sensor/detector.

Even in the second case, where the object is radiated with monochromatic light, the depth and layer from which information is derived cannot be accurately determined nowadays. The main parameters affecting this result are:

1. The materials existing in the stratigraphy.
2. The wavelength of the radiation used for illuminating the artwork.
3. The proportion of the pigment with the medium that exist in the layers as well as layer thickness
4. And last but most important, the accumulation of radiation from successive layers of the object that are penetrated by radiation.

These parameters constitute a stochastic problem since they are affected by many open technological issues, as well as by artistic issues based on each creator (e.g. proportion of pigment with medium, number of brush-strokes that provided a specific thickness etc.). Only techniques based on tomography could provide a solution to the depth-profile of the area from which infrared radiation is reflected.

The use of Multispectral imaging is common in many fields and areas of research and as a result, providers offer flexibility and custom design options regarding detectors, detector cooling and lenses. Examples of commercially available multispectral cameras are compared in Table 6.

Table 6: Comparison of multispectral cameras

	Spectral Range	Resolution	Available lenses	Frame Rate
FLIR A6250sc SWIR InGaAs	0.9-1.7µm 0.4-1.7µm	640x512	25mm 50mm 100mm	25kHz(64x4)
FLIR A8300sc MWIR	3.0-5.0µm 1.5-5.0µm	1820x720	17mm 25mm 50mm 100mm	60Hz@Full window 165Hz@1/2 window 388Hz@1/4 window
Xenics X-MID-640	3.0-5.0µm 1.0-5.0µm	640x512	*Not available*	25fps(line) 90fps

Fluke TiX1000	7.5-14µm	1024x768 2048x1536 (Super Resolution mode)	*Not available*	30Hz

2.1.9 Raman spectroscopy

Raman spectroscopy is a technique that is commonly used to identify or quantify the presence of chemical species by measuring the non-elastically scattered light. When a monochromatic light beam impinges on a material, most of the light will be either transmitted through or absorbed by the sample. A portion of the light will be scattered. Most of the scattered light has the same frequency of the incoming light beam, and is said to be Rayleigh scattered. A small fraction of the scattered light will have different frequencies, and the differences correspond to the vibrational or rotational modes of the molecule. This inelastic scattering phenomenon was first discovered by the Indian Scientist Sir C.V. Raman in 1928, and is called Raman scattering. Compared to other chemical analysis techniques, Raman scattering has many advantages.

The Raman spectrum contains well defined peaks that form a molecular finger print of the sample, and the peak intensities are proportional to the concentration, therefore Raman spectroscopy is capable of both qualitative and quantitative chemical analysis. Different wavelengths ranging from UV to near Infrared can be used for excitation, which can be tailored for the specific application. Visible and near infrared light can go through water, glass, and other transparent material, enabling noncontact, non-invasive, and non-destructive analysis. Often samples can be studied without any preparation, making it very easy to use. Laser light can be easily focused into a tight spot, giving the technique the desired spatial resolution. Both the excitation and the scattered light can be transmitted by optical fibres, making remote measurement by mean of fibre probes possible. However, due to the very weak effect and technological bottlenecks to observe it, Raman spectroscopy did not become a mainstream analytical technique until the 1990s, when the advent of powerful and compact diode and diode pumped solid state lasers, highly efficient detectors such as CCDs, InGaAs arrays, and high performance laser rejection filters caused a proliferation of compact and easy to use Raman instruments. The Raman renaissance continues today, with surface enhanced Raman spectroscopy (SERS) pushing the detection limit down to single molecule level. Tip enhanced Raman spectroscopy (TERS) achieves nm spatial resolution, nonlinear techniques such as coherent anti-Stokes Raman spectroscopy (CARS) and stimulated Raman spectroscopy (SRS). It allows to obtain chemical specific images at video rate, UV excitation and time gated detection enabling stand-off measurement at a distance, handheld analysers extending the applicability to common use in material inspection, law enforcement, and emergency response.

A disadvantage of Raman spectroscopy is a possible occurrence of fluorescence interference that may rise from the sample itself or contaminants. This may be a particular problem for studying untreated art objects aged in the outdoor environments. Fluorescence is caused by excitation of molecular electronic states, and a common way to avoid it is by using longer excitation wavelengths, such as those in the NIR. However, Raman scattering efficiency is inversely proportional to the 4th power of the excitation wavelength, thus this gain comes with a loss of sensitivity in detectability of certain chemicals.

The use of Raman spectroscopy in cultural heritage applications is well established. The noncontact, non-destructive nature of the technique lends itself naturally to the analysis of art objects and antiquities. Inside laboratories, many pigments and minerals used in artworks can be readily identified with the technique. Coupled with microscopy, the distribution of these species can be mapped in great detail. Outside laboratories, the use of Raman faces the challenge of ambient light interference, which in broad daylight can be orders of magnitude stronger than the Raman signal. Additionally, conventional Raman microscopes are bulky and require a level of operational precision and sophistication unattainable in outdoor conditions.

2.2 Evaluations & Selection of Candidate Technologies

The candidate methods are compared in Table 6, with regard to their resulting information, the availability of portable or handheld instruments and if and what contact to the art object is required. The first criterion that the candidate methods must fulfil is that they must be non-destructive methods. The LIBS method has destructive characteristics and as a result cannot be used for the examination of valuable art objects. An important aspect in selecting the appropriate methods is the kind of information that is acquired. Raman spectroscopy, FTIR and UV-VIS, all produce surface information. However, as it was described in the state of the art part, every spectral range corresponds to different phenomena and hence the information acquired from different spectral regions are complementary.

Table 7: Comparative analysis of spectroscopic methods

Method	Kind of Information that is acquired and explored up to now	NDT Method	Qualitative Results
Raman Spectroscopy	Surface information is mainly acquired.	YES, but contact with the artwork may be required	YES
FTIR Spectroscopy	Surface information is mainly acquired.	YES, but contact with the artwork may be required	YES
XRF spectroscopy	Elemental analysis, no depth profiling information is provided.	YES, but contact with the artwork may be required	YES
LIBS	Elemental analysis.	NO, micro destructs (ablates) to the layers in order to "reach" the under layers	YES
UV-Vis Spectroscopy	Surface information/colour information	YES, but contact may be required	YES

Finally, considerations must be made for the footprint and portability of the candidate instruments. Fortunately, all of the candidate methods allow either for remote measurements or are handheld and can be integrated in a mobile system. We consider that a multisensorial system consisting of a Raman spectrometer, a UV-Vis spectrophotometer, an FTIR spectrometer, a multispectral camera, an XRF spectrometer and an ultrasonic microscope is up to the task.

Surface information as well as information from the under-layers still cannot be justified from which layer the information is received. The final result is the cumulative information from all layers. This technology can play an important role for a first analysis, i.e. the detection of the problematic region on the object. Its cumulative information indicates the region of interest which will be investigated in more detail by the other methods.

Table 8: Comparative analysis of spectroscopic methods (continue)

Method	Quantitative Results	Portable/Handheld
Raman Spectroscopy	NO, under research	portable, use of fibre optics for handheld module
Fourier Transform Infrared Spectroscopy	yes	portable
X-ray fluorescence spectroscopy	under research	handheld
LIBS	yes, under research	handheld
UV-Vis Spectroscopy	yes	No, but use of fibre optics and/or integration sphere allows remote measurement

By this short bibliographic review and under the scope of the proposed project, emerges the need for studying the propagation of higher frequency ultrasounds in multi-layered media of granulated materials, further extending the current level of scientific knowledge. The goal of this investigation shall be the explanation of the effects observed when ultrasound waves are transmitted in stratigraphy layers of artworks.

2.3 Directions for Applied Research

Applied research can be done in the level of specific modifications to the given spectroscopic apparatus. This research regards modifications that aim to *in situ*, faster, safer (non-contact) but not less accurate material investigation. Such approach consists of the incorporation of integrating spheres as probes and the simultaneous applications of multi-modalities. Also, another direction can be the alteration of the common practices about measurement and/or calibration.

Different modifications of the measurement setup will enrich the acquisition result. These modifications refer to different type of object excitation, for instance using additional light than the normal one, or using modulated light, or applying additional heating.

2.4 Conclusions

The need arises for developing an acoustic microscope with special features ought to be specified by the aforementioned study. This device shall extend the current state-of-the-art in artwork diagnostic hardware, and will have the capability to represent the three-dimensional stratigraphy information of artworks. The possibility of phased-arrays is not foreseen, due to the fact that phased-arrays are operating at a much lower frequency range for the time being. These frequencies will not provide the resolution required for analysing artworks in the proposed project.

B&W Tek is a company that specializes in portable spectroscopy solutions. B&W Tek iRaman series portable spectrometers have been used in a wide variety of applications, including study of CHOs. Our handheld Raman analysers are popular choices for raw material inspection and law enforcement applications. Within the Scan4Reco project frame work, we intend to provide a customized Raman spectroscopy solution to meet the unique challenges facing the analysis of CHOs. To achieve maximum applicability, we will overcome the fluorescence interference and sensitivity issue by utilizing two excitation wavelengths. Both modules will be integrated into a single rack mounted enclosure. The 785 nm excitation will provide the sensitivity for most chemical species encountered in CHOs, while the 1064 nm will enable the detection of species that may fluoresce with shorter excitation wavelengths. To overcome the limitation of conventional microscopy systems, each excitation laser will be connected to a fibre optic probe with an integrated video camera, providing the flexibility and ruggedness needed for the demanding outdoor environment, as well as sample visualization and sufficient spatial resolution. There will be no moving parts inside the probes, and acquisition of both video image and Raman spectra will be controlled electronically from the computer. Special consideration will be given to the design of the entire system to account for the presence of ambient light, enabling the operation in broad day light. To prevent possible sample damaged caused by the focused laser beam, power density on the sample will be limited by using relatively large spot size, and the total laser power will be capped to proper values. Laser power will also be adjustable from 0 to 100% by the controlling software. The optic and electric cables connecting the fibre probes with the rack mounted instrument can be made to the right length to accommodate measurements of large CHOs. These unique capabilities of the B&W Tek solution constitute the progress beyond the state of the art of Raman spectroscopy for CH applications, and will provide valuable chemical specific information and make a significant contribution to the Scan4Reco project.

3. High resolution surface microprofilometry

Micro-profilometry, namely the acquisition of the surface at micron or sub-micron scales, is routinely used for materials inspection in the engineering field but it is a recent experimental application in Cultural Heritage. Surface metrology of artworks requires the design of a suitable device for in-situ non-destructive measurement together with reliable tools for effective analysis of non-engineered, i.e. complex and unknown, materials.

3.1 State of the Art (SoA)

Advances in laser technology and increasing demand for optical 3D sensors have led to the development of non-contact profilometry techniques based on different measurement principles, and novel non-destructive applications are now possible thanks to the availability of engineered sensors and specifically designed laboratory prototypes [187]. Optical micro-profilometry is a non-contact technique able to provide the 3D quantitative representation of surfaces in small-scales (from microns to centimetres) at high-resolution (from tens of nanometres to tens of microns). Typical applications are high precision tasks in quality control as the measurement of roughness and the gauging of the 3D topology of machined surfaces [188]. Typical optical probes for micro-profilometry are interferometers, confocal, and triangulation sensors, suitable for laboratory applications [189]. Common-path interferometric techniques as conoscopic holography represent a solution for applications in hostile environments, e.g. outside laboratory conditions, where surface inspection with high precision is still a difficult problem [190].

Surface metrology is regulated by standards and measurements protocols, which are referred to certified targets, but there is a lack of rules when dealing with the capture of a “real” scene. The extension of the surface metrology toolbox for CH applications is not straightforward, due to shape irregularity, composite materials, even polychromy, of artworks. Measurement performance, reliability, and effectiveness of surface data analysis in microprofilometry depend on characteristics of the target object as shape, texture, response of materials to the probes.

Optical microprofilometry for acquisition of artwork surface topography at high-resolution has demonstrated its potential in pilot CH applications, leading to a growing interest towards this advanced tool. Non-contact microprofilometry based on laser-stylus systems has been applied in archaeology to obtain high-resolution 3D survey of artefacts for general features documentation [191], deciphering inscription [192], as a pilot tool for microstructure surface diagnosis in fragile fossil bones and inspections of marks and incisions [193], and for surface texture analysis as the decay monitoring of corrosion in bronze and marble statues [194]. The potential of 3D surface analyses and roughness computation was also demonstrated in the study of the morphological changes induced by laser cleaning treatments in stone samples [195][196], and in a joint use with microscopy analysis [197].

Portable optical microprofilometry using conoscopic holography and scanning techniques has been pioneered by the work of Fontana et al., which performed in situ surface measurements on the Michelangelo’s David statue [198] and roughness computation in selected regions. The scanning technique allows the acquisition of larger area, making microprofilometry a suitable tool for the study of features in paintings, from conservation status to artist technique. The conoscopy holography technique is not affected by colour gradient and was shown capable to measure surfaces with varied reflectance changes such as pictorial layers. This was demonstrated in experimental diagnostics of ancient canvas and panel paintings to support restoration [199]. Laser-microprofilometry was able to map small-scale features in paint layer and support structure, as repainting and retouches, incisions and marks, lacks, craquelure, micro-defects. The technique was applied in joint use with other techniques for a more comprehensive diagnostics, e.g. with thermal imaging for the characterization of defects in surface and sub-surface layers in frescoes [200], e.g. with confocal laser scanning microscopy for the analysis of the varnish layers during the cleaning treatment [201].

The pilot results obtained with surface microprofilometry have well received by the CH community and underscore the potential for further work in the field.

3.2 Evaluations and Selection of Candidate Technologies

Microprofilometry for CH applications is still experimental and very few technologies provide the possibility to analyze in situ large surface areas with high resolution; currently no ready-to-use set-up is available on the market to perform these kind of analyses.

Moreover, surface Metrology for CH is an unexplored field, and the analysis of small-scales 3D features (e.g. roughness) of an artwork, which is unique for manufacture and materials, is a crucial issue due to the lack of standards. Despite the recognized potential of microprofilometry, this advanced technique is not being used within museum laboratories due to the lack of a tailored acquisition and processing platform. Therefore, in the Scan4Reco project a suitable microprofilometry has to be designed and built with the specific requirements of in situ and large-field non-destructive measuring, and capability of acquiring the variegate CH materials.

To advance the state-of-the-art it is planned to implement a versatile and multi-scale optical microprofilometry taking advantage of the adaptability of the conoscopic holography interferometric technique, in order to operate with irregular shape, composite materials (diffusive and reflective) and polychromy of artworks, and of the scanning technique in order to obtain wide-field and high spatially resolved 2D profilometry. The Conoscopy laser holography has been chosen as the technology that best fit the project needs because it allows a contact-less surface measurement over a wide range of material with different reflectance and glossiness, aspects that are often encountered in CH diagnostics. Three different probes manufactured by Optimet [202] have been chosen as the best candidate satisfying the needs of the project. These probe are relatively affordable in price (order 10K euros) and very portable (they weigh approximately 700 gr) and can be coupled to micrometric stages for specific applications. Furthermore, they don't have any optical moving parts and so they can be transported to the location where the artwork must be analysed reducing the risk to damage the device. The scanning stages where the probe have been mounted have been chosen comparing the specifications and the prices of the available high resolution stages, and a PI micrometric stage [203] has been individuated as the candidate technology for precision (sub-micron) motion and positioning.

3.3 Conclusions and Directions for applied research

We design and implement the prototype of a scanning 3D microprofilometer on a basis of a modular scheme using different setups, both conoscopic probes and micrometric scanning stages. This newly developed scanning set-up will allow high resolution measurements on a scale that is usually neglected from the other technologies available in the market. The instrument can analyse area up to 900 cm2 in a single scan and so it can retrieve very precise surface topography maps that can be used for extracting sample features regarding the manufacturing processes (e.g. finishing) or monitoring the shape variation due to natural ageing or degradation (e.g. wood panel warping). The possibility of couple more than one probe to collect simultaneously information over reflective and diffusive material is also another research field that the project could benefit from.

A suitable processing tool for texture analysis and roughness computation, including multi-scale integration and visualization tailored to CH, is going to be implemented in order to advance the state-of-the-art. We will design descriptors for characterization of material morphology and for the extraction of the significant small-scale features for CH applications. A significant indicator of morphological variations in a surface is the roughness, which computation is regulated by standards (e.g. ISO[204]) in Surface Metrology but not discussed in CH. The microprofilometry acquisition and processing platform, will be completely characterized in the performance and validated on CH samples at different scales and micron-resolution; we will start from the application of ISO standards by tailoring to the problem of the documentation of the conservation status, decay monitoring, treatments controlling. Direct performance evaluation protocols of the set-up in different environments are currently under development, to asset the measurement repeatability also when the instrument is working outside the laboratory where environmental vibrations or hostile conditions could affect the analysis.

Finally, the surface profilometry data can be also used as a ground truth by others techniques that measure surface properties, namely the Scan4Reco newly-developed RTI systems [205].

4. Acquisition and Feature Extraction with Reflectance Transformation Imaging

The techniques to study materials used in cultural objects are of extreme importance in order to understand and preserve the Cultural Heritage (CH) assets. Curators, restorers, conservators and conservation scientists routinely use those approaches and exploit information on materials to have the proper insights about the time and way an artwork has been made, the techniques used, the environmental conditions of preservation, the previous conservation interventions, as well as to gather indications for planning future interventions. Materials in CH are studied under many different angles, ranging from the acquisition of basic information, such as surface average colour and roughness, to the analysis of their molecular and elemental components. State-of-the-art study and conservation practices, such as those that will be studied within Scan4Reco, thus combine a wide variety of measurement probes and analytical techniques. Moreover, in order to study dynamic processes, such as the effects of aging, weathering, and restoration treatments, laboratory studies are often done on appropriately prepared samples and mock-ups.

Among the different surface and material characterizations, the study of *surface appearance*, in terms of reflectance and geometric meso- and micro-structure is of particular importance, since the vast majority of the cultural information is conveyed through optical signals from the viewed artwork to the human vision system. Characterizing surface structure and appearance is thus paramount for a variety of CH applications, from the assessment of the visual effects of restoration treatments, to the high-fidelity virtual and physical replication of cultural objects through graphics and fabrication means.

Multi-light reflectance acquisition and processing techniques, such as Polynomial Texture Maps (PTM), Reflectance Transformation Imaging (RTI) and Photometric Stereo (PS) aim to visually characterize objects by observing them from a fixed point of view under different lighting conditions. They are currently emerging as a de-facto standard in appearance and geometry acquisition due to their cost-effectiveness and flexibility. Their range of application goes from qualitative estimation of image formation models, for applications such as visual enhancement or relighting, to the quantitative recovery of shape and material properties. While most of the time RTI and related techniques are applied in the visible spectrum, increased effectiveness is achieved combining them with the analysing visible and invisible optical properties of artworks, such as multispectral imaging (MSI) which is routinely employed to study material composition (mixture of pigments) and under-drawings.

It is far out of the scope of this document to present an extensive survey of RTI, MSI or, not to mention, the broad field of digital modelling of material properties. We thus refer the reader to established surveys in digital material modelling [1], geometry and reflectance acquisition[2][3], and MSI applied to CH [4]. In the following sections, we focus on recent state-of-the-art techniques closely related to the planned use of RTI and MSI for colour and geometry computation and analysis in Scan4Reco. We then discuss which techniques are more promising compared to the purpose and scope of the Scan4Reco project, and the corresponding rationale and direction of the research activity in this field.

4.1 State of the Art (SoA)

Reflectance Transformation Imaging (RTI) [6][7][8] is nowadays a de-facto standard in appearance and geometry acquisition, due to its cost-effectiveness and flexibility. It is fundamentally based on the acquisition of multiple photographs of the same subject under fixed camera position with varying lighting conditions. The information from acquired photographs is used to derive properties of the surface material and geometry. On one hand, light lies at the core of the artistic process, and illumination under multiple light conditions and directions is known to have been used by artists throughout time in order to obtain a more holistic representation when depicting a composition[9]. Correspondingly, in order to decipher an artistic technique or to understand the underlying information about an artefact, multi-light imaging at raking angles [10] provides a fair solution for the documentation, recording and decoding of CH objects [11]. Based on the same rationale, RTI embodies a mathematical framework to transform a high amount of visual information (2D image sets) into 2.5D multi-layer representations [12], which include surface attributes such as gradient, local curvature, normal, and albedo [13]. The data acquired by RTI are processed by mainly using either Polynomial Texture Map (PTM)[7] or Photometric Stereo (PS)[14] techniques. The PTM computes an interpolation function from the captured images, and provides a way to perform implicit re-lighting of an object without explicitly focusing on estimating any geometrical or appearance property. Conversely, PS allows the user to measure fine surface details of paintings and artefacts by recovering accurate surface normal and by computing a material reflectance characterization. Recent studies used RTI in order to increase perception of fine geometrical details that are almost invisible to the naked eye for the visualization of cuneiform tablets and sealing [15], the characterization of coin surfaces [16], and also the enhancement of the perception of petroglyphs [11]. Artal-isbrand and Klausmeyer [17] used RTI to examine the relief and contour lines on a group of ancient Greek red-figure vases and vase fragments, and they are able to answer questions regarding tools, techniques, and production sequences used by Greek vase painters. Some approaches try also to monitor the material weathering or other types of degradation. For instance, Kocour and Valach [27] use the reflectance to examine how the surface becomes more matt over time.

4.1.1 Multispectral RTI

Although both MSI and RTI are widely, but separately, used for CH applications, few works combine them in a unified system. The prospective synergy between RTI and multispectral imaging has been discussed recently by Schroer and Mudge [18], and Castriota and Serotta [19]. Such synergy has a strong potential for further investigation, especially because the information that is given by the two technologies regarding the intrinsic properties of an object is of complementary nature. While RTI exploits the directionality of light and its relation with the reflectance behaviour, MSI focuses on the spectral composition of light so as to retrieve more precise colour attributes [81]. The latter is particularly when colour and its use are distinctive features essential to characterize the DNA of a CH object, such as paintings, frescoes, manuscripts. Nonetheless, there are only fragmented and limited examples of uses of such technologies [20] rather than a deep and focused research on this topic. For instance, Nam and Kim [21] use a six light setup and a multi-spectral imager, and combine PS approach and MSI. They exploiting this captured data to remove surface inter-reflection and to better estimate surface normal. While that work proves the feasibility of a multi-spectral RTI, no extensive and general study and evaluation has been done, neither related to material modelling nor to multi-spectral analysis. In this scenario, multi (or even more hyper) spectral RTI remains an open field, yet in its embryonic stages.

4.1.2 RTI acquisition systems

In this scenario, a wide variety of RTI acquisition setups exist, ranging from low-cost and transportable kits [22], to different sizes of fixed light domes [22][23][24]. Many of them are based on the simple but very efficient four-source photometric stereo model [28][33]. They typically consist in a common DSRL camera and four illuminants [29][35][36]. Ti et al. [32] exploit this simple configuration in a hybrid setup by coupling it to a time-of-flight sensing device. In addition, the four-source setup is typically very suitable for miniaturization, by placing both cameras and LED lights within a customized printed circuit board. This is very useful for fast 3D micro-structure measurement [34]. Depending on the applications the four-light setup is extended with the constraint that it remains a portable and simple acquisition device [30]. Weigl et al. [31] employ a system with two groups of four LED sources with two different baselines. They use the reflectance measurements in a photometric-stereo based industrial application for quality control of the surface of coated composite materials.

Fixed constellation of light sources with more than four illuminants but yet pretty small are also widely used in robotic applications, where the photometric stereo acquisition setup is attached to a mechanical arm [37]. Martins et al. [38] present an integrated system that combines a robotic arm, a high-resolution DSRL, and an illumination rig with high intensity LEDs; they combine multi-view and RTI/photometric stereo like approaches to generates accurate 3D models of biological objects. They show how extracting texture and geometric features from reflectance data can be helpful for quantitative phenotyping in biomedical science field. Taguchi [39] presents a similar setup, but with the lights arranged along a ring; they use appearance profile to extract edges in the scene, and provide a demonstration of their system capabilities on a bin-picking application. Miniaturize ring-like setups are also broadly used not only in cultural heritage, but also in many real-time industrial monitoring; for instance, the analysis of the scene under different light conditions is a powerful process analytical technology (PAT) tool that can improve process understanding and control, mostly in facilitating the production of high-quality pharmaceutical products [40].

Conversely, large domes with a high number of lights are able to extract much more reflectance information, but have the drawback of high cost and both mechanical and time complexity (long acquisitions) [41][42]. This delicate trade-off between quality and feasibility is a crucial aspect in system design. Schwartz et al. [44] provide a very useful analysis and in-depth discussion on three particular implementations they did, and a survey of the existing literature about these acquisition setups. Depending on the application and the type of object under study, it is easy to see how these reflectance data capture devices can reach a very large size (human-like size) [45]. Some methods try to overcome the high recording and processing times, by harnessing the available powerful graphics cards and by providing to users the ability for real-time feedback on the recording process [43]. Other approaches try to keep a large amount of lights but to reduce as much as possible the size of the dome to fit some particular applications and to meet the requirement of a portable system [46]. Although sacrificing the acquisition time, many solutions employ one or a small number of real illuminants, but they use movable parts to provide the RTI/Photometric Stereo algorithm with a high number of light directions [48]. These types of systems are very useful in geometry reconstruction and material modelling [47].

Apart from these RTI/PS setups, there is a group of methods that employ very specific arrangements. In the case of flat objects, a flatbed scanner can be modified to meet the needs of the photometric stereo method [49]. Tominaga et al. [50] use a six-band, two bulb scanner to extract surface properties of art paintings. Similarly, Skala et al. [51] use a common flatbed scanner to provide the four-source images by rotating the sample and aligning the resulting images; then, they extract the geometry and produce 3D printed copy of it. A photometric stereo technique is also employed in a tactile sensor device used for robotic application, the so-called GelSight [52]. Other devices are designed specifically to measure material properties, though they are very complex and they can only perform the task on small mock-ups [53].

Finally, some dome solutions have been recently presented that use both visible and invisible light wavelengths [25][26], in a MSI system.

4.1.3 Light calibration

Another important aspect of RTI and Photometric Stereo is the nature of the light sources and the computation of their positions. While some techniques exist for recovering shape and material information under unknown environmental illumination conditions [54][55], the most widespread approach used in many application fields, including Cultural Heritage (CH) investigation [11], medical interventions [56][57], and underwater data gathering [58], considers a single calibrated camera taking multiple images of a scene illuminated by a single moving light, whose position is known. Classic methods, however, assume for simplicity either a collimated and uniform light source (e.g., far point light), which means that the light direction and its intensity are the same across the entire image domain, or a local point light, which means that the only variation of illumination is due to the inverse-square distance falloff [59][60]. These assumptions do not hold for common off-the-shelf illuminators, such as LED lights, which, in addition to being placed arbitrarily close to the objects, present a variable angular radiation pattern [61]. Such simplifying conditions induce considerable errors in the estimation of shape and material properties. For this reason, the calibration of spatially-varying light direction and intensity has attracted the attention of many researchers in the last decades. Some approaches try to calibrate light direction and intensity by interpolation means in the 2D image domain [62]. Ciortan et al. [63] estimate light directions in a small set of image locations by using reflective spheres (highlight pixels). They find a per pixel light direction across the entire image by linear interpolating the sampled values of x and y light direction components, and imposing unit module. They include a white planar target of known normal and albedo in the framed scene behind the captured object, and exploit the interpolated light direction information to first remove the Lambertian effect from measured radiance of white planar pixels, and then to compute light intensity for that region. Finally, they apply a quadratic interpolation to find light intensity values for the remaining part of the image domain. Their image-based computation does not take into account the different depths of highlight points compared to the plane, and, although they do not impose a constraint on a light model, nonetheless they both force the light direction to follow a linear polynomial, and they make the assumption that the light intensity on the plane behaves as a quadratic function. Moreover, they do not explicitly take into account the fall-off due to the inverse of squared distance, by implicitly including it into the quadratic coefficients. Similarly, other methods [64][65] use a flat reference object with known albedo to calibrate an arbitrary lighting vector field. They don’t use polynomial interpolation, but they exploit measured spatially varying intensities to compensate the input images, and to convert the problem into a standard collimated case. Unfortunately, since these calibrations avoid to adopt a light model defined in the whole 3D space, they completely neglect direction and intensity variations in the z-axis. Hence, they are not generally applicable, being valid only in the vicinity of the calibration plane.

Considering the light form factor and a model of its behaviour in the 3D space for PS analysis is a very old and well known topic; for instance, the seminal approach by Ikeuchi and Horn [66] models the image formation process given a linear light source and a specular object. More recently, Mecca et al. [67] proposed a mathematical formulation based on quasi-linear Partial Differential Equations, which solves a perspective, near field photometric stereo given point light sources. Beside directional lighting, Quéau and Durou [68] show how to derive lighting models for several real-world scenarios, such as isotropic, near punctual model, extended light sources, and LCD-screen based illuminants. Although these works pose the mathematical bases for dealing with more general lighting conditions, however, the inverse calibration problem remains challenging, i.e., computing lighting model parameters from a given set of intensity measurements.

4.1.4 Semantic features from RTI data

In order to go from the RTI image stack to a parametric representation of surface attributes, the appearance profile should be processed. There are various models for fitting the reflectance distribution data obtained with RTI acquisition, e.g., the polynomial based interpolation (such as the seminal work of Malzbender et al. [7]). As explained in Drew et al. [71], polynomial approximation improves Lambertian Photometric Stereo (PS) by solving a higher order polynomial and, coupled with a dedicated reflectance model, allows for more realistic reproduction of the material's radiance. The bi-quadratic function in typical polynomial approximations can be solved with linear regression by minimizing the least-squares error or obtaining more robust results by trimming the outliers with least median squares method (LS) [72][71] [73]. The regression outputs a set of 6 coefficients for each pixel in the image dataset, which can be treated as six spatial maps with the same spatial resolution as the original images, but with a reduced resolution in the angular space due to the n image-to-6 approximation [13].

Once the parameters have been fitted, the main aim is to find the proper space of descriptors to classify materials. Previous attempts have been made in the direction of material classification based on the fitted coefficients, e.g. HSH [75], PTM [62] and PS coefficients coefficients. In cited papers, point-wise reflectance parameters are used to characterize the materials and segment different regions of a planar surface by means of clustering algorithms. This approach has clear limits due to the difficulty in light calibration, the dependency of the reflectance on local geometry, and other complex factors.

4.2 Evaluations and Selection of Candidate Technologies

The Scan4Reco project demands for two different setups for RTI data capture. One system is devoted to sample/mock-up acquisition and characterization, while the other is involved in on-site scanning campaign. The designs of both must also meet the requirements of usability, limited cost and quality of the measurements. Moreover, we need to understand the best technological path for system calibration and RTI data processing.

4.2.1 RTI acquisition systems for off-site appearance characterization

Supporting in-depth study and capture of materials in the laboratory requires a very flexible system. In order to capture the appearance of samples/mock-ups, we need a high number of sampling light directions to be sure to capture enough data. In this context, fixed domes have high cost and a number of limitations in terms of number of multi-spectral lights, positions and general versatility w.r.t. possible configurations. Conversely, the same result can be achieved by adopting a moving light strategy, which can be very useful when the need of low-cost equipment and flexibility is mandatory. Moving lights are easily customized, and one can add the desired number of lights (light positions and wavelengths) without substantially increasing the overall cost. The price to pay is in terms of acquisition time; the positioning of the light in a free-form solution is a slow process. A free-form acquisition also requires a per-image light calibration, which is non-trivial and requires research advances. However, a high acquisition time for our laboratory environment is a negligible drawback compared to the high versatility of the system. Moreover, it proved to be a low-cost solution that responds well to the project end-user requirements, since it can easily capture a wide variety of materials, and the results are suitable for quantitative characterization. Thus, the moving light solution is considered as the best candidate technology appropriate for the acquisition and the analysis of the materials involved in the project, from metallic materials to those employed for painting creation. In this scenario, the capture setup will be capable of providing a multi-spectral RTI acquisition setup that will be both cost effective and simple to implement, and can be highly configurable. Although it will be tailored to the project need of performing multi-spectral reflectance measurements of flat material samples/mock-ups or, possibly, very small flat objects, nevertheless it will be able to deal with a wide range of different appearance behaviours, i.e., from pure Lambertian to specular. Compared to the more qualitative state-of-the-art common approaches, it will be designed in order to provide data suitable for calibration for more quantitative and repeatable measurements.

4.2.2 RTI acquisition systems for on-site measurement

The on-site measurement system of Scan4Reco has a different scope that the on-site one. Its purpose will be to extract meaningful information for further processing from small flat patches of the object under study. Such information can be used, e.g., for feature extraction (edges, cracks, …), local measurement of surface properties (e.g., roughness), and/or segmentation/classification. For this reason, the RTI acquisition system for on-site data gathering must be mounted on a mechanical positioning device. The best approach in this context is thus a fixed light source constellation, conceptually similar to those mounted on robotic arms [38][39][40]. Similarly, to the laboratory version, the best candidate technology consists in a multi-spectral camera and a series of light sources. In this approach, the light will change in position and in emitting frequency. Conversely, the structure of the lights and the acquisition baseline will be fixed. The literature shows how this is the most broadly used solution, which has to be adapted for the Scan4Reco project needs.

4.2.3 Light calibration

The choice of low cost and versatile capture systems results in the need of a more accurate calibration of light sources, which ensures repeatable measurements for material surface characterization, and provides a more quantitative reflectance estimation with a proper level of precision and accuracy. While for fixed domes, laboratory pre-calibration techniques do exist (with, however, limits related to repeatability), achieving good calibration online and/or with free-form solutions is an open problem. The most promising state-of-the-art approaches in this direction are those that allow the user to have a complete calibration of light directions and intensity (up to a per-pixel intensity estimation). The recent literature contains two very interesting approaches that are worth mentioning, and they put the base for further investigation during the project.

Huang et al. [69] propose an alternating minimization formulation for computing near-light positions and surface normal. Their model takes into account several non-idealities, such as fall-off due to the squared distance and camera vignette. Although they are capable to calibrate the system without knowing the light positions in advance, however, they impose a point light model, which limits the method applicability. A similar model has been presented by Xie et al. [70], which propose a LED-based photometric stereo system. They calibrate a seven LED lamp setup through the estimation of lighting positions and principal axis. They use a LED lighting model and a diffuse sphere of known shape as a calibration target; the sphere exhibits also a small specular signal. Unfortunately, they rely on a fixed light rig (not free-form), and on the fact that the optical axis of the LED is collinear to the incident light direction at a specular point on the sphere, which is not always the case, e.g., it is very rarely met in a free-form acquisition. Moreover, their approach depends on a fixed LED light, whose parameters are known a-priori.

4.2.4 Semantic features from RTI data

The pipeline that leads from the raw RTI data to meaningful material descriptors consists in two steps, i.e., the processing of RTI image stack to obtain its parametric representation, and the extraction of descriptors from these parameters. For the first step, robust statistics methods are the selected candidate technology. One of the most robust methods for fitting the reflectance data is the trimmed least-square [73]. It is based on a simple and fast outlier diagnostic strategy and proves to be efficient even in the case of a considerable amount of black noise and highlights caused by materials with very low diffuse albedo or a high shininess. Moreover, a similar strategy is very powerful and can be applied as well on other fitting functions like Hemispherical Harmonics (HSH) or higher order polynomials [74][72]. Other more precise solutions exist in the robust estimation literature, but incur in considerable costs when applied to large datasets such as those of this project. Evaluating speed-ups for these techniques, in particular exploiting similarity among measurements in different areas of the image, seems a promising solution.

For descriptor extraction, we intend to leverage the improved light calibration to harness the power of available techniques for material classification from PTM or PS coefficients [75][62], and to overcome their current limits, and to overcome their current limits. Then, a thorough analysis of common, robust classification techniques [76] will be perform to see which one fits best the Scan4Reco project requirements.

4.3 Directions for applied research

From the analysis of the recent state-of-the-art approaches, we have seen how RTI-based methodologies are a well-known and well established practice in Cultural Heritage applications. Consolidated guidelines for RTI acquisition have been proposed in the literature [77], and several different solutions exist, ranging from fixed or portable multi light domes, or hand-held light setups [22]. On this basis, the direction of research during the Scan4Reco project will lead towards the study of two reliable and efficient combinations of MSI and RTI technologies. The effort will be put in enhancing their measurement outcomes and in defining new and improved methodological approaches for examination of surface patches. We also focus the attention on their characterization, recording and documentation. We will investigate novel acquisition and automatic processing procedures towards the solution of the issues on unevenness in illumination, which reduce the reliability of current free-form solutions. Apart from geometry and appearance reconstruction from RTI data, in the field of sematic feature extraction we will study sophisticated pattern recognition frameworks, where classifiers acting on different features can be combined in various ways to derive semantic annotations [78][79][80]. Different methods will be investigated for the extraction of statistical features related to surface attributes from RTI image stacks, e.g., normal and albedo. All this research will be undertaken with an eye on the usability of these techniques for a large variety of applications, not only those involved in the Scan4Reco project.

4.4 Conclusions

The large body of research, together with promising preliminary results, encourage the use of RTI as an appropriate imaging technique for meeting important needs of cultural heritage objects, out of which: documentation, recording, archiving and characterization. Even though the research done so far is relatively extensive and validates RTI as a good direction for exploration, it is not at-all exhaustive, as there is room for many improvements and innovation on the following levels: acquisition setup, equipment kit, pre-processing and post-processing protocols and fusion with other technologies (MSI). Furthermore, the complex tasks of material characterization and spatiotemporal simulation that Scan4Reco envisages to solve still require a huge amount of acquisitions, measurements and experiments to be carried out.

5. Holistic 3D shape scanning

5.1 State of the Art

Over recent years, 3D scanning has become part of a coherent and non-contact approach to the documentation of cultural heritage and its long term preservation. High-resolution 3D recordings of sites, monuments and artefacts allow us to monitor, study, disseminate and understand our shared cultural history – it is essential that the vast archives of 3D and colour data are securely archived. An integral component of this work is to record surfaces and forms at the highest possible resolutions and archive them in raw formats, so the data can continue to be re-processed as technology advances. In some cases, the data will need to be re-materialised as a physical object - and this is where a great deal of misunderstanding exists.

Digital models are used to be associated with virtual environments, but now the ability to re-materialise data as physical 3D objects is demanding new explorations into the types of information the data contains. The levels of damage and destruction of heritage sites caused by mass tourism, wars, iconoclastic acts, the ravages of time, commercial imperatives, imperfect restoration and natural disasters has led to a re-evaluation of the importance of high resolution facsimiles. Exact representations are being made possible through advances in 3D recording, composite photography, an assortment of multi-spectral imaging techniques, image processing and output technologies.

A number of different 3D scanning methods exist, each with their own advantages and limitations. The challenge is to identify the right system for the right application. No one system can do everything. The diverse methods of capturing 3D data evidences this. Time of flight, triangulation, photogrammetry and a host of different approaches are redefining the relationship between image and form. The 3D data can be on a vast scale, recording the topography of a landscape from great distances or it can be close range and accurate enough to document the surface of a carving; marks that are not easily visible to the human eye can be visualized for reconstruction study or condition monitoring. While some systems can obtain colour data as well as 3D information, currently no 3D scanner is able to record colour to the standard required for the production of an exact replica. All 3D recording is based on metrology; the science of making measurements. Outlined below are the main techniques and scanners that are commonly used and the reasons they are used in the way they are.[1]

The project needs are twofold, from one side a correct representation of object shape (geometry), from the other one dealing correctly with difficult materials to capture their correct colour and appearance. The focus of this chapter is capturing the global shape, whereby some of the presented commercial technologies show potential for correct representation of object appearance as well.

5.1.1 Long-Medium Range 3D Scanners (LiDAR)

The Long-Medium Range 3D Scanners are used to record the general shape of large objects and surfaces with the aim of getting accurate metrological information. It is commonly used for topography and the recording of buildings. Such scanners cannot be used for recording the subtle detail of surfaces that is required to make an accurate facsimile or for epigraphic study due to their limited precision in capturing smaller details. Long-medium range scanners use time-of-flight or laser-pulse based systems where a laser light is bounced off the target at a distance. A laser range finder calculates the distance to a surface by timing the round trip of a pulse of light using the known value for the speed of light. In cultural heritage documentation, long-medium range scanners are normally used in combination with close-range 3D scanners to generate models with both global metrological accuracy and high resolution surface detail.

5.1.2 Close Range 3D Scanners

Close Range 3D Scanners (more than 8cm and less than 1m working distance) are used to record the shape and surface of objects in great detail. Close recording distance is usually associated with higher resolution. They can be used for scanning the surface of paintings and reliefs, recording shape and surface of sculptures and complex forms or for determining a decay on the surface of the sculptures. The output can be both for study using screen-based applications or to be re-materialised for a range of purposes including tactile objects for the blind and partially sighted, facsimile production and exhibition display. They cannot be used for recording large structures for screen viewing. Close range scanning is also slower than long-medium range scanning or photogrammetry. Close-range scanners use either laser or a structured light system. Triangulation based 3D laser scanners use a laser light and one or two cameras to record a subject. Through trigonometry, the distance of the object to the scanner can be calculated thus creating a precise map of the surface. Structured light scanners also use triangulation but use projected patterns of light instead of a laser. The camera(s) records the projected patterns and calculates the distance of every point in the field of view. Close-range 3D scan-

[1] Factum Arte: http://www.factum-arte.com/pag/701/3D-Scanning-for-Cultural-Heritage-Conservation

ning in its many variations is essential for recording 'at risk' heritage. To meaningfully document the past, it is essential to be able to document not just the general shape but also the subtle details of object surface.

5.1.3 Photogrammetry or stereoscopic scanning

Photogrammetry or stereoscopic scanning is the technology of making depth measurements from raster photographs. It can be used for quick recording of vulnerable and inaccessible sites. Photogrammetry is also ideal way to obtain 3D information in situations where it is not possible to use 3D scanners (inaccessible locations, conflict zones), or when high-speed recording is required (scanning people, living organisms, liquids in movement). It is ideal for the recording of translucent surfaces like alabaster and marble. Due to the composite nature of the image capture, colour and form can be extracted from the data. Until recently achieving highest resolution recording of surface for facsimile production and featureless, reflective and dark surfaces was not feasible. However, recent software developments (e.g. by Pix4D Mapper[2], Autodesk ReMake[3] and many other ones) it became possible through improvements to photogrammetry technology to become soon the dominant method for recording at risk cultural heritage in 3D and colour. A special version of the photogrammetry is structured light scanning, whereby pre-defined shapes (commonly horizontal and vertical lines) are projected onto the object surface. By analysing the change in line shapes from images captured by the camera, the shape of an object can be determined. However, methods like this do not offer high precision, which is dependent on projector and camera resolution as well as object complexity.

Photogrammetry has been used since the birth of modern photography in fields such as topographical mapping, architecture and archaeology. The data can be recorded with commercially available cameras that capture multiple shots of the entire surface of an object. Close-range photography can result in high-resolution data. Basic processing is required in the field to ensure that no areas have been missed. Post processing is time consuming and hence suitable for applications where accuracy and precision of 3D scans predominates the speed of model creation.

5.2 Examples of 3D photogrammetric scanners used for Cultural Heritage

5.2.1 Witikon Photogrammetric 3D Scanner

Witikon 3D scanner[4] has been developed by EDICO SK plc., technological company active in the area of 2D and 3D digitisation of cultural heritage and industrial companies. It has a track record of 25+ years: founded in 1990 funded by capital from Switzerland.

Figure 2: Witikon photogrammetric 3D scanner

[2] Pix4D Mapper: https://pix4d.com
[3] Autodesk ReMake: https://remake.autodesk.com
[4] Witikon 3D scanner: http://witikon.eu

The system has been used over 10-year period by e.g. Slovak National Museum and 80 other museums in Slovakia, largest gas company in Slovakia SPP, a.s. and largest refinery in Central Europe Slovnaft, a.s. Witikon has been created in collaboration with Phase One since 2011 – being was the first system to use 4 Phase One Cameras simultaneously.

The design comprises a large turntable for placing objects with dispersed lights switching on/off dependent on the relative position of the camera with respect to the object such that to minimise shades and reflections. Raster images are then taken by a Phase One camera system placed on a gimbal connected to the frame allowing three degrees of freedom, including tilting, raising/lowering the camera and bringing it closer and further away from the object.

Main features of the Witikon system include:

- Scanning up to in 100 objects in 24 hours, generating 100×288=28800 photos
- Scanning objects of sizes ranging from 5 cm to 3 meters
- Scanning speed up to 6 minutes per object
- Accuracy up to 0,001 millimetre
- Object with difficult materials e.g. dark, silver, glossy etc.
- Creating high quality photography using PHASE ONE medium format DB with up to 100 Megapixels
- Creating high quality 360° photography, to be viewed without ned for special hardware or software
- Generating photorealistic 3D models in excess of 50 million triangles

The cost of the system is available on request, although rental options are also available.

5.2.2 Fraunhofer Cultlab3D scanner

The Cultlab3D[5] scanner is being developed at the Competence Centre for Cultural Heritage Digitization at Fraunhofer Institute for Computer Graphics Research IGD, in Darmstadt, Germany. CultLab3D also stands for the corresponding research project funded by the German Federal Ministry for Economic Affairs and Energy.

Figure 3: Fraunhofer Cultlab3D scanner

CultLab3D aims at implementing an encompassing approach to 3D mass digitization, annotation and storage. What is planned is the development of a scanning technology, which digitizes large amounts of three-dimensional objects both time and cost efficiently in 3D due to an automated process. At the same time, an object representation true to the original in the best possible quality is aspired to by acquiring not only the geometry and texture but also the optical material properties in order to make the objects available for 3D printing processes as well. The project CultLab3D faces the increasing demand for 3D mass digitization in the cultural heritage domain by developing comprehensive and economic solutions to approach the challenges of fast 3D digitization.

[5] Cultlab3D scanner: http://www.cultlab3d.de

CultLab3D uses the latest generation of autonomous, compliant robots and automation systems as well as optical scanning technologies, which keep full control of environmental lighting. The modular pipeline consists of a conveyer belt, which transports the artefacts to two scanning stations, first to the CultArc3D, then to the CultArm3D. With the help of the software CultSoft3D these two scanning stations are controlled and configured. CultLab3D is currently designed for high-precision 3D acquisition of cultural artefacts with up to 50kg in weight, 60cm in height and 60cm in diameter providing a high throughput. The entire scanning process of an object takes less than ten minutes on average and attains accurateness in the sub-millimetre range.

The design comprises two distinct parts:

1. The first station (**CultArc3D**) comprises two aluminium arcs, each of them forming an entire hemisphere around the object. Variable motion sequences and image-based methods make it possible to capture the geometry, texture and optical material properties of artefacts in high resolution. Whereas the first arc consists of nine cameras, nine sources of daylight are attached to the second. At the moment ten Mpx cameras, which capture the visible spectrum of light, are used. In the future, these will be extended by multispectral sensors. The lightning sources of the inner arc, capturing the visual sector, shall henceforth and in analogy with the first arc be supplemented by multispectral lights. This can help, for instance, in making further details such as traces of the creation processes visible under ultraviolet light.
2. The second station (**CultArm3D**) serves the refinement of the first scan. Selectively, either a structured light scanner or another camera with a ring light records the artefacts' geometry and texture. When combined with CultArc3D, CultArm3D is used to capture remaining holes, occlusions or geometrically complex surface areas in more detail. For this, an iterative plan for scanning with the CultArm3D is calculated based on the results of the first station. In this way, occlusions and possible gaps in the first 3D model can be eliminated with a targeted approach to the missing view angles. The use of a camera with a ring light attached to CultArm3D allows for the fully automatic digitization of an artefact on a turntable.

5.2.3 Other commercial high precision 3D scanners

An overview of commercial 3D scanners is provided in this section. The project target is to achieve visual light 3D scanning (i.e. not-penetrating) with accuracy preferably better than 50 microns, being the estimated accuracy that may be expected using photogrammetric scanning technology described earlier. The list of possible solutions for achieving resolutions in this range with price ranges (if available) are presented for comparison below:

- **SURVEYOR® ZS-Series system**

  Features: The Surveyor® ZS-Series sets a new standard for precision and ease of use in 3D measurement. Systems are available in many sizes to accommodate a variety of parts and applications. The turnkey system is highly automated to quickly and easily scan simple prismatic shapes and geometry, free-form surfaces, or complex-shaped objects for inspection, analysis, or reverse engineering applications. Using its patented laser line scanning technology, Surveyor ZS-Series scans parts from all orientations, and then easily rotates the data back into a common coordinate system. The scanner controls up to 7 axes of motion for unattended operation or interactive joystick. Scanning accuracy is 0.2 micrometres for objects 40" x 63" x 24" in size.

  Availability: price range for Surveyor ZS 4060 is between 180,000 and 240,000 USD

  WEB portal: http://www.laserdesign.com/products/surveyor-zs-series.

- **MicroCAD 3D Metrology System from *LMI Technologies***

  Features: LMI's MikroCAD 3D scanner is the first 3D surface metrology system ever to use structured light fringe projection profilometry to achieve sub-micron level detail of surface micro-textures and generate complete 3D surface scans in just seconds. With MikroCAD, you can acquire critical sub-micron surface information in a variety of applications, and scan with stunning resolution, analyse with industry standard measurement tools and report with highly effective visualizations. Best of all, MikroCAD is available for an industry leading one-third of the price of competing solutions. MikroCAD's fringe projection structured light technology enables greater resolution — seeing down to 0.1 of a micron on a 2mm X 2mm target — while laser- solutions suffer from laser speckle effects preventing scanning at sub-micron level.

  Availability: price range 35,000 - 45,000 Euros

  WEB portal: http://lmi3d.com/products/mikrocad

- **OptimScan 5M from *Shining3D***

  Features: OptimScan-5M 3D ScannerShining 3D OptimScan-5M 3D scanner is the latest blue light 3D scanner in the market, featuring high-end outlook, structure, component and configuration. Its 5 mega pixel cameras and blue light scanning technology bring users amazing scanning speed. Its single scan accuracy reaches 5-15 micrometres for objects up to 30 x 40 centimetres in size with scan time below 2 seconds.

  Availability: £28,873 from http://www.robotshop.com

  WEB portal: http://en.shining3d.com/digitizer_detail-3540.html

- **HANDYSCAN 700 from CREAFORM**

  Features: The HandySCAN 700 is the latest addition in the new generation of 3D handheld scanners manufactured by Creaform3D achieving resolutions of 0,030 millimetres for objects 225 millimetres in size.

  Availability: 56,600 USD

  WEB Portal: http://www.creaform3d.com/en/metrology-solutions/

- **HD 3D Scanner from *Next Engine***

  Features: NextEngine delivers an unprecedented combination of power and affordability. At 12 micrometre accuracy, it rivals systems costing 10 times the price. An all-new electro-optical architecture and sophisticated new algorithms use an array of Lasers to scan in parallel. Compatible with SolidWorks, provides models in STL, OBJ, VRML, XYZ, and PLY formats.

  Availability: 3,000 USD

  WEB portal: http://www.nextengine.com/products/hd-technology

- **SLS-3-HD from *DAVID3D***

  Features: This advanced model enhances the well proven structured-light-technology. The scanner is mobile and can be positioned easily in front of the surface to be scanned. A single click in the well proven DAVID software starts the scanning process and a few seconds later the digitised 3D model appears on the screen – even the colours of the object can be optionally captured and reproduced in the resulting scan! The 3D model can be exported to standard 3D file formats (such as OBJ, STL and PLY) and processed in other applications50 micrometres. Accuracy is

0.05% of scan size, which is up to 50 centimetres. Scan takes between 2 and 10 seconds producing mesh with density up to 2,300,000 vertices per scan.

Availability: 4,000 USD

WEB portal: http://www.david-3d.com/en/products/sls-3

- **3D industrial scanners from *Rexcan CS 2+***

  Features: Rexcan CS2+ is equipped with two high resolution scanning sensors that use built in blue light technology. Industries first 3-axis turntable (TA-300 Plus) is optimized for ideal scanning angles combined with the high-end dual CCD cameras that enable users to effectively scan areas beyond the pre-existing limits with no loss in quality. Scans objects up to 50 centimetres in size and up to 10kg in weight achieving point spacing up to 36 micrometres.

  Availability: 59,000 USD

  WEB portal: http://eqtinc.com/rexcan-cs2-plus

- **3D Scanner MFS1V1 from *Matter & Form***

  Features: It is an affordable, high resolution 3D scanner that is compact, portable, fully assembled and easy to use right out of the box. Use your Mac or Windows PC to produce accurate, detailed colour scans at resolution qualities that match or top what more expensive scanners can achieve. It works with almost any 3D printer or online printing service, and it allows users to scan solid items to create a digital 3D model.

  Availability: 450 USD from Amazon

  WEB Portal: https://matterandform.net/scanner

- **XLP Laser Scanners 250, 500, 1000**

  Features: The XLP laser scanners are able to scan diverse surface materials without any special coatings, is up to 50% more accurate, up to 70% faster scan rate, and up to 30% higher resolution. Accuracy range is 6/12/24microns for FOV up to 26 centimetres.

  Availability: price range 45,000 to 60,000 USD

  WEB portal: http://www.laserdesign.com/products/xlp-laser-scanner

5.3 Overview of 3D Modelling Software

The image below shows the sub-systems that create and process 3D models. In principle such applications range from 3D scanning, through 3D models integration to 3D processing and finally 3D printing.

In this section software that allows recreation of 3D models from real objects through scanning is considered. This excludes creation of models by hand e.g. by digital artists.

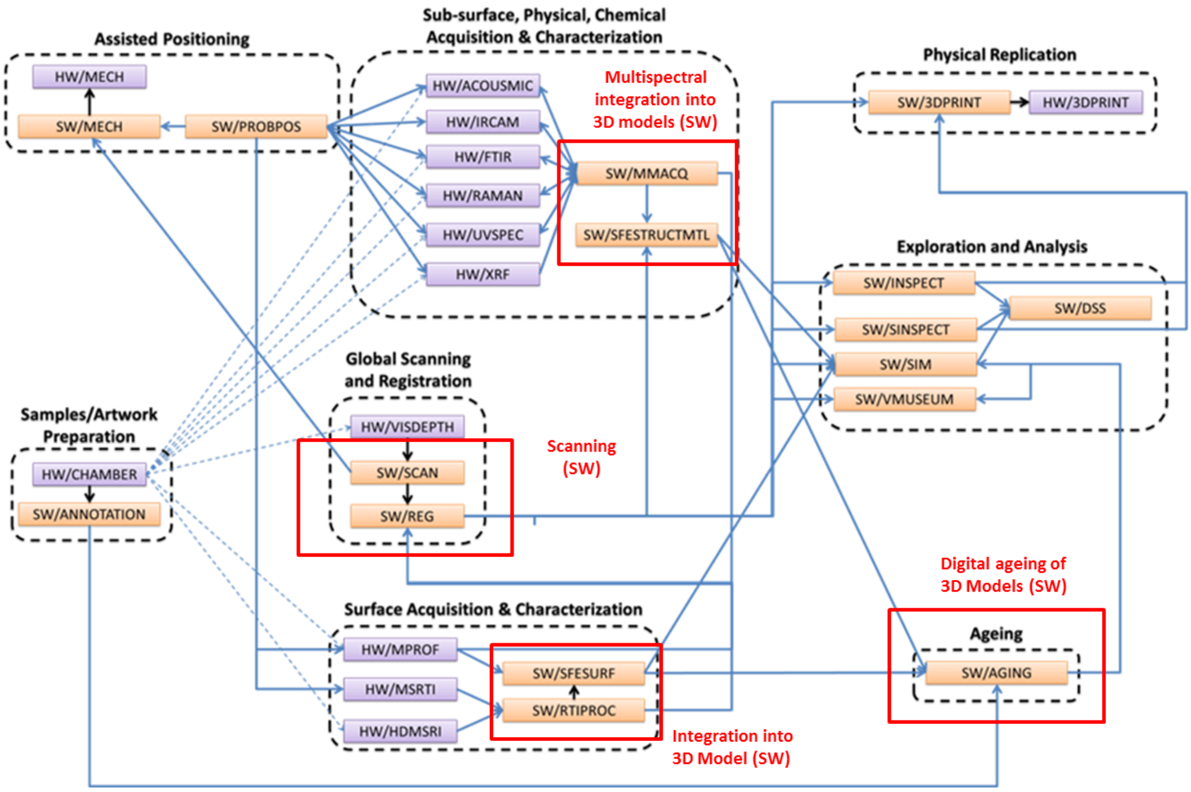

Figure 4: SCAN4RECO Architecture, indicating sub-systems depending on 3D models

Hence approaches employing 3D modelling from images and generic 3D scans are includes in order of best to worst quality (subject to evaluations performed by RFSAT throughout Task 2.1 and Task 5.6):

- **Pix4D Mapper Pro**

  Features: The software automatically converts images taken by hand, by drone, or by plane, and delivers highly precise, georeferenced 2D maps and 3D models. They're customizable, timely, and complement a wide range of applications and software.

  Availability: commercial, offers discount for scientific and non-commercial use

  WEB portal: https://pix4d.com/product/pix4dmapper-pro

- **Autodesk ReMake (NEW product under development)**

  Features: It is an end-to-end solution for converting reality captured with photos or scans into high-definition 3D meshes. These meshes that can be cleaned up, fixed, edited, scaled, measured, re-topologized, decimated, aligned, compared and optimized for downstream workflows entirely in ReMake. It handles reverse engineering as support for design and engineering, for asset creation for AR/VR, film, game, art, for archiving and preserving heritage, digital fabrication or publishing interactive experiences on the Web and mobile.

  Availability: commercial, offered for FREE to academia

  WEB portal: https://remake.autodesk.com

- **Agisoft Photoscan**

  Features: performs photogrammetric processing of digital images & produces 3D spatial data

  Availability: commercial, currently without academic discounts

WEB portal: http://www.agisoft.com

- **ArTec Studio**

  Features: software for professional 3D scanning and data processing

  Availability: commercial, currently without academic discounts

  WEB portal: https://www.artec3d.com/software/artec-studio

5.3.1 Pix4D Mapper

Experimental evaluation of the Pix4D Mapper software has been made in order to assess its capabilities for the SCAN4RECO. The software is originally used for both scanning large scale geographical areas as well as large 3D structures, such as buildings, although it has been used also for large Cultural Heritage objects, such as statues. The results are shown below:

5.3.1.1 *Experiment #1: Large scale area*

In this experiment 227 raster images of the mountain area 195 x 95 meters have been taken. Images were taken over the regular grid (four parallel corridors) from the height of 40 meters. Over 65 million points cloud (limited by available 16GB memory) has been produced, out of which a 3D model has been created that contained over 10 million faces, with results as presented in the figure below, with zoom into the selected interest area:

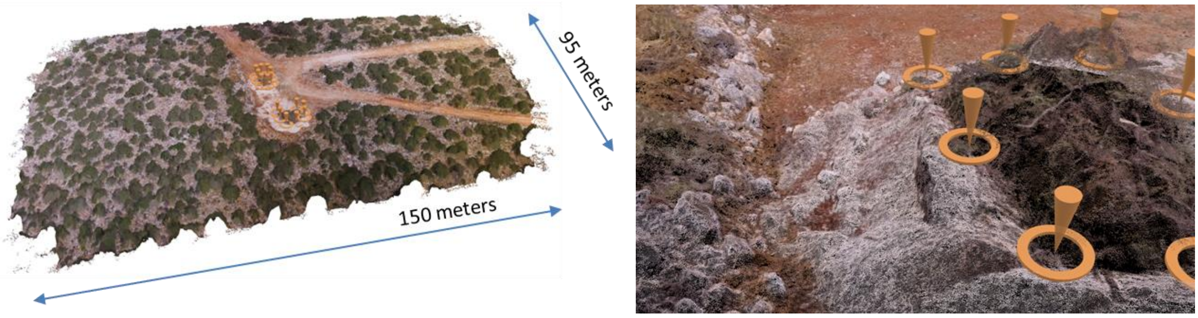

Figure 5: 3D modelling of large-scale areas from raster images with Pix4D Mapper software

The results have shown that from the distance of 40 meters, such small details as individual tree branches (2-3 centimetre details) could be clearly determined, thus showing a potential for such a technology to produce scans reaching accuracies of nearly 100 micrometres for objects sized half a meter from a distance of 40 centimetres – approximate distance foreseen for the robotic arm. The disadvantage of this approach is significant processing time. The model produced in this experiment took over 24 hours using 2.8GHz Inter core 7 with NVidia 980 CUDA processors and 16GB memory. It is expected that using faster processor with higher CUDA count and higher memory would allow to achieve significant reduction of processing time, while increasing the overall model resolution.

5.3.1.2 *Experiment #2: Painting*

Following a successful results of Experiment #1, an attempt has been made to scan a small painting (30 x 40 centimetres) from the distance of 40 centimetres using hand-held 20 Megapixel SONY camera. In total between 9 and 27 images were taken, out of which 3D model has been produced. The painting exhibits degradation of its water-based paint surface, which can be clearly seen on the cross section of its 3D model. The accuracy of the surface variation was estimated at between 0.1-0.4 millimetre. The processing time was over 8 hours using the same system as in the previous experiment.

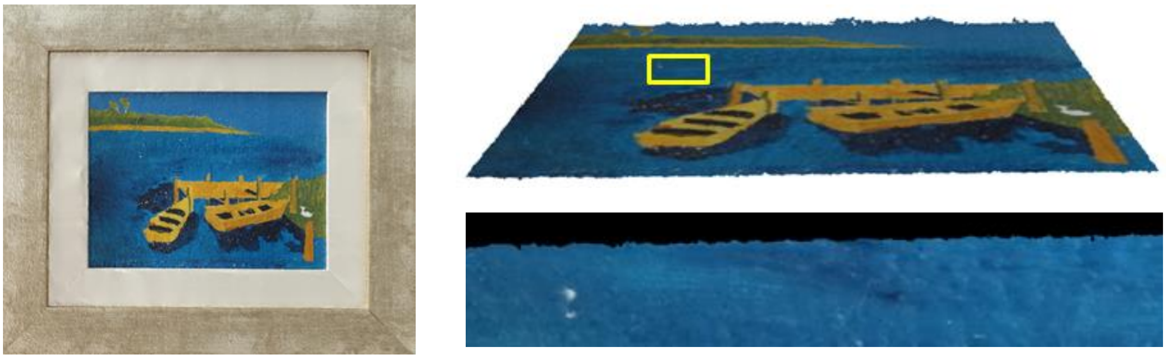

Figure 6: 3D modelling of paintings from raster images with Pix4D Mapper software

5.3.1.3 *Experiment #3: Sculpture*

The third experiment involved scanning of a life sized sculpture (images are courtesy of Pix4D S.A.) of 1.5 metre in height. The 44 raster images were used to produce a model with 3-million-point cloud with estimated accuracy at approximately ~0.25mm. The result is presented in the figure below.

Figure 7: 3D modelling of sculptures from raster images with Pix4D Mapper software

This experiment, in addition to previous ones show the capabilities for this technology to produce 3D models with accuracies reaching the precision usually required by CH restoration facilities.

5.3.2 Autodesk ReMake

ReMake (formerly known as Autodesk Memento) is a long awaited 3D modelling application from Autodesk that uses photogrammetric algorithms, thus allowing 3D model creation both from raster images as well as in the future also from images incorporating depth information (as shown in Figure 8). The latter one is what differentiates it from other similar software as Pix4D Mapper or AirTek Studio.

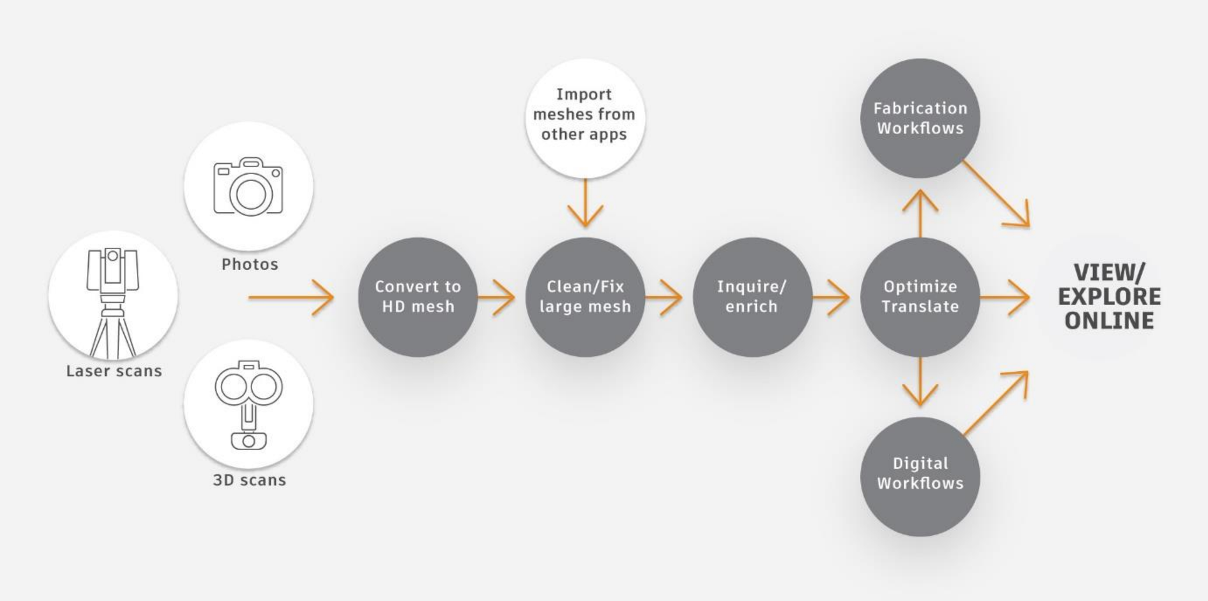

Figure 8: Processing workflow of the Autodesk ReMake application

ReMake is an end-to-end solution for converting reality captured with photos or scans into high-definition 3D meshes. These meshes that can be cleaned up, fixed, edited, scaled, measured, re-topologized, decimated, aligned, compared and optimized for downstream workflows entirely in ReMake. It handles reverse engineering as support for design and engineering, for asset creation for AR/VR, film, game, art, for archiving and preserving heritage, digital fabrication or publishing interactive experiences on the Web and mobile. ReMake plays well with Autodesk® ReCap 360, helping clean up, fix, edit, optimize and prepare the generated meshes from laser scans or photos for downstream use. ReMake simplifies complex processes since it was designed for users who require top-quality digital models of real-life objects but have little or no 3D modelling expertise.

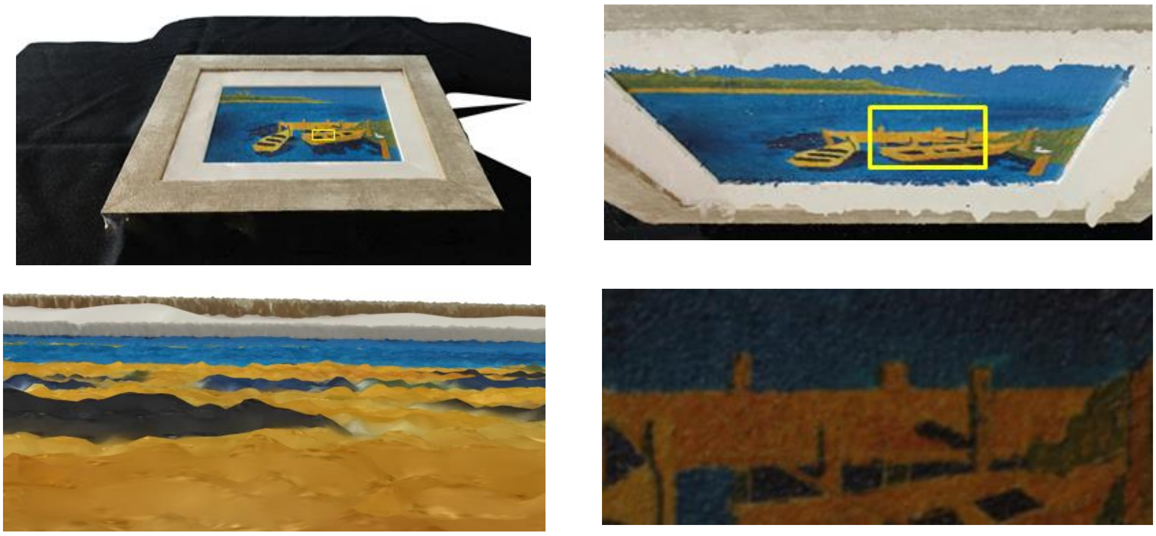

Figure 9: Quality comparison between Autodesk ReMake (left) and Pix4D Mapper (right)

For those with greater expertise, ReMake offers tools to dig deeper. For the first time, Reality Computing is scalable and accessible to a wide variety of users. The software is fully integrated into the suite of 3D application from Autodesk, whereby e.g. ReCap allows cleaning up and simplifying its models e.g. to prepare them for 3D printing, while 3DS Max and 3D Studio offer possibilities of processing and modifying the resulting models further.

The early experiments with Autodesk ReMake in the SCAN4RECO project have shown several advantages, such as smoother edges and cleaner model mesh as compared to Pix4D Mapper, although the precision is significantly lower and models lack high object count, as yet. The results, for the same example picture as for experiments with Pix4D Mapper (Figure 6), are shown in Figure 9.

5.3.3 Comparison to other types of ToF scanners

- Laser scanners: the best ones reach 10 microns of better for small objects (usually up to 25cm in size). An indicative list of respective commercial scanners was provided in section $5.2.3.
- Microsoft Kinect 2.0[6] for Windows: evaluation tests proved that the best accuracy that can be achieved with the Kinect device is 3mm with the standard deviation of 3mm when scanning from a distance of 1.5 meters[7]. The 3D model creation using raster images achieves at least an order of magnitude better accuracy without any (potential) loss of valuable information!!!
- Structure.io Sensor[8]: allows to capture dense geometry in real-time, thus creating 3D models with high-resolution textures in seconds. However, models produced are of limited level of accuracy, below what is required for the SCAN4RECO project.

5.4 Conclusions and Directions for applied research

The price of laser scanners reaching (sub-)micrometre accuracy is too high, preventing wider adoption among CH restoration communities. Even cheaper solutions are in excess of the budgets foreseeing in SCAN4RECO project for such solutions. On the other hand, more affordable solutions compromise both in accuracy model complexity. Therefore, the photogrammetric technology appears to offer a good compromise between the achievable accuracy (@ 50 micrometres) and overall cost (12,000Euros including camera, workstation and 3D processing software). The applied research on combining raster images with rough depth information offers a potential for further improving the achievable accuracy.

Although only few software applications have been presented in section 5.3, certainly the list is far from exhaustive, missing such software like Meshlab from CNR[9], Scanalyze[10] from Stanford, VisualSFM[11] and other ones. The reasons for such choice was that the presented applications were tested on example CH objects in Task 2.1. Once tests are made with other software, they will be added successively to this section.

The results from initial evaluation of photogrammetric technologies led to the following conclusions:

- Having a-priori knowledge of the precise camera position and following a fixed grid at known distance as well as increasing the overlap among images is expected to reduce border effects, reduce distance discrimination error and likely achieve an overall reduction of the number of faces.
- Increase of the number of point cloud in excess of 100 million and the faces count in excess of 10 million will naturally improve surface resolution, with rough estimate to reach better than 100 micrometres. In order to achieve such performance a dedicated processing system will be required in order to reduce processing time to single hours (depending on the model complexity). The intended setup will employ multiple NVIDIA GeForce 1080 (SLI connected) graphics cards with high CUDA core count.

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6 MS Kinect for Windows: https://developer.microsoft.com/en-us/windows/kinect

7 Jeremy Steward, Dr. Derek Lichti, Dr. Jacky Chow, Dr. Reed Ferber, and Sean Osis "*Performance assessment and calibration of the Kinect 2.0 time-of-flight range camera for use in motion capture applications*", FIG Working week 2015, "Wisdom of the Ages to the Challenges of the Modern World" Sofia, Bulgaria, 17-21 May 2015

8 Structure.io sensor: http://structure.io

9 MeshLab (open source) software: http://meshlab.sourceforge.net

10 Scanalyze application from Stanford: http://graphics.stanford.edu/software/scanalyze

11 Visual SFM application: http://ccwu.me/vsfm

Relevant new research areas will further investigate:

- Use of depth data associated with raster images for (potentially) reducing borderline effects to negligible levels and overall resolution, hopefully leading to lower model complexity
- Extend the photogrammetric technology to penetrating imaging. First test will be made with combination of already owned thermal and visual imaging. Subject to positive results, investigation will follow to other sensors used by other project partners.

6. Mechatronic Systems for Sensor Probe Positioning and Scanning

To explore technology related to sensor probe positioning mainly two aspects have to be evaluated:

1. Number and configuration of axes to be employed.
2. Mechanical engineering solutions to maximize stiffness and minimize weight for given translation ranges and sensor probe weights.

6.1 State of the Art

This section addresses research and considerations of available technology on the positioning and scanning technologies as well as mechanical engineering approaches to implement positioning and scanning systems for cultural heritage analysis. Classical designs range from large structures with rotating tables and cameras moving around the object. In some cases, cameras are placed either on an arm of a robot (e.g. Witikon shown in section 5.2.1), on a semi-circular frame (e.g. Cultlab3D shown in section 5.2.2) or on a stationary frame for the case of photogrammetric scanning in order to ensure stability of images taken from multiple cameras (as in Cool Dimms 3D Portrait Studio[12]).

6.1.1 Number and Configuration of Axes

For digitization of cultural heritage object, so far no multi-modal platform has been established. Instead, for acquiring 3D data from objects, archaeologists and conservators employ mechatronic systems which suit the size of the object and the requirements of the sensor involved and commonly used by the respective group. Mainly, these efforts target the regime of what is called global scanning in the context of the Scan4Reco project.

The systems used depend mainly on the object size and geometry. Here is list of a few examples in the order of decreasing object size:

a) For LIDAR measurements on large temple areas or ancient cities, the mechatronic system will be a plane. A similar approach are ultrasound or radar measurements of the ground of lakes or the sea based on ships.

b) For ground based measurements of architectural sites laser scanners can be used which may be placed on a static tripod at various points in the terrain.

c) Larger statues or parts of architectural structures such as gates, pillars or reliefs will most commonly be measured based on dedicated scaffolds or rails custom-fit for the specific object. Starting from this object size, multi-modal acquisition starts being an option.

d) For objects of up to very few meters in size, a variety of custom positioning devices exist in museums or conservation institutes, each usually dedicated to carry the sensor probes of the modalities prevailing in the respective institution.

12 Cool Dimms 3D portrait studio: http://www.cooldims.com

e) Objects of only few millimetres or centimetres in size can be fully assessed with laboratory equipment like 3D microscopes or optical coherence tomography, which carry precision stages for object positioning.

Many of these examples share the need of post-processing of the data, including stitching together of independently acquired smaller area data sets to form one comprehensive data set. This makes use of overlapping information contained in adjacent data sets. The benefit of stitching are reduced ranges required for the positioning system. Increase local positioning precision may also compensate errors introduced by the stitching process.

Also, it becomes obvious that it is unrealistic to assume that one positioning system can cover all needs. This is particularly true when looking at very large and very small objects – it will be hard and also not very reasonable trying to replace airborne LIDAR or specialized microscopes by mid-sized, ground-based mechatronic positioning systems.

Consequently, the Scan4Reco coarse positioning system should best target objects from a few centimetres to a few meters in size. This is the regime of item d) and may be also c) in the above list of examples.

A true and portable platform for multi-modal acquisition in this regime could not be identified. A variety of systems compete already on the market, but concentrate either on automated 2D image acquisition or purely 3D scanning. None has been found which is capable of adapting various sensor modalities taking into account their different physical properties and associated sensor requirements.

Having a common position reference for both overview 3D scans and local measurements of physical, chemical and morphological details is a key ambition of the Scan4Reco concept. Hence, the capabilities of a positioning system for Scan4Reco has to be seen in the context of the software and vice versa: The better the stitching capabilities of the software, the smaller the range of the positioning system can be, which will enhance portability and enable end-users to readily make use of the system within their daily workflow. For example, the company Creaform offers three types of hand-held 3D scanning systems, namely

- a “low-cost” system (as advertised) which requires reflective markers placed on the object (according to Creaform the only option if working on unstable ground such as scaffolds)
- GoScan system without a need for markers, but requiring sufficient shape or colour structure (resolution 0.1 mm, accuracy 0.3 mm on 1 m distance), costing EUR 23,000 including colour option
- the CTrack Metra with absolute tracking of the scanner costing EUR 80,000

The company Geomagic offers a software to read, merge and process 3D data sets. It supports stitching supported either by assigning 3 points in space or by finding groove structures in the data. EUR 10,000 for the stand-alone software, less for a plug-in for SolidWorks

The above examples show that the State of the Art to reconstruct 3D models by stitching together smaller, coherent recordings. It also indicates for Scan4Reco that it might be economically sound to separate the positioning hardware for 3D scanning of the entire object from the positioning system for local measurements. The latter would then still need to have 3D overview surface scanning capabilities, but only have to acquire enough data to reference precisely enough with the previously acquired, high resolution 3D model of the whole object.

6.1.2 Mechanical Engineering Solutions

Mechanical engineering solutions can be chosen from a broad range of technologies well established in industrial automation. Mainly, these are

- propulsion techniques such as spur gears, cam belts, spindles or linear drives,
- gears for power transmission such as planetary gears, spur gears or worm gears, and
- bearings such as ball and roller bearings or plain bearings.

Certainly, these techniques are commercially available in packages as industrial grade axes. Partially, these are even configurable and rudimentary building block solutions exist for standard axis configurations. When having a closer look, the standard industrial solutions exhibit one of two major shortcomings when considering the environments and needs for positioning sensor probes for cultural heritage object analysis:

Those solutions based on roller bearings are reasonably stiff, but specified for relatively clean and temperature-controlled industrial environments. They require lubrication and clean guides to avoid strongly reduces life-time. In addition, there is a tendency to heavy weight, since these components largely tend to rely on steel components.

On the other hand, lubrication and maintenance-free plain bearings – especially those made from high-tech plastics, tend to be specified with lower tolerances and exhibit a certain degree of elasticity in the bearings.

6.2 Evaluations and Selection of Candidate Technologies

The evaluation and selection of candidate technologies will, as in the previous section, be assessed for the number and configuration of axes on the one hand and the mechanical engineering solutions on the other hand.

6.2.1 Number and Configuration of Axes

Despite limiting target object size to the range between few centimetres and few meters, this is still a very broad and challenging range, especially when considering the masses and geometries of potential sensors and the degrees of freedom.

For the maximum mass and size, the Bruker Alpha spectrometer was taken as reference. Regarding the number of degrees of freedom, there is not upper limit which could be considered as sufficient for all types of objects. Especially undercut structures can require far more than five degrees of freedom. This means that a truly versatile system must not have all potential degrees of freedom implemented, but be flexible enough to add axes if needed – even if it might add significant cost in specialized cases.

Several different approaches were proposed by AVASHA and evaluated, such as:

- **Quadrupod Approach**

  Here, a heavy-duty, tripod-like member with four legs would form a base to connect to the ground even in problematic terrain or on scaffolds. On top, various axis configurations could be mounted, however, the range would be limited to allow enough stiffness.

  Advantages: low weight, easy to use even in inconvenient places, very portable
  Disadvantages: limited stability, can acquire data on object basically from one side only

  Estimated Cost EUR 20,000

- **Portal Approach**

  To be able to go around medium-sized statues in-situ, a rigid cell would be built around the object with a rotary axis above the object. At a cell size of (2 m)3, six degrees of freedom would be possible with high positioning accuracy.

Advantages: mid-sized statues can be measured from all sides within a single reference frame without relocating the positioning system

Disadvantages: basically not portable or complicated to set up, risk for the object due to need for heavy members to be mounted above the statue, impossible to use on scaffolds.

Estimated Cost: EUR 100,000

- **Base Rail Approach**

  A horizontal base axis will provide gross linear motion, with several linear and rotary degrees of freedom on top. An accessory rotating table can be used to measure all sides of medium-sized statues.

  Advantages: almost truly portable, scalable

  Disadvantages: due to its mass the system will be hard to install on scaffolds

  Estimated Cost: EUR 38,000

The quadrupod approach would be a good component if having two independent positioning systems – one for high resolution 3D measurements of the entire object and a compact one capable of carrying heavy sensor probes and acquiring just enough 3D data to correlate the limited positioning range with the objects gross 3D model.

The portal approach in not appealing – neither in cost nor ease of use. So in the end, the decision was made for the base rail approach, even though it is exceeding the available budget. Still, it has potential to be expanded by accessories to broaden the potential use-cases without having to alter the core components.

6.2.2 Mechanical Engineering Solutions

All movements of the system will be slow compared to general industrial automation, which is a result of general workflow and safety requirements. Therefore, three-phase alternating current motors with frequency converters need not be employed – instead compact state of the art DC motors with planetary gear stages will be chosen.

For the rotary axes (Θ and Φ), either worm gears with custom bearings or commercially available planetary gears with integrated rolling bearings are most promising technologies. The latter would add considerable weight for diameters with sufficient stiffness. Therefore, most probably a custom worm gear solution will be integrated.

For the linear base axis (X), spur gear (rack and pinion) and cam belt propulsion are the most promising candidates, since they can extend over long ranges. Here, rack and pinion systems are easy to extend and may even allow curved motion in the long run, with the drawback of need for lubrication. The same applies for the vertical (Y) and sensor (Z) axis, respectively, however, for the sensor axis a spindle gear may be the better choice due to the higher precision and naturally limited stroke.

6.3 Directions for Applied Research

Ongoing research affecting the coarse positioning system hardware includes General Work on:

- grouping of components within the control unit and the coarse positioning system
- electrical and mechanical standardization of sensor controller devices with manufacturers
- solving the wiring challenge, mainly given by the cables between control unit and sensor probe (lengths, bending, multiplexing, fastening near probe adapter)
- ergonomics (weight, portability, set-up time)

- vibration sensitivity (passively aimed for by design)
- suitability for various environmental conditions
- object safety
- identifying out user scenarios to derive application related groups of sensors to limit the maximum number of sensor controller device slots needed in the control unit

6.4 Conclusions

From the struggle for high stiffness at low weight, it becomes obvious that with the boundary conditions set by the consortium on registration needs and sensor weights, any solution will suffer from reduced portability and uncomfortable setup procedures, unless such a system will be used on even and firm ground. To really overcome these problems, more efforts would have to be made for standardization of sensor probe sizes and weights, sensor controller devices and the control unit electromechanical integration. This would require involving manufacturers of cultural heritage analysis equipment and adaptions of sensor controller devices and probes existing within the consortium.

7. Artificial Ageing for Paintings and Metals

7.1 State of the Art

Many aspects of accelerated ageing (aims, mechanisms, methods, requirements) have been reviewed by Feller in his *Accelerated aging. Photochemical and thermal aspects. (*L.A. The Getty Conservation Institute, 1994), which is a fundamental reference for the community of conservation and heritage researchers and scholars. The main factors affecting ageing and weathering of materials are light, heat and humidity. Hence, such three parameters are most often controlled in accelerated ageing devices. When the aim of artificial ageing is the development and application of a prediction model, accelerated test conditions must be consistent with real exposure ones. In some cases, artificial ageing is aimed at ranking different materials (coatings, varnishes) and the conditions can be more unrealistic.

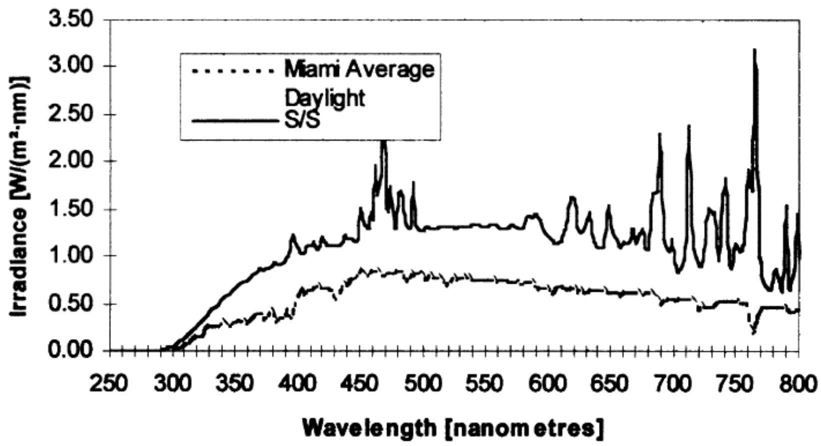

Figure 10: Xenon arc with borosilicate inner and outer filters vs miami average optimum daylight

The design of the ageing devices may vary, but they should be constructed from corrosion resistant material and, in addition to the radiant source, may provide for means of controlling temperature and relative humidity. In some cases, they are equipped for the spraying of water on the test specimen for the formation of condensate on the exposed face of the specimen or for the immersion of the test specimen in water. The radiant source(s) shall be located with respect to the specimens such that the uniformity of irradiance is assured. Light sources available on the market consist mainly of xenon arc, carbon arc and fluorescent. For most applications, the xenon arc spectrum modified with specific filters gives a good simulation of sunlight. Figure 10 shows the xenon arc spectrum and its relationship to the sunlight spectrum.

Other kind of lamps of common use are fluorescent UV ones. Fluorescent UVA lamps are available with a choice of spectral power distribution that vary significantly. UVA 340 has actual peak emissions at 343 nm and mostly applies to the short and middle UV wavelength region of the daylight (Figure 11 left). UVA 351 lamps is peaked at 351 nm and is used for the short and middle UV wavelength region of the daylight, which has been filtered through a window glass (Figure 11 right). For simulations of direct solar UV radiation, the UVA-340 lamp is recommended. Because UVA-340 lamps typically have little or no UV output below 300 nm (that is considered the "cut-on" wavelength for terrestrial sunlight), they usually do not degrade materials as rapidly as UVB lamps, but they may allow enhanced correlation with actual outdoor weathering.

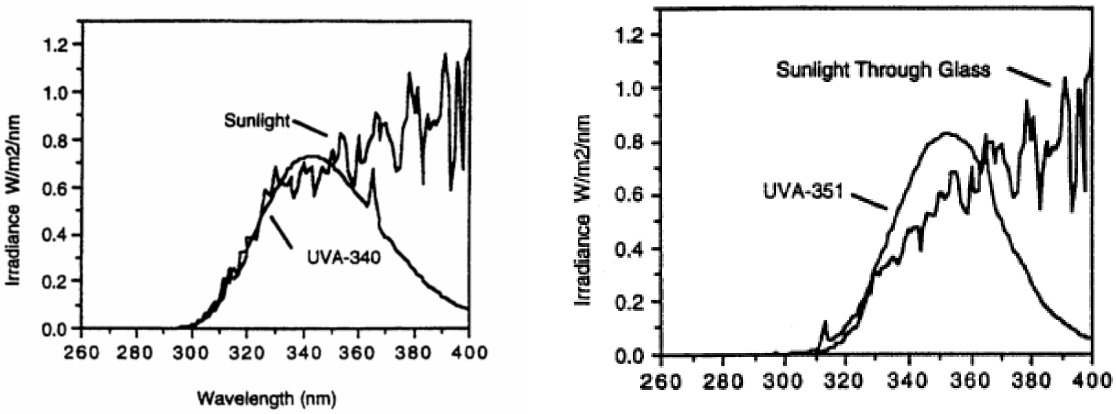

Figure 11: Spectral power distributions of UVA -340 lamp and sunlight (left) and Spectral power distribution of UVA 351 lamp and sunlight distribution through window glass (right)

Two factors are of main importance when selecting a light source for accelerated testing. Firstly, the spectrum should at best have a cut on at the same or very similar wavelength to that of the actual exposure environment, since short wavelengths present in an artificial source can induce unnatural chemical degradation and provide an erroneous test result. In addition, it is also desirable to make sure that the full sunlight spectrum is simulated. Secondly, the intensity of the irradiance level should be controlled and maintained at the set level. The ‘average optimum daylight’ for Miami, a spectrum often used as reference, has been measured using a spectro-radiometer. Measurements were made at periods throughout the day at the spring equinox, and the average data was taken. If the *Miami average optimum daylight* curve is used as a baseline reference for sunlight, a setting of 0.35Wmsq.nm can be used to simulate sunlight intensity. Acceleration of photo degradation has been achieved by even further increase the irradiance level, however it has been found that this acceleration technique may also lead to unnatural chemical degradation if the level is too high.

Many accelerated-aging tests expose samples continuously to lamp emission, whereas under natural conditions exposure takes place under alternate periods of daylight and darkness. The conditions of continuous exposure produce different results from those observable under alternating conditions, even if this aspect of testing is not very clear [Feller, R.L. 1994. *Accelerated aging. Photochemical and thermal aspects.* L.A.: The Getty Conservation Institute, 1994, and references therein]. Another important factor of acceleration is heat. To get comparable conditions of heat, a frequently reported parameter is the ‘Black Panel Temperature’, which theoretically represents the maximum surface temperature achieved during exposure. The most commonly used outdoor black panel sensor is a black coated steel panel with a thermocouple fixed to either the front or the back of the panel. Some black panels are constructed using resistance temperature detectors. The primary function of the black panel in a weathering device is to be used to control the temperature in that device and to set it to reproduce actual exposure conditions. This more realistically describe the specimen condition than if the ambient temperature were used.

Actual irradiance levels at the test specimen surface may vary due to the type or manufacturer of the lamp used, or both, the age of the lamps, the distance to the lamp array, and the air temperature within the chamber and the ambient laboratory temperature. Consequently, the use of a radiometer to monitor and control the radiant energy is recommended.

The presence of water may be necessary for some degradation reactions to occur, depending on the material being tested. Water causes damage to materials by both physical and chemical processes. Absorption of water into a material, from humid air or surface deposition causes a volume expansion causing stresses within the material. The test specimens may be exposed to moisture in the form of water spray, condensation, or high humidity. The test chamber may be equipped with a means to introduce intermittent water spray onto the test specimens under specified conditions. The spray shall be uniformly distributed over the samples. The test chamber may be equipped with a means to cause condensation to form on the exposed face of the test specimen. Typically, water vapour shall be generated by heating water and filling the chamber with hot vapour, which then is made to condense on the test specimens. The test chamber may be equipped with a means to measure and control the relative humidity. Such instruments shall be shielded from the lamp radiation.

Apart from the three environmental agents, light, heat and water, gaseous and saline pollutants can play a fundamental role in degradation, as well as particulate matter. Gas air pollutants of importance for degradation are SO_2, NO_x, HCl, HF, O_3, as well as H_2SO_4, HNO_3. Dry and wet depositions are the processes for bulk transportation of the pollutant to a surface. Some devices are also equipped with the inlet for gases but sometimes the effects of pollutants are properly reproduced by spraying an acidic solution containing SO_4^{2-}, NO_3^-, Cl^-, organic anions and others contaminants.

7.2 Relevant Standards

In order to set properly the artificial ageing experiment of the materials tested in Scan4Reco (paints, metals and coatings), the main ISO standards for paints, varnishes and metals are taken into account. Despite these rules have been set for industrial checks and comparison of the performance of different in-service materials, they can provide useful recommendations on the setting of an accelerated aging experiment aimed at the simulation of the actual behaviour of heritage materials in their regular display conditions and at the prediction of their future changes.

The most relevant referenced standards are:

- ASTM G53 Practice for operating light and water exposure apparatus (Fluorescent UV-Condensation Type) for exposure of non-metallic materials
- ASTM G154 Standard Practice for operating fluorescent light apparatus for UV exposure of non-metallic materials
- ISO DIS 11507 Paint and Varnishes: Exposure of coatings to artificial weathering in apparatus-Exposure to Fluorescent Ultraviolet and condensation apparatus
- ISO16474-1:2013 Paint and Varnishes-Methods of exposure to laboratory light Sources-Part 1: General guidance
- ISO16474-2:2013 Paint and Varnishes-Methods of exposure to laboratory light Sources-Part 1: Xenon-arc lamp
- ISO 14993 Corrosion of metals and alloys— Accelerated testing involving cyclic exposure to salt mist, "dry" and "wet" conditions
- ISO 16151 Corrosion of metals and alloys. Accelerated cyclic tests with exposure to acidified salt spray, "dry" and "wet" conditions

- ISO 16701 Accelerated corrosion test involving exposure under controlled conditions of humidity and intermittent spraying of salt solution
- ISO 21207 Corrosion tests in artificial atmospheres - Accelerated corrosion tests involving alternate exposure to corrosion-promoting gases, neutral salt-spray and drying

As for outdoor metals, the NORDTEST Technical Report [Bo Carlsson Göran Engström Anne-Lise Hög Lejre Mikael Johansson Roy Johnsen Reima Lahtinen Mats Ström, Guideline for selection of accelerated corrosion test for product qualification, NORDTEST Technical Report TR 597 – approved 2006-04] indicates the most relevant cycling tests that applies properly to metals and alloys as well as to organic coatings on them. They involve the exposure to humidity and to salt spraying (ISO 14993, ISO 16151, ISO 16701, ISO 21207). The ISO 14993 involves cyclic exposure of test specimens to a mist of salt solution, to drying conditions, and to periods of high humidity It reproduces the corrosion that occurs in outdoor salt-contaminated environments. The specimens are sprayed with a NaCl solution (50 g/l, 35°C) during two hours. Then a phase of dry conditions follows, where the specimens are kept at temperature = 60°C and relative humidity < 30% RH for 4 hours. The third phase is exposure to wet conditions (Temperature = 50 °C Relative Humidity > 95 %RH) for two hours. The specimens are supported in the rack 20° to the vertical.

The ISO 16151 specifies two test methods A and B, which involve cyclic exposure of test specimens to a mist of acidified salt solution, to drying conditions, and to periods of high humidity. Method A applies to metals and their alloys, and organic coatings on metallic materials. Times and conditions do not differ from those of ISO 14993, but for the fact that the salt solution is acidified down to pH=3.5.

The ISO 16701 refers to accelerated corrosion test involving exposure under controlled conditions of humidity and intermittent spraying of salt solution. The method is especially suitable for comparative testing in the optimization of surface treatment systems. It is recommended to simulate corrosion on open surfaces.

The ISO 21207 describes two cyclic corrosion test methods involving a short period of neutral salt spray testing, followed by drying and a longer time of exposure to an air flow containing corrosion promoting gaseous pollutants and high humidity. The methods are intended for use in assessing the corrosion resistance of products with metals in environments where there is a significant influence of chloride ions, mainly as sodium chloride from marine sources or by winter road de-icing salt, and from corrosion promoting gases from industrial or traffic air pollution.

For painting materials, relevant standards are ISO16474-1:2013 and ISO16474-2:2013. They deal with the exposure of specimens to laboratory light sources under controlled environmental conditions. The ISO 16474-1 deals with the requirements for laboratory exposure devices, the form, number, size and preparation of mock-up samples, the test conditions and procedure, the periods of exposure and evaluation of results. The standard indicates that the exposure must take into account irradiance, temperature, humidity and moisture and gives some specifications for them. The ISO 16474-2 gives requirements of Xenon lamps and of their calibration and check.

7.3 Direction of Applied Research and Conclusions

For the definition of relevant aging conditions and parameters, the Scan4Reco project refers to the many scientific papers in the conservation field dealing with accelerated ageing of painting materials, metals and coatings. These papers are aimed at reproducing accurately the features of naturally aged objects of art in order to understand the factors affecting their degradation/ageing, to test new analytical techniques for their investigation and to develop new restoration/preservation strategies. The authors therefore propose some tailored variations of the standardized procedures in order to better adapt them to the purpose. Sometimes they use commercial ageing apparatus but homemade devices are proposed as well, especially for tarnishing of silver, a process that is not included in the standards.

Among the huge literature, a few publications have been selected to describe the most chosen procedures for the ageing of metal and painted reconstructions of real objects of art. For **painting materials**, important references are:

- Colombini M.P., Modugno F., Characterisation of proteinaceous binders in artistic paintings by chromatographic techniques, J. Sep. Sci. 27 (2004) 147–160
- Manzano E., Garcia-Atero J., Vidal A.D., Ayora-Caneda M.J., Capita'n-Vallvey L.F., Navas N., Discrimination of aged mixtures of lipidic paint binders by Raman spectroscopy and chemometrics, Journal of Raman Spectroscopy, 43,6, 2012, 781-786
- Matteini P., Camaiti M., Giovanni Agati G., Baldo M., Muto S., Matteini M., Discrimination of painting binders subjected to photo-ageing by using microspectrofluorometry coupled with deconvolution analysis, Journal of Cultural Heritage 10 (2009) 198–205
- Pallipurath A., Skelton J., Bucklow S., Elliot S., A chemometric study of ageing in lead-based paints, Talanta, 144, 2015, 977–985

In Matteini et al., accelerated photo-ageing of these specimens was conducted for a 600 hours period using a Xenon lamp equipped with an "outdoor filter" (λ> 280 nm) for simulating outdoor exposure (Solarbox 3000e, Co.Fo.Me.Gra, Milan, Italy) and fixing BST (Black Standard Temperature) at 40 ◦C.

In their works, Manzano et al. focused on the evaluation of the accelerated ageing process – represented by the UV light exposure – of proteinaceous binding materials in simulated pictorial samples both when proteins were single and when they were in a complex matrix. They used for accelerated test a high-speed exposure unit SUNTEST CPS, Heraeus, equipped with a Xenon lamp; a special UV glass filter was used for limiting the radiation at wavelengths greater than 295 nm, corresponding to outdoor solar exposure. Irradiance was set at 765 Wm−2, and the maximum and minimum temperatures of the samples were maintained between 30–35 °C and 15–20% relative humidity.

Based on the above-mentioned literature, the following conditions were chosen:

- -Ageing apparatus: with temperature (without humidity) ranging from -40°C to 150°C and from 10°C to 90°C with humidity; RH ranging from 15% to 98%.
- Light source: mercury vapour lamp HSW-400W E40 with a window glass filter
- Cycle: continuous light exposure, temperature ramping from 48°C to 60°C and humidity ramping from 40% to 60%
- Cycle period: 2 weeks
- Overall number of cycles: 6

Examples of application of artificial ageing on metals are provided by the following papers:

- Bernardi E., Chiavari C., Lenza B., Martini C., Morselli L., Ospitali F., Robbiola L., The atmospheric corrosion of quaternary bronzes: The leaching action of acid rain, Corrosion Science 51 (2009) 159–170
- Bernardi E., Chiavari C., Martini C., Morselli L., The atmospheric corrosion of quaternary bronzes: An evaluation of the dissolution rate of the alloying elements, Appl. Phys. A 92, 83–89 (2008)
- Chiavari C., Bernardi E.; Martini C.; Morselli L.; Ospitali F.; Robbiola L.; Texier A.,Predicting the corrosion behaviour of outdoor bronzes: assessment of artificially exposed and real outdoor samples, in: METAL 2010: Proceedings of the Interim Meeting of the ICOM-CC Metal Working Group, CHARLESTON, Clemson University, 2010, pp. 160 - 166
- Storme P.,Schalm O.,Wiesinger R., The sulfidation process of sterling silver in different corrosive environments: impact of the process on the surface films formed and consequences for the conservation – restoration community, Heritage Sience, December 2015, 3:25

- Reedy C.L., Corbett R.A., Long D.L., Tatnall R.E., Krantz B.D., Evaluatiion of three protective coatings for indoor silver artifacts. Objects Speciality Group Postprints, AMerica Institute for Conservation of Historic&Artistic Works, (1999) p. 41-69.
- WEATHERING OF TREATMENTS FOR BRONZE CONSERVATION Results of natural and artificial weathering Work performed for the European Project ARTECH – Access, Research and Technology for the conservation of the European Cultural Heritage

For **bronze ageing**, the group of Bernardi, Chiavari and Martini developed the dropping test method, where the atmospheric exposure is simulated through a cyclic exposure of the alloy to a precipitation runoff with an artificial rain periodically dripped on the sample. It means that this test simulates a severe runoff condition with a solution reproducing natural acid rain. The synthetic rain contains the same quantities of the main inorganic and organic ions as in natural rain of a particular site and in a particular time of the year. The same authors propose also wetting and drying cycles where the specimens were periodically dipped (no run-off is taken into account in this study, i.e., the specimens were cyclically immersed in the same weathering solution at each cycle) either in synthetic or in natural rain: 50 min of immersion, 10 min of drying. The weathering periods had a maximal length of 40 days for each series of tests. Each test was performed at room temperature. An example of composition of synthetic rain is Cl^- (1.27mg/L), NO_3^- (4.64mg/L), NH_4^+(1.06mg/L), $SO_4^=$(1.9mg/L), $HCOO^-$ (0.05mg/L), CH_3COO^- (0.23mg/L), Na^+(0.53mg/L), Ca^{2+}(0.34mg/L), pH = 4.25. In the work performed for the European Project ARTECH, a two-part experiment was proposed: I) UV radiation exposition to promote degradation of treatments and (II) a salt solution exposition in a salt fog chamber to promote corrosion. In the first part of the procedure, UV exposure was carried out according to the standard EN ISO 11341 in a Xenon-arc radiation chamber, for the second part, a salt spray chamber was used for the acid salt solution exposure, following the standard ISO 9227 exposure conditions definition and the sprayed solution had the following composition: NaCl (0,5 g/L + $(NH_4)_2SO_4$ (3,5 g/L), with a pH close to 4,5 in order to be approximated to the urban rain water composition. The treated samples were exposed alternatively to the UV radiation and to the salt solution, for periods of two weeks in each test chamber, till having reached a total of 2000 h of exposition.

The following conditions and parameters will be used in Scan4Reco ageing:

- Ageing apparatus — with temperature ranging from 50°C to75°C (without dew) and from 40°C to 60°C (with dew)
- Light source: — UVA lamp
- Cycle: — 4 hours' dry conditions (T= 60°C) with UV exposure + hours wet conditions (T=40°C, RH=90%) dark+ manual spraying every 6 cycles with solution A (Cl- (1.27mg/L), NO3 - (4.64mg/L), NH4 +(1.06mg/L), SO4 =(1.9mg/L), HCOO- (0.05mg/L), CH3COO- (0.23mg/L), Na+(0.53mg/L), Ca2+(0.34mg/L), pH = 4.25)
- Cycle period: — 8 hours
- Overall time of cycling: — 12 weeks.

For **silver ageing**, Reedy et al. used a two chamber device, one for a wet environment and one for a dry environment. In the wet environment chamber, conditions were maintained at 50° C and 100% RH. The second chamber was maintained at typical room temperature and RH conditions. Room conditions were not strictly controlled, but were constantly measured (with RH between 50-60% and temperature between 20-21° C). To take into account possible synergistic effect, the accelerated tests exposed specimens to a 'cocktail' of volatile pollutants, as well as to fluctuating temperature and relative humidity that may cause stress on the coatings. In a recent paper, Storme at al. proposed to age silver samples in order to achieve surfaces reproducing actual tarnished silver objects. They tested three ageing methods:1) a controlled gas environment of H_2S and SO_2) thioacetamide method; 3) Na_2S solution alternated with exposure to air. Conclusions of this study was that the composition and microstructure of the corrosion layers are strongly dependent on the sulfidation method used and on the kind of silver-copper alloy. Therefore, artificially corroded sterling silver is not necessarily representative for naturally tarnished historical objects and the extrapolation of the cleaning results obtained on dummies to historical objects must be performed with care.

Conditions for ageing in Scan4Reco:

- Ageing unit: dessicator with temperature and humidity sensors
- Light source: none
- Cycle: continuous exposure to H2S both by introducing H2S from a gas cylinder (SAMPLE SET 1, H2S concentration A) and by the decomposition of Na2S from a solution at pH=7 (SAMPLE SET 2, H2S concentration B).
- Overall time of exposure: 100 hours

For simulation purposes, Scan4reco needs to acquire surface and subsurface properties at different stages of the ageing process. A practical pipeline to link the artificial ageing with capture and simulation is provided in the following.

7.3.1 Painting materials

Check before ageing (T0), half way and at the end of the process with the following list of techniques:

- HW/VISDEPTH – Acquisition of 3D of surfaces with variable extent of gloss and reflectivity.
- HW/ACOUSMIC - Structural characteristics of the samples.
- HW/FTIR- Molecular fingerprint of the coating polymer and the corrosion products.
- HW/RAMAN- Molecular fingerprint of the coating polymer and the corrosion products.
- HW/UVSPEC- UV and visible emission properties of the coated and uncoated surfaces
- HW/MPROF - Quantitative measurements of surface texture and roughness at micrometric level
- HW/HDMSRI- Check of the surface appearance of material samples
- HW/MSRTI- Check of the surface appearance of material samples
- HW/IRCAM- Check of the IR reflectance of material samples
- HW/XRF- In-depth check of the elemental composition of material samples

Checks every two weeks:

- HW/VISDEPTH – Acquisition of 3D of surfaces with variable extent of gloss and reflectivity.
- HW/ACOUSMIC - Structural characteristics of the samples.
- HW/FTIR- Molecular fingerprint of the coating polymer and the corrosion products.
- HW/RAMAN- Molecular fingerprint of the coating polymer and the corrosion products.
- HW/UVSPEC- UV and visible emission properties of the coated and uncoated surfaces
- HW/IRCAM- Check of the IR reflectance of material samples

7.3.2 Bronze materials

Check before ageing (T0), half way and at the end of the process with the following list of techniques:

- HW/VISDEPTH – Acquisition of 3D of surfaces with variable extent of gloss and reflectivity.
- HW/ACOUSMIC - Structural characteristics of the samples.
- HW/FTIR- Molecular fingerprint of the coating polymer and the corrosion products.
- HW/RAMAN- Molecular fingerprint of the coating polymer and the corrosion products.
- HW/UVSPEC- UV and visible emission properties of the coated and uncoated surfaces
- HW/MPROF - Quantitative measurements of surface texture and roughness at micrometric level
- HW/HDMSRI- Check of the surface appearance of material samples
- HW/MSRTI- Check of the surface appearance of material samples

Check at 3 and 9 weeks:

- HW/FTIR- Molecular fingerprint of the coating polymer and the corrosion products.
- HW/RAMAN- Molecular fingerprint of the coating polymer and the corrosion products.
- HW/MPROF - Quantitative measurements of surface texture and roughness at micrometric level
- HW/HDMSRI- Check of the surface appearance of material samples
- HW/MSRTI- Check of the surface appearance of material samples

7.3.3 Silver materials

Check before ageing, after 4 (T1) and 10 (T2), 24 (T3), 48 (T4) and 72(T5) hours of exposure with the full-list probes reported for bronzes.

8. Spatiotemporal Simulation and Reconstruction

8.1 State of the Art (SoA)

The role of material ageing simulation is quite relevant in many Computer Graphics applications, in particular for simulation, visualization and printing of 3D reconstructions of Cultural Heritage artefacts. Relevant efforts have been carried out in recent years to render images and 3D objects with simulated changes in shape and appearance due to ageing phenomena, and interesting results have been obtained regarding the photorealistic rendering of aged surfaces, but the intrinsic complexity of the problem, including different types of ageing processes (chemical, mechanical, biological) and the enormous number of factors influencing each process, depending also on the external environment, on the object geometry, etc. makes very hard to develop a modelling/simulation pipeline.

These processes affect in a visible way, sometimes even simultaneously, one or more object features: reflection properties, colour, texture or geometry. Hence, it is indicated to consider in all these dimensions, as excluding one attribute might give misleading clues on the holistic aspect change of an object [84]. Obviously, the interaction between the aging agents and the material composition creates a strong dependency between the progressive behaviour of the aging effect and the “host” material. Therefore, even though a generic model is desired, a not-negligible starting point for inferring behavioural rules may also be an object-wise approach. It is noteworthy to mention that the main objects of concern in the Scan4Reco project are metallic samples (bronze-based, silver-based), paintings, frescoes and icons. In terms of appearance, bronze and silver objects can be mainly altered by: patina, erosion, scratches, dust and dirt accumulation. Meanwhile, paintings, frescoes and icons are strongly affected by fading, bleaching, and discoloration due to the use of not-stable pigments or darkening provoked by the varnishing layer [105-107], as well as the occurrence of cracks and fractures [108].

Interesting surveys about ageing simulation methods are available in the computer science literature, like the work of Merillou and Ghazanfarpour [83] or the more recent by Frerichs et al. [84]. Among the various techniques used to simulate ageing effects proposed, we can distinguish methods to model and simulate cracks and fractures, methods to model and simulate microscopic structure and appearance due to material specific physical and chemical behaviours, data driven reflectance and texture modelling. Another important aspect is then related to the spatial modelling of different ageing effects. In the following sections we summarize the state of the art related to these selected tasks.

8.1.1 Cracks, fractures and material specific chemical phenomena

There are several works on modelling and simulating three-dimensional cracks and fractures, with the majority of the respective papers falling in two categories. In the first one, there are approaches that pre-compute a crack pattern and apply it to a three-dimensional model of an object in order to speed up computation. The other category consists of on-the-fly algorithms that achieve a more realistic physical behaviour at the cost of an increased computational burden.

On-the-fly methods typically adopt a segmented 3D representation, such as a tetrahedral mesh and then rely on physically-based techniques such as mass spring systems, Finite Element Method (FEM) [123] or Boundary Element Method (BEM) [124] to achieve a realistic simulation. In [85],[86], the object is represented by tetrahedral meshes, where the vertices act as point masses and the edges as springs forming a mass-spring system governed by the laws of spring dynamics. The size of the mesh is crucial for the visual accuracy and usually, a 'jagged' crack appearance is the result of the restrictions of the cracking path to the mesh's edges.

Although mass spring systems are a simple and fast method, they present some restrictions concerning the flexibility of the mechanical behaviour representation and thus, the realistic visual outcome. In this way, for increased physical accuracy finite differences methods are preferred. In [87], the FEM method is used to solve elastoplastic dynamics for ductile fractures that evolve on a level set using the Griffith's energy minimization as the fracture evolution criteria. However, level set methods are restricted in representing thin geometry and usually are memory expensive. Another approach was presented in [88] which considers inelastic deformations and defines bending strains on the faces of a triangulated mesh, where the fracture paths are formed. The triangle vertices constitute the finite element discretization to solve the elastoplastic equation using FEM. Fracture paths are not restricted to triangle edges, but can fracture individual triangle faces, too. A work that handles cracking and fracturing of heterogeneous multiple layer objects is the one in [89], which simulates thin-plate fracturing of paper-like objects represented by a triangle mesh that is used as a finite element discretization to solve the thin plate dynamics. In this framework, another notable work was presented in [90], where the boundary element method (BEM) is used in combination with a coarse computational mesh and high-resolution crack propagation. Crack initiation depending on stress is handled separately from crack propagation, which is governed by stress intensity factors. A low-resolution mesh and the interpolation of the stress intensity factors during crack propagation manage to decrease the computational complexity of the BEM method.

Methods that create crack patterns offline and apply them to objects at run-time include a series of works. One such method was described in [91], which creates cracks as two-dimensional meshes with depth values that can be mapped onto the object. The shrinkage volume propagation method was used for the crack propagation. Because of the surface representation choice, the cracks can only start from and run along the surface of the object and thus, internal cracks' representation is not possible. A method that considered volumetric fracture patterns was described in [92], where the bounding box of the object is used to create a volumetric fracture pattern that is rotated and translated until its impact point, where it emanated, matches with the respective point of the simulation mesh. In order to merge the volumetric fracture pattern with the simulation mesh a level set representation of the object should be constructed.

Another method that avoids the use of level sets was presented in [93], which uses Voronoi decomposition to segment the mesh into convex pieces, where the pre-computed fracture patterns can be applied directly. Accurate representation of cracks' details is possible through this method along with a real-time simulation for large objects. However, the fracture patterns in this work are not physically-based created, but they are designed by specialists. A related non-physically-based approach is described in [94], where fracture-related statistics are extracted from an object's photographs through time and then applied to the 3D object.

On the other hand, the geometrical structure of artworks can be destroyed by chemical phenomena such as the creation of patina. In the work presented in [95] a layered representation of the object is used, where each layer is homogeneous with space varying thickness. The layers' thickness changes using special operators and representing in this way the adding or removing of material. Fractal surface growth models are used to control the depositing and growth pattern of patina. The physical phenomena behind patina are not simulated in this way and unfortunately, no geometric deformations are modelled by this method. Simulation methods have been proposed as well for corrosion of metals [28] and weathered stone [111], even if it the huge number of parameters of corrosion models and the variety of environmental conditions influencing it [112] makes a more controlled and sophisticated simulation quite hard.

8.1.2 Appearance modelling and simulation

To overcome the problems of physically motivated simulation rules, requiring the knowledge of a lot of material and environment parameters, a common trend in appearance and geometrical change simulations in Computer Graphics is the use of a data driven approach extrapolating temporal /and spatial) degradation models from example measures. A well-known example of modelling of appearance variation depending on different ageing factors has been proposed by Lu et al. [99] who also defined the classification of ageing phenomena used also in [84].

In computer graphics methods, the common implementations to model surface properties are the BRDF (bidirectional reflectance distribution function) and BTF (bidirectional texture function) [99]. In [109] it is thoroughly exposed how BTF offers a highly realistic approximation of the texture appearance, especially for rough surfaces that can otherwise be rendered unrealistically flat by traditional methods which discard changes in view and illumination. In [100], the concept of Space-Time Appearance Factorization (STAF) is introduced and based on extended versions of BRDF and BTF: time and space-varying BRDF (TSV-BRDF) and time-varying BTF (TBTF). STAF is a data-driven model that segregates the aging effects into changes in the spatial dimension and, respectively, changes in the temporal dimension. Treating distinctively the spatiotemporal variations into its components allows for the estimation of a “temporal characteristic curve” that is exclusively dependent only on the physical aging process, letting aside the spatial constancy of the unchanged textures. The complete separation of space and time allows the interchange between different combinations of temporal effects and static surfaces, meaning that the STAF model provides estimations that can be applied on data external to the data used for the creation of the model.

Wang et al [101] estimated a time dependent appearance model from single spatial-varying acquisitions of surfaces and a complex texture synthesis method able to incorporating time evolution of patches. Bellini et al [102] proposed a method to estimate de-weathered and weathered images from single examples. They associate the time parameter (degree of weathering) at different regions of the input texture to the prevalence of anomalous texture patches.

8.1.3 Modelling various weathering factors

Another approach for weathering phenomena simulation consists of modelling the behaviour of weathering entities in the environment. An example of this approach is presented in [96], where special particles called, gamma-tons, carrying wear-inducing materials move through the scene, where the object is placed, and deposit or pick up materials from its surface every time they collide with it. Deposit materials are stored in “surfels” that are used for the weathering effects creation. On the other hand, the method described in [97] uses texture maps to store the deposit materials and the entire approach runs on the GPU. However, both these methods are non-physically based.

Finally, a framework for the geometrical and visual simulation of a wide variety of aging processes that may be interacting sometimes is introduced in [123]. In this framework numerous particles, called μ-tons, scatter in the environment and mutate and age the world. The decay effects and the underlying geometry of the object are discretized and the mutation process causes alterations both on the external surface of the object and on the internal volume substrate.

8.2 Evaluations and Selection of Candidate Technologies

As is described in [127], the Scan4Reco project requires two software components. SW/AGING processing probe measurements and associated semantic descriptors in order to derive parametric and probabilistic material-specific ageing models and SW/SIMULATION providing visual simulation of aging and weathering processes of various materials under a multitude of parameters defined by the computed material aging models. It simulates deterioration of appearance and composition.

There were some basic criteria defined for the evaluation and the selection of the candidate technologies for the spatiotemporal simulation and the reconstruction. The criteria were chosen based on the targets of the relative project tasks. Thus, the development of possibly unified approaches that will be able to simulate different kinds of phenomena at the same time in the shortest time possible and with the greatest realism and visual accuracy possible was put on the top priorities for the implementation of the spatiotemporal simulation system.

Table 9: Classification of literature related to geometrical ageing methods

Papers	Multiple aging phenomena representation	Material Heterogeneity considered	Physically-based method	Computational complexity	Visual quality
[4], [5]	No	No	Yes	Low	Medium
[6],[7]	No	No	Yes	High	High
[8]	No	Yes	Yes	High	High
[9]	No	No	Yes	High	High
[10]	No	No	Yes	Medium	Medium
[11]	No	No	No	High	High
[12], [13]	No	No	No	Low	High

Another feature of great significance for Scan4Reco would be the ability of the relative methods to handle heterogeneous objects made of a variety of materials with various properties. In addition, the representation and simulation of both the object's appearance and the geometrical structure's alterations are among the main goals of the spatiotemporal simulation task of Scan4Reco.

Finally, the overall novelty of the chosen methods is another important factor that should be taken into consideration during the development of the relative technologies. For geometrical-only ageing method we will consider the result of the following table, classifying the reviewed literature according to relevant criteria. For the modelling and the simulation of appearance the Scan4Reco approach will be based on a data driven modelling based on the processing of the multimodal measurements performed on samples. This means that we will use generic regression techniques to link the age-related parameters provided with the samples to the measurements and the extracted descriptors.

The current work on appearance capture with RTI could be a basis for the characterization with a simplified BRDF or spatially varying BRDF the tested materials, and we are currently evaluating reflectance functions fitting the reflectance data captured. This could in principle allow to estimate reflectance from acquisitions with other modalities by evaluating the regression functions relating different measures with reflectance measurements. The most challenging aspects of the study will consist in the availability of sufficient time samples and also in the characterization of the spatial pattern for measured simulated materials. From the research on data driven modelling we selected potential methods that could be applied to encode and synthesis of spatially varying reflectance functions.

Table 10: Synthesis of methods from literature and related to geometrical ageing

Papers	Model	Features/descriptors	Input data	User-input	Aging effects	Highlights handling	Weathering transfer
[18] Gu	Space-Time Appearance Factorization	TSV-BRDF; TBTF	Time-series data	No	Multiple	Yes	Yes
[17] Lu	Context-aware textures	Geometric local features (e.g.: curvature)	Time-series 3D scans and colour images	Yes	Rust, cracks, mould growth	No	Yes
[35] Bandeira	Appearance map	Chroma, Luminance	1 single 2D image	Yes	Rust, material growth, decay	Yes	Yes
[32] Zhou	Curvature Analysis and Colour Transition	Curvature; Colour	3D models; colour images	No	Dust accumulation, rust, colour fading	No	Yes
[9] Wang	Appearance manifold	SVBRDF	1 time-instant SV BRDF data	Yes	Appropriate for low-frequency effects/smooth transitions	No	Yes
[10] Bellini	Age map	Texture patch-prevalence analysis	1 single 2D image	No	Effects characterized by non-repetitive patterns: cracks, dust, stains	No	Yes
[32] Xuey	Appearance manifold	Chroma; Luminance	1 single 2D image	Yes	Rust, discoloration	No	Yes

Considering the reviewed literature, the following table synthetize the proposed methods features:

As the characterization of the materials will be made in lab, it is clear that its application for the characterization onsite on object differently exposed to aging factors due to geometrical and environmental reasons has to be considered with care. However, there are many examples in the literature of algorithms predicting aging effect strength according to geometrical and physical factors. Models available in the literature could be used to adapt the ageing process to real artefact non uniformly exposed to ageing factors [100,101]. The methods proposed in [99,100] could be a starting point for our appearance modelling/simulation method. However, we should not couple the time modelling of texture/appearance models with spatial map of environment- and shape-based ageing probability. This will be done in a separate simulation framework. Methods proposing more general frameworks able to deal with heterogeneous materials and ageing factors modelling are summarized in Table 11.

Table 11: Summary of methods related to heterogeneous materials and ageing framework

Papers	Multiple aging phenomena representation	Appearance alterations	Geometrical structure's alterations	Material Heterogeneity considered	Physically-based method	Computational complexity	Visual quality
[14]	No	Yes	No	Yes	Yes	Medium	Medium
[15], [16]	Yes	Yes	Yes	Yes	No	Medium	Medium
[41]	Yes	Yes	Yes	Yes	No	Medium	High

The most fully-featured approach that leaves also room for further research perspectives and covers most of the main goals of the spatiotemporal simulation and reconstruction for the Scan4Reco seems to be the "μ-ton" framework. It offers all the means for realistic simulation and visually approved representation of a wide range of aging processes deteriorating both the appearance and the structure of objects. A significant advantage of this method is also that many interacting weathering phenomena can be handled and for all these reasons, the “μ-ton” framework is chosen as the dominant candidate.

8.3 Conclusions and directions for applied research

From the analysis of the project requirements and the first experiments on the characterization of artworks materials surfaces, it is clear that we should focus the research on simplified, but useful and challenging tasks on specific types of degradation, exploiting the opportunity of having data samples. A data driven approach is therefore reasonable at least for training systems able to distinguish different material treatments and estimating time related variable from measurements. Considering appearance modelling and reproduction, it must be considered that, while many of the approaches presented in the reviewed literature deal with measurement and reproduction the same appearance parameters, in in Scan4Reco we have multimodal measurements. For rendering purposes, we need to simulate colour or BRDF/BTF functions, so that it will be useful to associate different kind of measurements (roughness, composition, etc.) with corresponding values for these appearance functions.

The key components of the systems we have to develop are therefore, are a Pattern Recognition tool able to map partial or global sets of measurements in a compact parametric representation of the material with an associated aging value and a simulation engine, able to generate BTF, BRDF, etc., from the estimated parameters. For this task, in addition to measurements conducted throughout Scan4Reco, data from past research initiatives [128],[129] will also be considered. There are a lot of methods for generating textures having examples [114-116] and we just have to select the most suitable for each expected application. Given a restricted range of materials and ageing conditions we can map measurements over predicted parameters and a database of reflectance/textures. Examples of prediction of reflectance properties using measurement have been successfully proposed in the literature [118,119], at least for micro-profilometry, and their use for artworks material is one of the goals of Scan4Reco.

For the implementation of the μ-ton framework, in order to make it work properly we need the definition of the aging-related parameters such as the kinds and portions of wear-inducing materials that the μ-ton will deposit or pick up from the object’s surface or the colour changes caused through aging. However, there does not exist any known mathematical relationship between the spectrogram data collected by the sensors and the material degradation procedure. In fact, there are high-dimensional non-linear relationships that are difficult to identify and model. Moreover, the current research works focus on the analysis of material degradation under known external influences (e.g. chemical substances, ultraviolet light etc.) and not on the modelling of material aging from spectrograms.

A proposed solution would be the modelling of the material aging using Deep Neural Networks (DNN). DNN are able to efficiently identify and model high-dimensional non-linear relationships between the input /output data and achieve state-of-the-art performance in multiple research fields, e.g. image recognition, natural language processing, recommendation systems etc. Moreover, they have not yet been directly used for material aging research, but they have been used for simulation/modelling [130] as well as for regression purposes (e.g. non-invasive cuffless blood pressure monitoring [125], time series modelling [125] etc.). In this way, DNN can be used to sample the learned data distributions for example to generate possible different material aging representations under the same spectrogram.

The implementation of ageing simulation requires empirical rules to be derived by performing speeded up ageing of real materials under simulated conditions. Such rules defining change in material chemical composition, speed of the process and depth over time and under given conditions will allow performing such operations on 3D models and thus making knowledge-based prediction of their future deteriorations, offering an invaluable tool for curators and restoration experts.

The current state of the art in surface ageing modelling and simulation includes a variety of approaches that present interesting features for Scan4Reco applications, but also constraints and limitations due to the intrinsic complexity of the task. The outcome of identified techniques will heavily depend on the quality and amount of data acquired for the material characterization. Simulation features and algorithms will necessarily have to be adapted to measurements and acquisitions carried out on project samples and on all the other available data found on the materials and ageing phenomena of interest.

9. Realistic 3D Printing

9.1 State of the Art (SoA)

In order to reproduce not only the shape but also optical material properties or visual attributes (spatially-varying colour, gloss and translucency), a 3D printing system must be able to combine multiple materials into the printing object with high spatial resolution. At least 300 dpi (allowing to print a material raster of approx. 85 µm) in each spatial dimension is required for obtaining visually pleasing colour reproductions for typical viewing conditions (office luminance level and 50cm viewing distance). For gloss reproduction a much higher spatial resolution is required. Only a few technologies allow multilateral 3D printing with this resolution. These are material jetting, binder jetting, laminated object manufacturing and multi jet fusion. The overview of 3D printing technologies is shown in Figure 12. Technologies marked in red are able to combine multiple materials into a single object.

9.1.1 Material Jetting (PolyJet and MultiJet Modelling) (Source [171])

Material Jetting technologies are similar to inkjet printing, but instead of jetting drops of ink onto paper, these 3D printers jet layers of liquid photopolymer onto a build tray and cure them instantly using UV light.

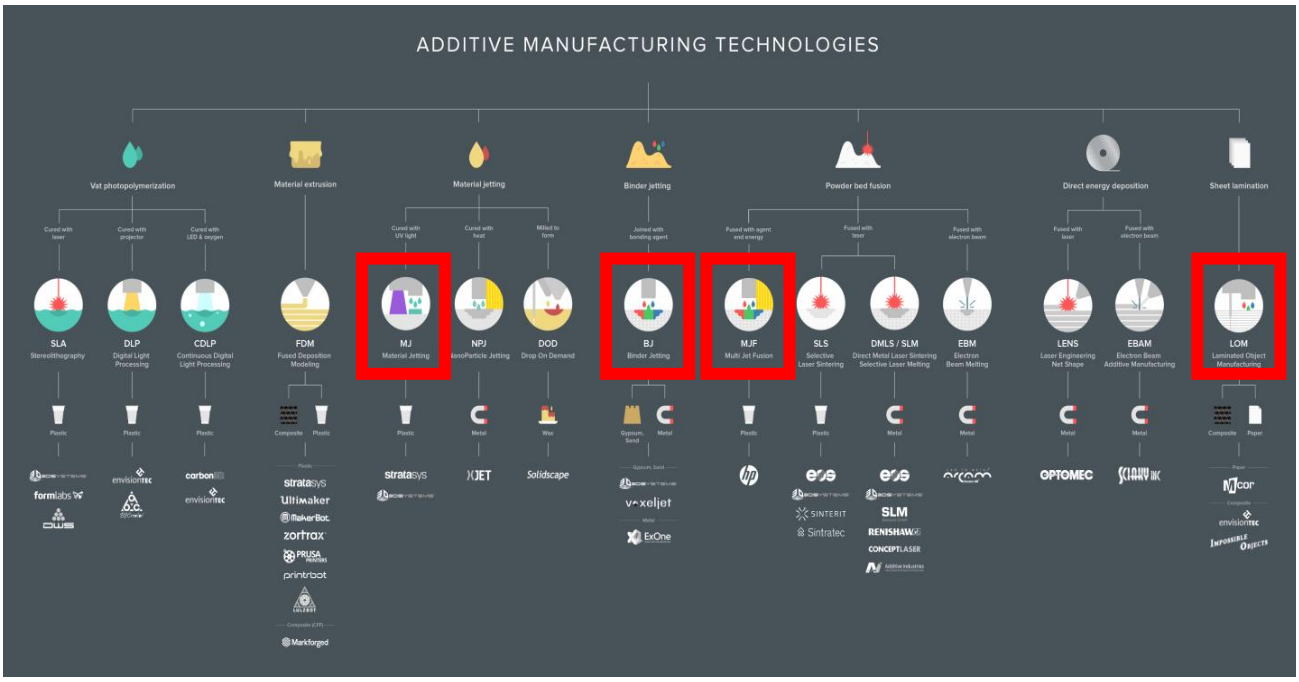

Figure 12: Additive 3D printing technologies incl. manufacturers13

[13] Additive 3D Manufacturing: https://www.3dhubs.com/talk/thread/additive-manufacturing-infographic

The build process begins when the printer jets the liquid material onto the build tray. These jets are followed by UV light, which instantly cures the tiny droplets of liquid photopolymer. As the process is repeated, these thin layers accumulate on the build tray to create a precise object. Where overhangs or complex shapes require support, the printer jets a removable gel-like support material that is used temporarily, but can be removed after the print is completed.

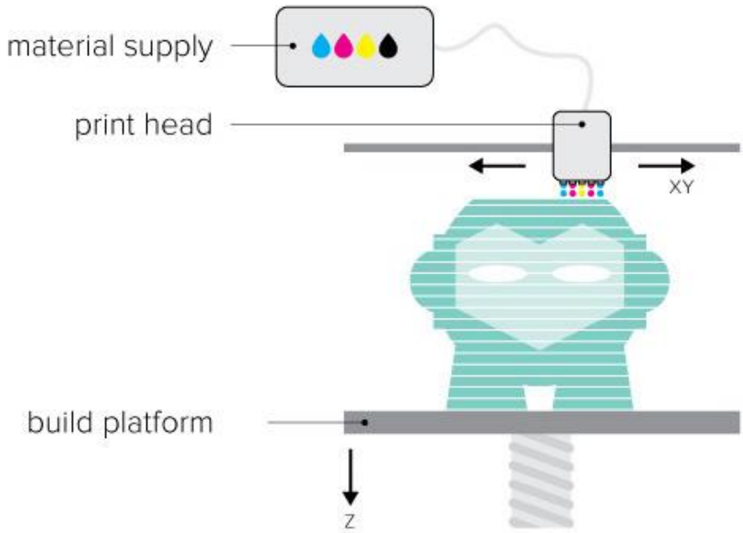

Figure 13: Material Jetting [171]

Material Jetting is used in industrial 3D printers (Figure 13). Material choices consist of liquid photopolymers that can provide the final objects various properties including toughness, transparency or rubber-like flexibility. The most advanced systems can use multiple jets that allow for the combination of different material properties and colours.

Material Jetting offers many advantages for rapid tooling and prototyping, as it allows users to create realistic and functional prototypes with fine details and precision. These are the most precise multi-material 3D printing technologies today, printing with up to 16 µm layers.

The most advanced 3D printer using this technology is Stratasys' J750 with 6 building materials (cyan, magenta, yellow, black, white and clear materials are available and can be simultaneously used in a single print) and a support material [171]. This allows not only printing in full colour, but also adjusting the translucency of the object using the clear material. Also experimental laboratory systems with this technology were proposed [178].

9.1.2 Binder Jetting

The binder jetting technology uses thin layers of powdered material to build up an object by extruding a binding agent from a nozzle to bind the powder together. [171]

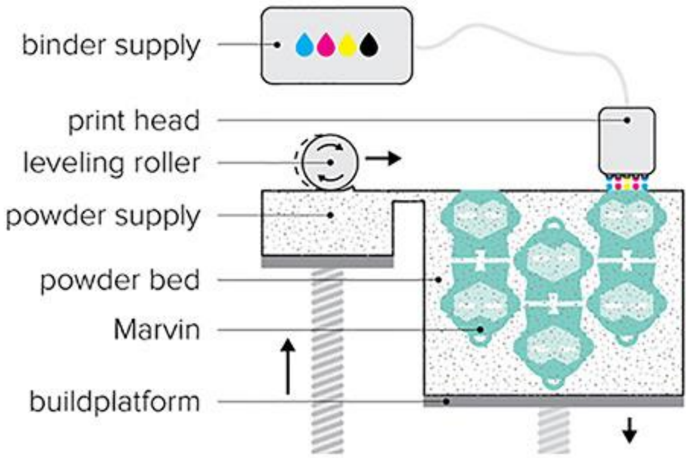

Figure 14: Binder Jetting [171]

The process starts with a nozzle spreading the binding agent across the first layer of the object and binding the powder together. Once the first layer has been fused with the binding agent, the printing bed moves down slightly and a thin layer of new powder is spread atop the object. This process repeats until the desired object has been fully formed. After it is removed from the print bed, the object is cleaned from excess powder and coated with an adhesive glue to give it strength and to make it resistant to discoloration. Example of full-colour 3D printers using this technology is the Project series from 3D System [173] is shown in Figure 14.

9.1.3 Laminated Object Manufacturing

A laminated object manufacturing 3D printer uses sheets of material — plastic, paper or (less commonly) metal — which is fed into the build space. [174] Plastic and paper build materials are often coated with an adhesive. To form an object, a heated roller is passed over the sheet of material on the build platform, melting its adhesive and pressing it onto the platform. Alternatively, the sheets can also be glued using a jetted binder. Using multiple coloured binders allow full-colour prints. A computer-controlled laser or blade then cuts the material into the desired pattern. The laser also slices up any excess material in a crosshatch pattern, making it easier to remove once the object is fully printed.

After one layer of the object is formed, the build platform is lowered by the thickness of one layer. New material is pulled across the platform and the heated roller again passes over the material, binding a new layer to the one beneath it. This process is repeated until the entire object has been formed. Once an object is printed, it is removed from the build platform and any excess material is cut away.

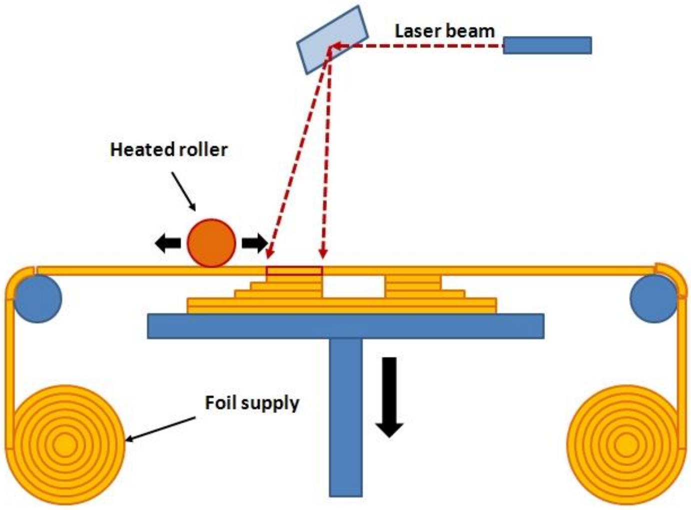

Figure 15: Laminated Object Manufacturing [177]

The MCor company manufactures full-colour printers possessing this technology. Also a small desk-top 3D printer, the Mcor ARKe, is available [175]. The process is shown in Figure 15.

9.1.4 Multi Jet Fusion

As with many 3D printing processes, Multi Jet Fusion starts by laying down a thin layer of powdered material across a build area. [176] Then, the carriage containing an inkjet array passed from left-to-right, printing chemical agents across the full working area. The technology uses a multi-chemistry process, including a fusing agent that is selectively applied where the particles will fuse together, as well as a detailing agent that is selectively applied where the fusing action needs to be reduced or amplified. As one example, the detailing agent reduces fusing at the boundary to produce parts with sharp and smooth edges. Multiple fusing agents can be used to produce spatially-varying color and translucency. A multimaterial printing system using the multi jet fusion technology is not on the market so far. However, sample full-color prints from a prototype 3D printer exist and HP announced that full-color systems will be delivered in 2018/2019.

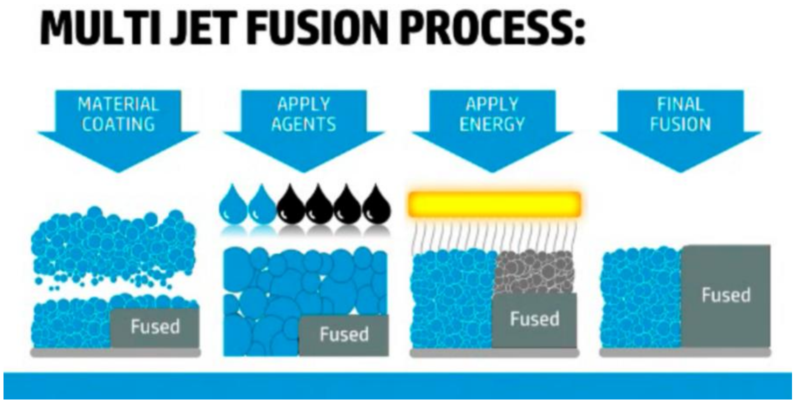

Figure 16: Multi Jet Fusion [176]

9.1.5 Controlling multi-material 3D Printers

Such software is necessary to load a 3D model with annotated visual properties (e.g. a colour texture) and to place available printing materials to reproduce both the shape and the visual properties of the input. Various signal processing steps are necessary to control the printers: slicing or voxelizing the shape, appearance or colour gamut mapping of non-printable visual attributes to be reproduced with minimal perceptual disagreement to the original, colour separation by inverting an optical printer model to obtain the amount of printing materials necessary to reproduce the gamut mapped visual attributes, and half toning or contoning on curved surfaces to arrange the printing materials in a visually pleasant way [178].

Almost all commercial multi-material 3D printers come with a proprietary software and are closed systems, i.e. no application programing interface (API) is available to allow accessing the printer's firmware. Which algorithms are used for the signal processing pipeline (slicing, voxelization, gamut mapping, separation, half toning, contoning) is unknown to the authors.

Only two 3D printing manufacturers allow controlling the printing systems by third parties: For Stratasys' J750, a *Voxelprint* interface is available for non-commercial purposes, allowing positioning printing materials on a droplet level. This allows Fraunhofer IGD's voxel-based 3D printer driver *Cuttlefish* [179] to reproduce both colour and translucency of input 3D models (RGBA texture). HP has announced that its multijet fusion printers are open for both materials (an HP certification is necessary for third party materials) and software. HP will provide an API for controlling the printers.

9.2 Evaluations & Selection of Candidate Technologies

Since no commercial multi-jet fusion full-colour printers are available so far, this printing technology cannot be considered for Scan4Reco. However, methods developed in the Scan4Reco project should be applicable also for controlling multi-jet fusion 3D printers.

In comparison to binder-jetting and laminated object manufacturing systems, multi-jet printers produce smoother surfaces at higher resolutions, and allow more control over the internal structure of the print. For instance, to reproduce given translucencies or to create fully transparent layers revealing structures underneath the surface. In the longer term, such printers have much greater potential to reproduce complex appearance properties. In fact, multi-jet printers with two materials have been used to approximate desired single-tone subsurface scattering properties [181][182], and opaque objects inside transparent shells [183].

In addition to the quality considerations, Stratasys' Voxelprint allows us to test developed methods by controlling a multi-jet printer with 6 materials on a droplet level. No other manufacturer of 3D printers on the market provides such a basic access to control material positioning.

In conclusion, the multi-jet technology is selected for the purpose of realistic 3D printing in Scan4Reco.

9.3 Conclusions and Directions for Applied Research

Research in the area of realistic 3D printing is in its infancy. Even though the problem of reproducing albedo colour is mostly solved [178], reproducing other visual appearance properties such as translucency, gloss or directional reflectance in addition to colour is still an active research area. In addition to developing new materials for enlarging the capabilities of printing systems to reproduce visual appearance properties, e.g. by using inks in material jetting with considerable different refractive indexes allowing to reproduce highly specular surfaces, the following two research directions are critical for realistic 3D printing:

- Developing a physical optical printer model, which is a predicting function of the Bidirectional Surface Scattering Reflectance Distribution Function (BSSRDF) [184] give an arrangement of printing materials and print-process parameters (e.g. UV exposure). Even though Monte Carlo path tracer [185] allow solving the radiative transfer equation [186] for a given arrangement of printing materials and thus theoretically provide an optical printer model, this approach is extremely slow and therefore not practicable. Furthermore, real material arrangements deviate considerably from the ideal voxel representation. Fast and accurate optical printer models requiring only a few printed samples for parameter fitting are a prerequisite for reproducing desired appearance properties. This is particularly important if multi-material printing system employ many printing materials for which data-driven approaches are limited.

- All printing systems are inherently limited in reproducing BSSRDFs. One of the fundamental challenges is to develop a gamut mapping algorithms allowing to reproduce non-printable visual attributes with a minimal perceptual disagreement to the input. Performing this gamut mapping in a low dimensional perceptually meaningful space (in particular perceptually-uniformity without cross-correlation between visual attributes) is beneficial because perceptual distances are nearly Euclidean and single attributes can be altered without changing others. This is directly linked to the low dimensional interim connection space that shall be developed in the Scan4Reco project (WP6) for communicating visual properties for 3D printing.

10. 3D Model Formats

The SCAN4RECO project develops digital technologies that directly employ 3D object models. They are produced from diverse types of both visual and penetrating scanning, which individually provide only partial; view of the object and hence they need to be integrated into a single model of the object, showing both its external shell as well as each of the material layers. Subsequently, those models are expected to be used for realistic reproduction using 3D novel printing techniques, going far beyond the current state of the art and hence putting stress on the flexibility of 43D model definitions, such that new features, e.g. occlusions, reflections and touch, to mention just few, could be reproduced realistically. Lastly, evolution of the 3D models will be required through morphing techniques, such that the artificial ageing process could be realistically simulated. The latter one will make use of experiences and rules established through speeded-up ageing of sample materials by OF-QADC and OPD.

In order to support all those types of 3D processing, it was necessary to investigate existing 3D model formats in view of determining the most suitable for both multi-layer modelling, flexible enough to offer ways of adding new features required for printing and ageing. The results of such analysis has been outlined below, starting from the list of known 3D formats, leading to the identification of the most suitable ones that will be used as common 3D format in the project. Since 3D model formats are used in the architecture for several specific needs (permanent storage, exchange between components, communication with external ones), hence formats presented in this chapter are mostly related to import/export and interfaces among project components, whereby internal data structures might vary depending on the specific needs of each of the component in the project architecture.

10.1 Common 3D File Formats

10.1.1 Wavefront OBJ format

OBJ is a geometry definition file format first developed by Wavefront Technologies[14] for its *Advanced Visualizer* animation package. The file format is open and has been adopted by other 3D graphics application vendors. For the most part it is a universally accepted format. The OBJ file format is a simple data-format that represents 3D geometry alone — namely, the position of each vertex, the UV position of each texture coordinate vertex, vertex normals, and the faces that make each polygon defined as a list of vertices, and texture vertices. Vertices are stored in a counter-clockwise order by default, making explicit declaration of face normals unnecessary. OBJ coordinates have no units, but OBJ files can contain scale information in a human readable comment line.

OBJ format specification can be found at: http://www.martinreddy.net/gfx/3d/OBJ.spec

[14] Wavefront Technologies: https://www.wvfront.com

10.1.2 STereoLithography (STL) format

STereoLithography (STL) is a file format native to the stereolithography CAD software created by 3D Systems. STL has several after-the-fact backronyms such as "Standard Triangle Language" and "Standard Tessellation Language" [4] This file format is supported by many other software packages; it is widely used for rapid prototyping, 3D printing and computer-aided manufacturing. STL files describe only the surface geometry of a three-dimensional object without any representation of color, texture or other common CAD model attributes. The STL format specifies both ASCII and binary representations. Binary files are more common, since they are more compact. An STL file describes a raw unstructured triangulated surface by the unit normal and vertices (ordered by the right-hand rule) of the triangles using a three-dimensional Cartesian coordinate system. STL coordinates must be positive numbers, there is no scale information, and the units are arbitrary.

STL format specification can be found at: http://www.fabbers.com/tech/STL_Format

10.1.3 X3D format[15]

X3D is a royalty-free ISO standard XML-based file format for representing 3D computer graphics. It is successor to the Virtual Reality Modeling Language (VRML). X3D features extensions to VRML (e.g. CAD, Geospatial, Humanoid animation, NURBS etc.), the ability to encode the scene using an XML syntax as well as the Open Inventor-like syntax of VRML97, or binary formatting, and enhanced application programming interfaces (APIs). The X3D extension supports multi-stage and multi-texture rendering; it also supports shading with lightmap and normalmap. Starting in 2010, X3D has supported deferred rendering architecture. Now X3D can import SSAO, CSM and Realtime Environment Reflection/Lighting. The user can also use optimizations including BSP/QuadTree/OctTree or culling in the X3D scene. X3D can work with other open source standards including XML, DOM and XPath.

X3D defines several profiles (sets of components) for various levels of capability including X3D Core, X3D Interchange, X3D Interactive, X3D CADInterchange, X3D Immersive, and X3D Full. Browser makers can define their own component extensions prior to submitting them for standardisation by the Web3D Consortium. Formal review and approval is then performed by the International Organization for Standardization (ISO). Liaison and cooperation agreements are also in place between the Web3D Consortium and the World Wide Web Consortium (W3C), Open Geospatial Consortium (OGC), Digital Imaging and Communications in Medicine (DICOM) and the Khronos Group. A subset of X3D is XMT-A, a variant of XMT, defined in MPEG-4 Part 11. It was designed to provide a link between X3D and 3D content in MPEG-4 (BIFS). The abstract specification for X3D (ISO/IEC 19775) was first approved by the ISO in 2004. The XML and ClassicVRML encodings for X3D (ISO/IEC 19776) were first approved in 2005.

There are several applications, most of which are open-source software, which natively parse and interpret X3D files, including the 3D graphics and animation editor Blender[16] and the Sun Microsystems virtual world client Project Wonderland[17]. An X3D applet is a software program that runs within a web browser and displays content in 3D, using OpenGL 3D graphics technology to display X3D content in several different browsers (IE, Safari, Firefox) across several different operating systems (Windows, Mac OS X, Linux). However, X3D has not received as wide acceptance as that of other, more notable software applications. In the 2000s, many companies such as Bitmanagement improved the quality level of virtual effects in X3D to quality level of DirectX 9.0c, but at the expense of using proprietary solutions. All main features including game modelling are already complete. They include multi-pass render with low level setting for Z-buffer, BlendOp, AlphaOp, Stencil, Multi-

15 X3D format (Wikipedia): https://en.wikipedia.org/wiki/X3D
16 Blender: https://www.blender.org/
17 Project Wonderland: http://openwonderland.org/

texture, Shader with HLSL and GLSL support, real-time *Render To Texture*, *Multi Render Target (MRT)* and post-processing.

Striving to become the 3D standard for the Web, X3D is designed to be as integrated into HTML5 pages as other XML standards such as MathML and SVG. X3DOM is a proposed syntax model and its implementation as a script library that demonstrates how this integration can be achieved without a browser plugin, using only WebGL and JavaScript.

X3D format specification can be found at: http://www.web3d.org/standards

10.1.4 Autodesk 3DS format

3DS is one of the file formats used by the Autodesk 3ds Max 3D modelling, animation and rendering software. It was the native file format of the old Autodesk 3D Studio DOS (releases 1 to 4), which was popular until its successor (3D Studio MAX 1.0) replaced it in April 1996. Having been around since 1990 (when the first version of 3D Studio DOS was launched), it has grown to become a de facto industry standard for transferring models between 3D programs, or for storing models for 3D resource catalogs (along with OBJ, which is more frequently used as a model archiving file format). While the 3DS format aims to provide an import/export format, retaining only essential geometry, texture and lighting data, the related MAX format also contains extra information specific to Autodesk 3ds Max, to allow a scene to be completely saved/loaded.

3DS format specification can be found at: http://www.martinreddy.net/gfx/3d/3DS.spec

10.1.5 Polygon File Format (PLY)

PLY is a computer file format known as the Polygon File Format or the Stanford Triangle Format. It was principally designed to store three-dimensional data from 3D scanners. The data storage format supports a relatively simple description of a single object as a list of nominally flat polygons. A variety of properties can be stored, including: colour and transparency, surface normals, texture coordinates and data confidence values. The format permits one to have different properties for the front and back of a polygon. There are two versions of the file format, one in ASCII, the other in binary. Files are organised as a header, that specifies the elements of a mesh and their types, followed by the list of elements itself. The elements are usually vertices and faces, but may include other entities such as edges, samples of range maps, and triangle strips.

PLY format specification can be found at: http://paulbourke.net/dataformats/ply/

10.1.6 3MF format

3MF is a new 3D printing format that will allow design applications to send full-fidelity 3D models to a mix of other applications, platforms, services and printers. The 3MF specification allows companies to focus on innovation, rather than on basic interoperability issues, and it is engineered to avoid the problems associated with other 3D file formats. 3D printers have evolved and innovated beyond the capabilities of today's 3D file formats. For example, one of the most common formats, STL, has significant limitations and issues, which the 3MF specification is specifically designed to avoid or overcome. 3MF is an XML-based data format – human-readable compressed XML — that includes definitions for data related to 3D manufacturing, including third-party extensibility for custom data. The 3MF format is designed to be an additive manufacturing format, with the complete model information contained within a single archive: mesh, textures, materials, colours and print ticket. 3MF provides a clear definition of manifoldness — open source code available for rapid validation and there is no ambiguity for models with self-intersections.

The 3MF format specification can be found at: http://3mf.io/specification/

10.1.7 Selection of Candidate technologies

For the time being the mutual agreement with Fraunhofer about the common 3D model format was that the most applicable formats are OBJ and 3MF. The first one is from one side the most commonly used, while being resistant to inconsistencies among various software than other formats. The 3MF format, even that still under development, shows a potential to become very flexible and future proof, especially that the 3MF consortium is willing to accept our suggestions for extensions to it.

10.1.8 Conclusions and Directions for Future Research

A review of existing 3D model formats has been performed by RFSAT in collaboration with Fraunhofer from the perspective of universality (ability to be used without conversions among vast number of software applications), interoperability (ability to be imported and used without loss of information) and flexibility for extensions (ability to add more features) to fit the needs of the Scan4Reco project.

The analysis has led to the following conclusions:

- Common 3D model format: the same 3D format should be used among project components such that to avoid translations, that might potentially lead to changed model representations and hence losses of information. Initially, the OBJ and 3MF formats have been selected as most universal and flexible for extension to fit the needs of the SCAN4RECO project.
- Water-proof 3D models are essential, i.e. without holes and undefined spaces/areas. This is a necessary condition for 3D models to be 3D printed correctly. This is also a condition for being able to perform integration from multiple 3D scans and then additional processing e.g. for simulated future deteriorations, etc.
- Integration of 3D scans may face problems when areas are overlapping. Hence, a detection of overlaps needs to be performed prior to integration, in simplest approach by performing weighted averaging, i.e. placing a common boundary to mid-ways between the overlapping areas using individual 3D scan accuracy as a weighting factor.

11. Summary of Findings

A constant technology inspection is the main objective of Task 2.2, such that to be aware of the continuous evolving of the state-of-the-art in the fields related to its activity within the project. Each participating partner has been assigned a role to perform a detailed analysis in the scientific areas he/she is involved within the framework of the project and thus, the pathways towards innovation and beyond state-of-the-art success would be identified and established. Among others, investigation and technical evaluation of various relevant hardware (HW) and software (SW) (e.g. budget sensors, high precision probes, infiltration capable sensors for 3D scanning, printers, etc.). Results of those experimentation will allow the selection of the most applicable 3D scanning sensors, modelling and reconstruction algorithms and SW, for the development of the realistic overall system architecture (Task 2.3) and the definition of necessary interfaces among sub-systems and modules, both HW and SW ones. Towards this target, the data fusion of requirements of the modules will be utilized will carefully selected, so as to prepare the ground for integration relevant tasks to follow, i.e. in Task 5.1 and Task 6.3.

Each chapter in this document has been dedicated to each individual subject and conclusions related to it have been discussed therein along with directions of further applied research and developments to be performed in order to mitigate any deficiencies and/or enhance list of features and/or the performance of the technologies and methods to be employed for the development of the final Scan4Reco system. In order to avoid repetitions, the reader is advised to refer for more details to each of the respective sections.

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