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Scan4Reco

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Deliverable

D2.2. System Architecture definition

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Executive Summary

This report describes the motivation and design of the architecture of the Scan4Reco system, which is intended to be modular and easily customized and to support flexible mixing and matching of individual components to address end-user needs. **This document is the public version of the deliverable D2.2 "System Architecture definition", which includes additional contents of interest only of the consortium.**

First, we provide a description of the scope and purpose of the document, and highlight the relation between the task leading to the definition of the architecture to other tasks of the project. Then, we summarize the end-user requirements, as identified in task T2.4 (project deliverable D2.3), and the conceptual architecture, as described in the project grant. This information is then analysed in order to determine high-level components, functionalities and system requirements that map the conceptual core elements to the end-user needs. The resulting architecture is then described in terms of macro component blocks and information flow among individual components.

A detailed initial description of each component is then presented in a standardized way. The component description includes, in particular, an initial functional specification, module interoperability specifications (e.g., data formats), and, where relevant, initial technical requirements (e.g., probes, hardware, software, storage, physiochemical procedures and protocols). **In this public version of the deliverable, the component description is shortened to remove unneeded details and currently confidential information.**

We conclude the document by describing how the various components and the entire system can be used in important cultural heritage use cases, as well as pilots in which the complete capturing and analysis pipeline will be tested during the course of the project.

The content of this deliverable is the basis for next project activities, such as work carried out in technological work-packages (WP3-WP6), as well as for the integration and validation trials (WP6-WP7).

Following the iterative project design guidelines, this document may be iteratively refined during project evolution to reflect the evolution of the state-of-the-art, as well as the improved understanding of end user needs and of their technological implications.

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1. Introduction

There is no single ideal signal that alone can succeed in analysing the whole nature of a cultural object (e.g., a painting or sculpture). In this scenario, Scan4Reco aims, through a modular and scalable multi-modal system, to bring significant innovations in the world of study and exploration of cultural heritage assets. In particular, by using both models derived from laboratory analyses and local and global measurements on cultural objects, Scan4Reco aims to combine in a seamless system functionalities that will include multi-modal scanning, time dependent and ageing analysis, interactive visualization, spatio-temporal simulation, rapid prototyping and support to conservators' decisions. All of these tools are strongly linked to specific requirements defined by scholars, conservators and other actors in the cultural heritage domain (see deliverable D2.3 or Sec. 2).

1.1 Purpose of this document

This report describes in detail the overall architecture of the Scan4Reco project, which is intended to be easily customized, user-friendly and modular (toolbox approach). The definition of the architecture relies on two main bases, i.e., the envisioned conceptual architecture and the end-user requirements. The conceptual architecture is the same proposed in the Grant [28], while the user requirements have been identified during the task T2.4 (project deliverable D2.3). Following the iterative project design guidelines, this document will possibly be iteratively refined during project evolution to reflect the evolution of the state-of-the-art, as well as the improved understanding of end user needs and of their technological implications.

In fact, the final system specification will be released in month 18 (D2.5), and the final architecture will be possibly refined until month 24. For this reason, a lot of attention has been put in balancing the level of detail of technical, functional and operational descriptions here, which has to be not too specific, in order to avoid useless constraints at this point of the project, but also not to general, in order to give a clear direction for all activities related to study, research and development. Taking into account this rationale, we will choose the proper level of granularity, which will be improved and developed in subsequent reports. We also present here the relationships between the end-users needs/requirements, the system functionalities and hardware, and the validation pilots, which all three help to define how the project must continue and the high-level view of its expected outcome.

1.2 Scope of this document

The scope of this document is the definition of an architecture that consists in the definition, the reinforcement and the consolidation of the partners' agreement and view about:

1. Scan4Reco general concepts and abstraction
2. Type of important use cases/pilots, taking into account the perspective of scholars, technicians and general public
3. Strong connection between stakeholders' needs and Scan4Reco research and development goals
4. Interoperability standards
5. An architecture fully compliant with end-user requirements

These results are the major fundamental guidelines for all tasks and WPs in Scan4Reco project, ranging from hardware/software specification and development to real world validation/test scenarios.

With this scope in mind, we first review the end-user requirements (Sec. 2) and the conceptual architecture of the project (Sec. 3). Then, we take these two elements and, by analysing end-user requirements in detail (Sec. 4) we present a breakdown of the conceptual architecture into functionalities and corresponding components. We present the description of the overarching system architecture, with a detailed view of its components, their modular design, their mutual relationships (Sec. 5), and the data formats used by the components (Sec. 7). Finally, we complete the document with a discussion of how components can be mixed and matched in several use cases and for the project planned pilots (Sec. 8). The document concludes with a summary of achievements and on their impact on other important tasks in the work plan (Sec. 9).

1.3 Relation with other WPs and deliverables

This deliverable is the outcome of the task 3 of work package 2. The main scope of the work behind this deliverable is to take all kind of inputs from end-user and technical actors, and transform them into system requirements first and finally into a coherent architecture (see Figure 1).

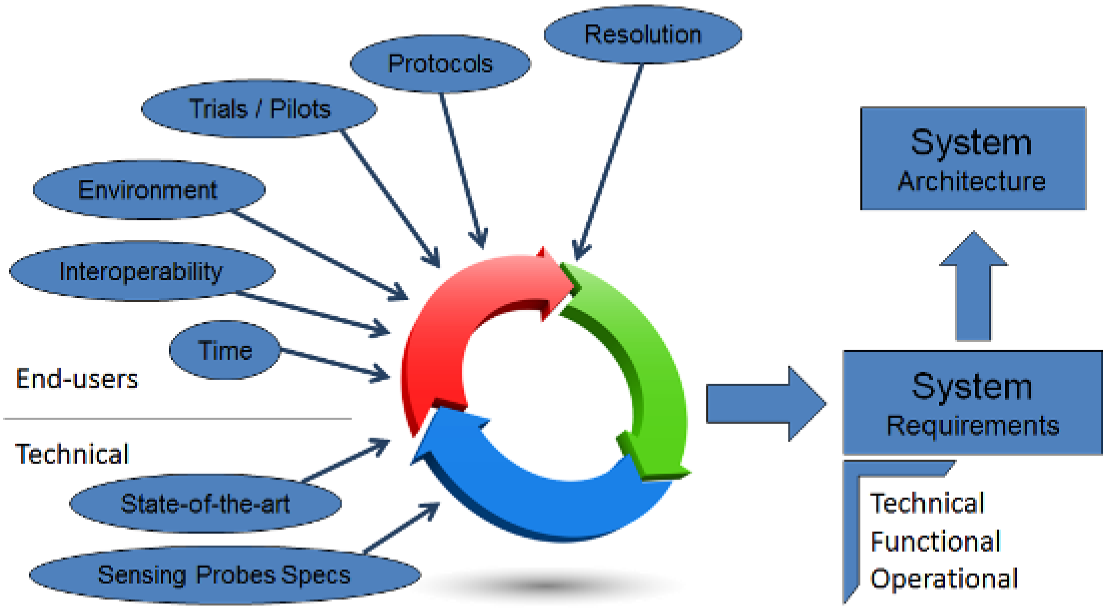

Figure 1 The definition of the system architecture started from input from CH end-users (environment conditions, protocols, trials/pilots, etc.) and technical partners (technology state-of-the-art, sensing probes, etc.). This information has been merged to identify technical, functional and operational requirements, responding to needs from CH scholars and ensuring technical feasibility.

Since it describes the designed global architecture of the project, it stands to reason that it has the majority of connections with all the other tasks and work packages. Figure 2 shows a schematic and simplified view of those relationships and dependencies.

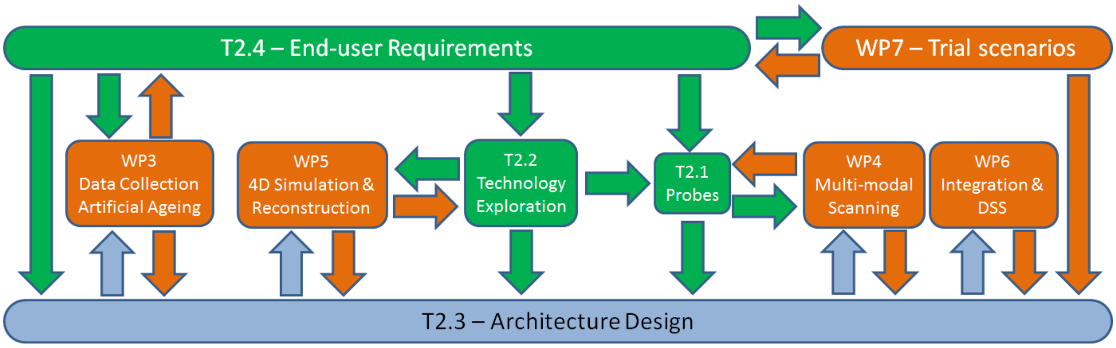

Figure 2 Summary view on how the architecture specification is connected with the rest of work packages and tasks in the Scan4Reco project.

The more evident dependencies are those with the task 2.4 (End-user Requirements) and the WP7 (Trials Scenario), which create a strong and necessary link between the technical design/implementation and the needs of scholars in the field of cultural heritage. These are represented by direct arrows from those tasks/WPs and the architecture design. In particular, the task 2.4 has a lot of influence on several choices and research activities within the project. It demands a particular selection of materials, artificial ageing procedures and restoration treatments, which will strongly influence and be influenced by the architectural structure. Moreover, these elements lead to the choice of particular sensing probes, which pave the way to a more wide and complete digital documentation. Of course, between the requirements and their technical implementation, a lot of study has been done to understand the current state-of-the-art in the Scan4Reco field (task T2.2). Finally, the inter-connection and inter-dependencies between the architecture design and both WP4 (multi-modal scanning) and WP5 (integration and decision support system) are strong and evident. All of these relationships mark how important is the architecture design for the rest of the project, and how delicate is the choice of the proper design granularity, in order to drive the development of the project neither too tightly nor too loosely.

2. Summary of End-user Requirements

The Scan4Reco System Architecture will have to respond in technical and functional terms to the end-user needs. All the choices of hardware and software, and the definition of the corresponding use cases must be driven and justified from specific end-user requirements, while leading to a modular and feasible system advancing the scientific and technological state-of-the-art.

In this section, we provide an overview and recap of the main outcomes of the Scan4Reco deliverable D2.3 "Scientific end-user and public requirements", and we show how they conceptually relate to the System Architecture. We will first present the main targeted end-user categories and the outcome of D2.3 as a list of end-user requirements. Then we will provide a description of the main two pilots, and show how this information has to be mapped to core system functionalities, which are the main bulk for the definition of a modular architecture in section 5.

2.1 Targeted End-users

The definition of the end-user requirements has taken into account input gathered from domain experts inside the consortium (in particular, OPD, OF-ADC, UVR), as well as a series of interviews and questionnaires that involved a broad range of scholars and stakeholders in various fields of cultural heritage. In particular, we focused on expertise mostly related to the Scan4Reco scenario of pilots, i.e., analysis, restoration and conservation of painting and metal art objects. From this perspective three main classes of targeted end-users have been identified:

- **Curators**: experts in charge of collections, belonging both to national or local institutions (art historians, archaeologists). They take care of collections, plan maintenance operations, set up the display and storage conditions, make decisions on performing restoration interventions.
- **Restorers/conservators**: they take care of the material state of the work of art, monitor their conditions over time, deal with active and passive protection methods, and apply restoration treatments such as cleaning, consolidation, protection.
- **Conservation scientists**: they have a scientific background and apply scientific investigation techniques for art history, conservation and monitoring purposes. They span from chemists, physicists, computer scientists, engineers, material scientists and so on.

The rationale behind the choice of such targeted end-users built on the fact that the presence of experts from these specific sectors assures that the gathered information about their needs and requirements stays in the cutting edge between best practices/state-of-the-art and important research issues not yet completely solved. An architecture addressing those challenging requirements will increase the value of Scan4Reco results in terms of both technical soundness and relevance in cultural heritage field. It should also be noted that the identified end-users are all experts in their respective domains. This also means that user interfaces and levels of information provided by the various components should be suitable for them (except for the single dissemination component, virtual museum, which should be designed for the general public).

2.2 List of requirements

The analysis of the feedback from end users led to the definition of end-user requirements (EURs), which have been summarized in Deliverable D2.3, and serve as a guide to define the overall system architecture.

For ease of reference, we summarize here the full list of EURs, listing for each EUR its unique ID, its name, a short description, and the level of priority. There are three possible levels of priority:

- **Mandatory** requirements are those which, according to users, are absolutely needed otherwise the core value of the system is missing. All these requirements form a coherent set of functionality that can be applied to the Scan4Reco workflow.
- **Important** requirements are those that add the necessary functionalities to ensure that the tool will deliver enough value, but are not necessary for all users.
- **Optional** requirements bring in benefit if present, but do not hamper the value of the tool if absent. They nevertheless augment the pertinence of the tool and reinforce its potential success.

(EUR/GR) General Requirements			
EUR/GR/01	**Documentation on acquisition**	Measurements are documented and easily accessible to the end-user	**Mandatory**
EUR/GR/02	**Paradata documentation**	Make end-users able to understand and interpret computer-based visualization and outcomes in the context of CH study.	**Mandatory**
EUR/GR/03	**Reduce manual interventions in measuring**	All the measurements on artworks must be made as quick and easy as possible. A certain degree of automation is wished.	**Important**
EUR/GR/04	**Safety of operation**	Devices and procedures must increase safety of operation and avoid the risk of damage of cultural objects.	**Mandatory**
(EUR/MC) Material and surface appearance characterization			
EUR/MC/01	**Standardized preparation of material samples/mock-ups**	The preparation of samples/mock-ups for the simulation of dynamic processes must be done taking into account the artistic techniques and the composition of the past.	**Important**
EUR/MC/02	**Acquisition and digital representation of surface structure and appearance of material samples**	The acquisition of the outmost surface structure and appearance.	**Mandatory**
EUR/MC/03	**Acquisition and digital representation of sub-surface physical and chemical material properties**	Acquisition of the physical and chemical properties of the multilayer subsurface structure.	**Mandatory**
EUR/MC/04	**Inducing changes of surface structure, appearance and**	Inducing changes of artworks by using factors such as temperature and relative humidity cycles, restoration procedures, exposure to outdoor agents, interaction with UV	**Important**

	chemical-physical properties	light, chemical reactions and application of coatings.	
EUR/MC/05	**Characterize and model different materials or material states based on surface appearance**	Surface characterization through descriptors from superficial measurements of mock-ups, such as multi-spectral color, roughness, normal distribution, or micro-geometry.	**Mandatory**
EUR/MC/06	**Characterize and model different materials or material states based on sub-surface physical and chemical properties**	Sub-surface physical and chemical characterization through descriptors from sub-surface measurements of mock-ups.	**Mandatory**
EUR/MC/07	**Virtual explorations of replicas of mock-ups**	Visualization techniques to inspect the surface and volumetric structure of a material.	**Important**
EUR/MC/08	**Real-world replication of mock-ups using 3D printing**	3D physical replication devices and methodologies in order to inspect the real-world replicas of surface appearance, surface geometry and volumetric structure of a material.	**Important**
(EUR/MO) Metallic object analysis			
EUR/MO/01	**Metallic object dimensions, shape and environment**	List of possible examples of types of objects and corresponding environment, including outdoor and indoor metallic sculptures and reliefs. Requirement of an on-site acquisition setup.	**Important**
EUR/MO/02	**Collection of a series of local multi-modal measurements across a metallic object surface**	A set of local, multi-modal acquisition of both compositional and optical characteristics of metallic objects. A tool to assist expert in choosing critical sampling points, and to easily position local probes on small, flat areas.	**Mandatory**
EUR/MO/03	**Checking changes of metallic objects**	End-users need to identify changes in metallic objects due to ageing or restoration intervention. Indicators of such changes are surface and sub-surface properties.	**Mandatory**
EUR/MO/04	**Interactive exploration of analysis results on metallic objects**	A tool to explore the various analyses performed on a metallic object using a user-interface capable to provide simplified access to the documentation. A tool to access all the punctual analyses, relations among them. A tool to help taking decisions on future analyses and on conservation issues.	**Important**
EUR/MO/05	**Exploration of the evolution of single-material metallic objects**	A tool to provide a spatio-temporal simulation of the evolution of the single-material metallic object conditions, in order to make reliable	**Mandatory**

	through spatio-temporal simulation	prediction on the object behavior over time and the effect of the restoration treatments.	
EUR/MO/06	**Replication of single-material metallic objects using 3D printing**	Real-world 3D printed copy of single-material metallic objects. This can be done at the current state, at possible level of ageing or after a simulated restoration treatment.	**Optional**
(EUR/PA) Painting analysis			
EUR/PA/01	**Painting acquisition environment**	End-users require that large size paintings are left on site for acquisition, in environments such as museums, private collections and churches or monasteries.	**Mandatory**
EUR/PA/02	**Collection of a local multi-modal measurements across a painting**	A set of local, multi-modal acquisition of both compositional and optical characteristics of paintings. A tool to assist expert in choosing critical sampling points, and to easily position local probes on small, flat areas.	**Mandatory**
EUR/PA/03	**Mapping of local/punctual measurements onto a global proxy of a painting**	The end-users need a unique and global reference frame, i.e., a geometric and color proxy, onto which the local, punctual data will be registered.	**Mandatory**
EUR/PA/04	**Construction of a stratigraphy of visible and non-visible paint layers in a painting**	The conservators need to know the stratigraphy of the painting, and use a schematic diagram that can highlight the presence of varnish, intermediate preparation layers, some particular pigments (e.g., Red Ochre, Carbon Black, Lead White), the presence of pollutant-dirt within the paint, and a quantitative measure of the layer thickness.	**Optional**
EUR/PA/05	**Interactive exploration of analysis results on paintings**	A tool to explore the various analyses performed on a painting using a user-interface capable to provide simplified access to the documentation. A tool to access all the punctual analyses, relations among them. A tool to help taking decisions on future analyses and on conservation issues.	**Optional**
EUR/PA/06	**Exploration of the evolution of paintings through spatio-temporal simulation**	A tool to provide a spatio-temporal simulation of the evolution of the painting conditions, in order to make reliable prediction on the painting behavior over time and the effect of the restoration treatments.	**Mandatory**
EUR/PA/07	**Use 3D printing to explore real-world replicas of paintings**	Real-world 3D printed copy of a painting (material or volumetric structure). This can be done at the current state, at possible level of ageing or after a simulated restoration treatment.	**Mandatory**
(EUR/OR) Other requirements			

EUR/OR/01	**Create a Decision Support System to help scholars in the planning of restoration interventions**	An oriented Decision Support System (DSS) that has the mission to process all relevant data, and to export in a human-comprehensive way the actions need to be taken for better preservation and conservation of the cultural object under study.	**Mandatory**

2.3 Application scenarios

As seen from the subgroups of end-user requirements, the Scan4Reco project aims at applying the developed techniques to a large amount of types of artworks, which are of great importance for scholars in Cultural Heritage. Apart from the constant feedback from relevant end-users about all single sub-modules and their integration in a unique modular system, the evaluation of the integrated prototype of the Scan4Reco system will be specifically carried out in two pilot experiments involving the participation of real conservators/archaeologists. One pilot will target the exploitation of the system on paintings, while the other one will investigate the exploitation of the system on metallic 3D objects.

3. Conceptual Architecture

The goal of the Scan4Reco project is to develop a novel portable, integrated and modular solution for customized, cost-effective, automatic digitization and analysis of cultural heritage objects, even in situ. A multi-sensorial 3D scanning, facilitated by a mechanical device, will collect a series of different signals, and then, a hierarchical approach for 3D reconstruction of artworks will be applied, enabling multi-layered rendering. This will advance both analysis and 3D printing procedures. The goal will be to create highly accurate digital surrogates of works of art, providing detailed insight over their surface, the volumetric structure, material composition and shape/structure of underlying materials, and enabling rendering either via visualization techniques or via multi-material 3D printing.

The conceptual architecture of Scan4Reco, as described in the project Grant Agreement [28], and summarized in Figure 3, achieves these goals by identifying the main steps and functionalities required to perform all the intended activities. Such conceptual architecture is refined in this document on the basis of an analysis of end user requirements, state-of-the-art solutions and technical capabilities available to the project.

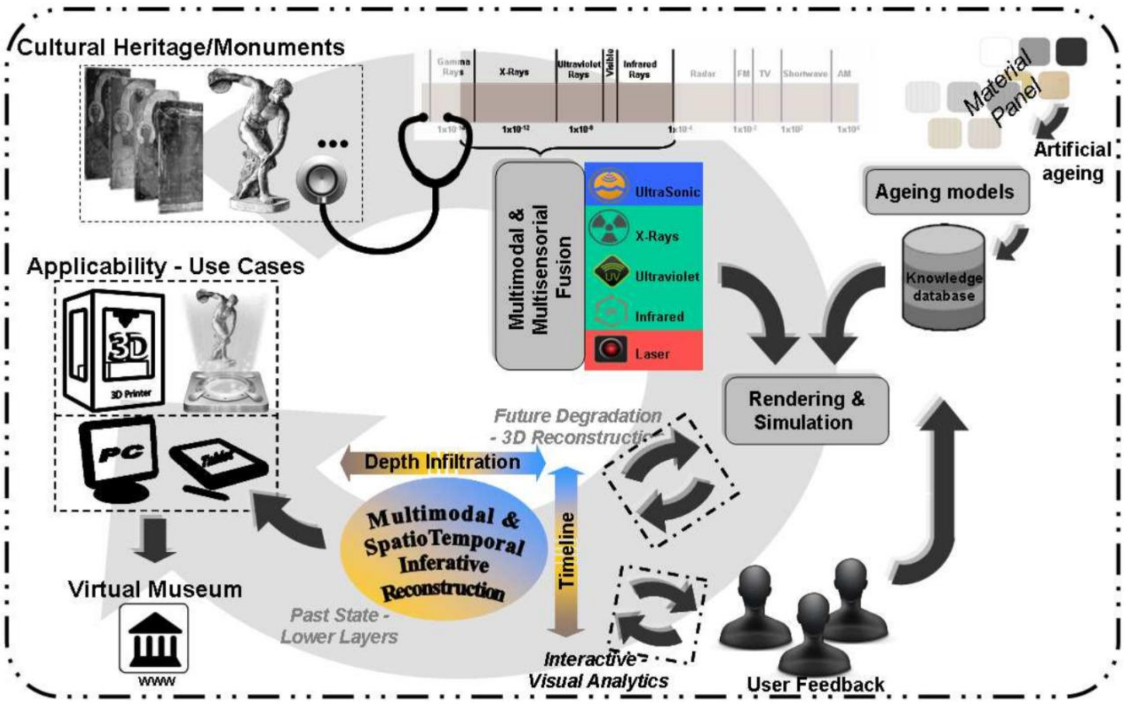

Figure 3 Conceptual architecture of the Scan4Reco project

The major steps of this conceptual workflow are thus the following:

- **Multi-modal acquisition** of the cultural objects achieved via the utilization of a series of different sensing devices. It includes measurements of both compositional and optical characteristics of cultural heritage objects, e.g., surface, sub-surface, physical and chemical properties;
- **Multimodal fusion** of local and global measurements derived by the multi-sensorial scanning platform for material and stratigraphy characterization, representation and/or identification. An alignment of all measurements of probes onto the same reference frame will be provided;
- Creation of a **multi-material mock-ups** for the investigation of their physiochemical properties (via measurements of the multi-sensorial

platform) before and after controlled and artificial ageing or restoration interventions;

- **3D reconstruction** and **rendering** of the generated virtual reality model. A hierarchical approach for 3D reconstruction will be followed, which enables an object rendering in a multi-layered way. The visualization of such virtual model will facilitate the analysis and the study of the original artwork;
- **Spatio-temporal simulation**. A tool to provide a spatio-temporal simulation of the evolution of the cultural heritage items conditions, in order to make reliable prediction on the object behavior over time and the effect of the restoration treatments. It is going to be based on the parameterized environmental/contextual conditions input provided by the user, as shown in the envisioned system architecture below;
- **Decision support system** and visualization tools. Their scope is to give scholars a support to understand the form of the cultural object in the restored state (i.e. backwards in time), and after the degradation that takes place due to the environmental and environmental changes conditions. Moreover it provides a semantic/comprehensive (e.g. statistics, AR, etc.) representation of the generated model to the end-user;
- **Visual representation/3D printing.** Spatiotemporally parameterized visual representation/3D printing of the reconstructed object for the direct and holistic assessment or demonstration of the current conservation or educational method, respectively. Continuous adaptations based on the monitoring input and the results of the decision support tools;
- A **virtual museum** for raising public awareness**.** It responds to the project dissemination purposes, through a web-based application that allows researchers, scholars and the general public to remotely explore captured data and project's results.

This conceptual architecture is based on the expected workflow of the system (right part of Figure 4). It starts with the definition of environmental conditions and metadata. After a cultural heritage object has been digitally sampled/acquired, all the data, coupled with proper calculated material ageing models, are used to provide a spatio-temporal simulation of its most important features. This serves to generate an analysis of the artwork and the proper guidelines for conservation and/or restoration purposes. Moreover, a visual and interactive presentation is performed, together with a physical replication of the item by rapid prototyping.

This workflow can be broken down into the following abstract core elements that compose it (see left part of Figure 4):

- **Multi-modal Scanning Platform.** This core element includes all the distinct components of the multi-sensorial plat-form. Herein, several scanning sensors/probes aim at covering a wide range of the E/M spectrum achieving thus an accurate data collection (via sampling and/or holistic scanning) not only from the objects surface but also from its underneath layers. A mechanical device will improve the process by increasing the level of acquisition automation.
- **Training Data Collection.** Through the preparation of panels and mock-ups and the setting of proper artificial ageing procedures, the reference data needed for the training of the ageing modeling algorithms is produced. Specific materials, environmental effects, and restoration treatments will be selected for study, on the basis of end user interest and feasibility of measurements. This module includes also the mock-ups measurement in a controlled laboratory environment, which will be undertaken by using a lab version of the multi-sensorial platform.

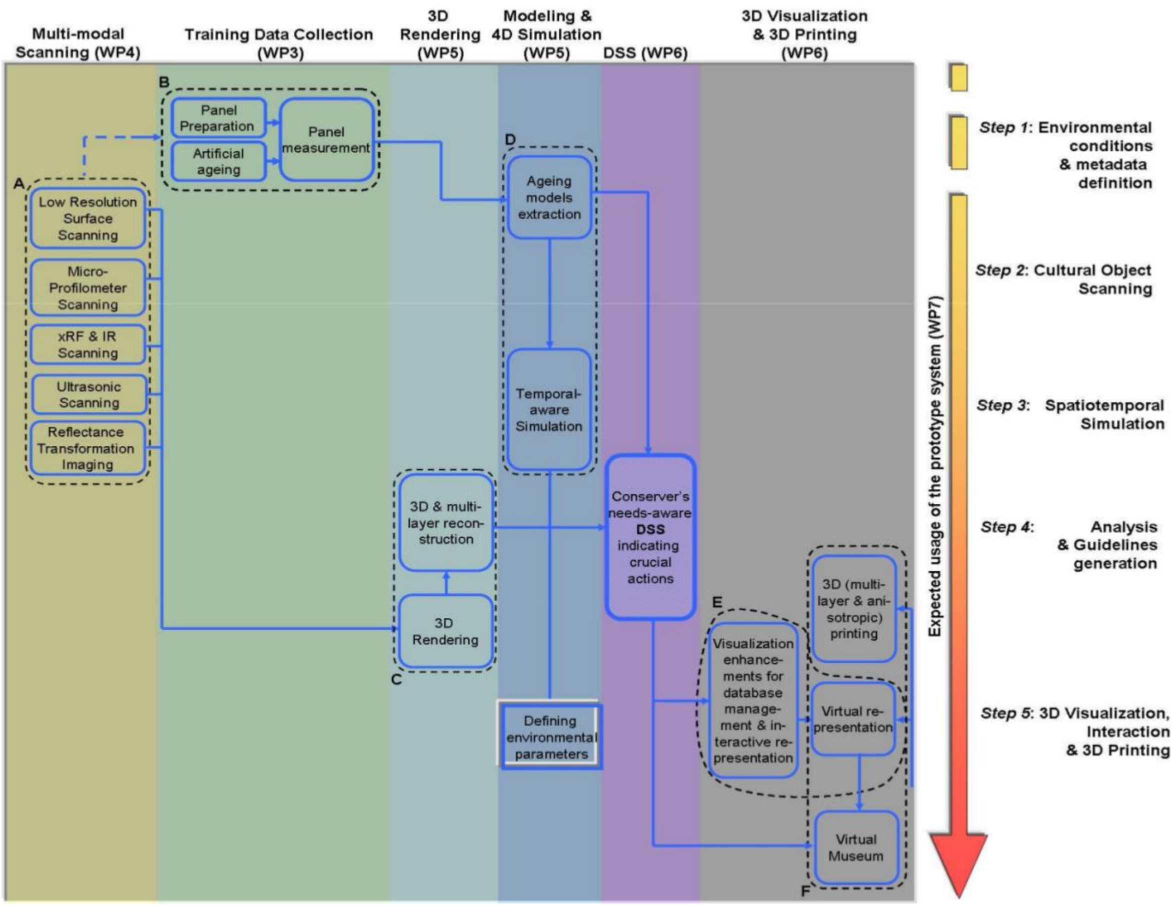

Figure 4 Structure and core elements of the initial Scan4Reco envisioned architecture. The expected usage steps are presented as well (right).

- **3D Reconstruction and Rendering.** After the multi-modal acquisition, the captured data is processed in order to produce a final and intra-registered model. The multi-scale and multi-modal signals will be registered to a common reference frame, and the final representation will consists in a low resolution geometrical proxy (from the surface scanner) with all the local/punctual measurements registered onto it. The reconstruction will involve also the fusion of subsets of signals (e.g., volumetric layers), and the modeling of material attributes. All this processed information will be used for simulation, visualization, and rendering purposes.
- **Spatiotemporal Simulation.** The reconstructed 3D model with all its attributes is visualized within a spatio-temporal visual simulation framework. The ageing models will be used to feed the rendering engine for temporal simulation of the 3D VR model. During the development we will also explore possible techniques to reverse observed weathering on materials in order to provide an estimation of the original appearance of artworks.
- **Decision Support System.** The mission of this core architectural element is to process all relevant data (i.e. initial 3D model, ageing factors, simulated data, etc.), so as to export in a human-comprehensive way the actions needed to be taken for better preservation and conservation of the cultural object under study. In other words, the Decision Support System (DSS) will provide the layer of intelligence and comprehensiveness of the algorithms' outcomes to the Scan4Reco portable system. The DSS will receive input from several modalities of the system, and a dedicated small database with simple conservation-oriented instructions in a format similar

to fuzzy-like approaches/commands. It will output its decisions/suggestions/results related to where and how to apply a certain type of conservation approach, accompanied with a confidence factor.

- **3D Visualization and Printing.** This core element concerns all the graphical presentations of outcomes of the previously described architectural core elements. It aims at combining 3D models with registered measurements with useful metadata and paradata information on the models and measurements, and provides a visual Human Machine interface, so as to facilitate the work performed by the end-user and to provide an enriched and comprehensive view of the analysis of cultural objects. Moreover, this core element includes the generation of actual tactile surrogates of the cultural objects with high precision via state of the art multi material (including transparent ones), multi-layered and multi-colored 3D printings. For dissemination purposes, a virtual museum website will also be developed.

This conceptual architecture, initially defined in the project Grant [28], defines the general scope of the project, and is refined in this document on the basis of an analysis of end user requirements and of the technical feasibility of the individual implementation approaches.

More specifically, starting from the End User Requirements that will be summarized in Sec. 2, we have performed a technical analysis that led to the identification of specific hardware and software components, as described in Sec. 4. This analysis then led to the definition of a modular system architecture, whose structure and initial component specification is defined in Sec. 5. As we will see, the resulting architecture is a significant evolution of the initial conceptual one, but conserves its general scope and structure.

4. Analysis of end-user requirements

The first step in the definition of the Scan4Reco architecture is to identify the functionalities addressing the end-user requirements. These functionalities have different level of abstraction, ranging from a more specific definition of conceptual modules/functions/environments down to the single operational component. In this section we will discuss the breakdown of the Scan4Reco architecture into a series of high-level functionalities and required components that are needed to address end user-requirements.

Starting from a distinction of the environments in which the activity will be undertaken, we will group the functionalities into three main high-level functions, i.e., the material and surface appearance characterization, the acquisition of artworks and their analysis. For each of these functions, a series of components and relations among them are then identified.

4.1 Environments

Apart from general guidelines that must be taken into account in all the activities during the project (EUR/GR), from a global analysis of end-user requirements it is clear that the entire set of functionalities can be divided according to three types of environments in which operations must be carried out, i.e., laboratory, on-site and off-site (see Figure 5).

Laboratory (LAB). The goal of laboratory environment is to acquire and study the properties of particular materials as a function of aging or restoration treatments. For each material under study, the main idea is to obtain different samples of it at different aging/restoration conditions. Then some key acquisition procedures and modalities are defined with which to gather meaningful data to extract features and descriptors in order to classify and recognize types of materials and their conservation conditions. This environment is strongly requested by the end-users in the section "Material and surface appearance characterization" (EUR/MC).

On-site (ONSITE). The activity that may performed on-site is related to the data capture performed on real artworks in a more general environment (e.g., outdoor, museums, etc.). In this scenario, end-users identified two main pilots, which will guide the implementation of the system functionalities. These pilots are metal objects (EUR/MO) and paintings (EUR/PA). Each of them requires specific functionalities, and this will result in a system able to adapt itself to different types of objects in a toolbox approach. The data gathered during the acquisition campaign will be used to digitally represent and to analyze artworks from those two wide categories. In any case, the pilot-oriented customization won't affect the general applicability of the Scan4Reco analysis pipeline, making Scan4Reco architecture be as "generic" as possible. Moreover, it should be noted that, while on-site acquisition should be supported, it is not mandatory that all acquisitions of artworks are performed on-site, as some studies of particular objects, especially small ones) are often performed in laboratories for a variety of reasons (controlled environment, restoration, etc.). If there is a need for on-site acquisition, however, the system should be able to support it for the largest practically possible number of modalities compatible with on-site use.

Off-site (OFFSITE). The main purpose of the work done off-site is to merge the information gathered on-site with the knowledge derived from the laboratory environment, in order to provide some advanced tool for research and study of CH items. This environment responds to the user needs related to both the virtual and physical representation and simulation of data from metallic object and painting (EUR/MO, EUR/PA), and to the mandatory requirement of a powerful tool of analysis and decision support system (EUR/OR). It should be noted that some of the off-site work could also be performed on-site, but it is not mandatory to do it there. In particular, while on-site work requires the presence of artworks, off-site work, even when performed on-site, could be performed just by analyzing the digital data.

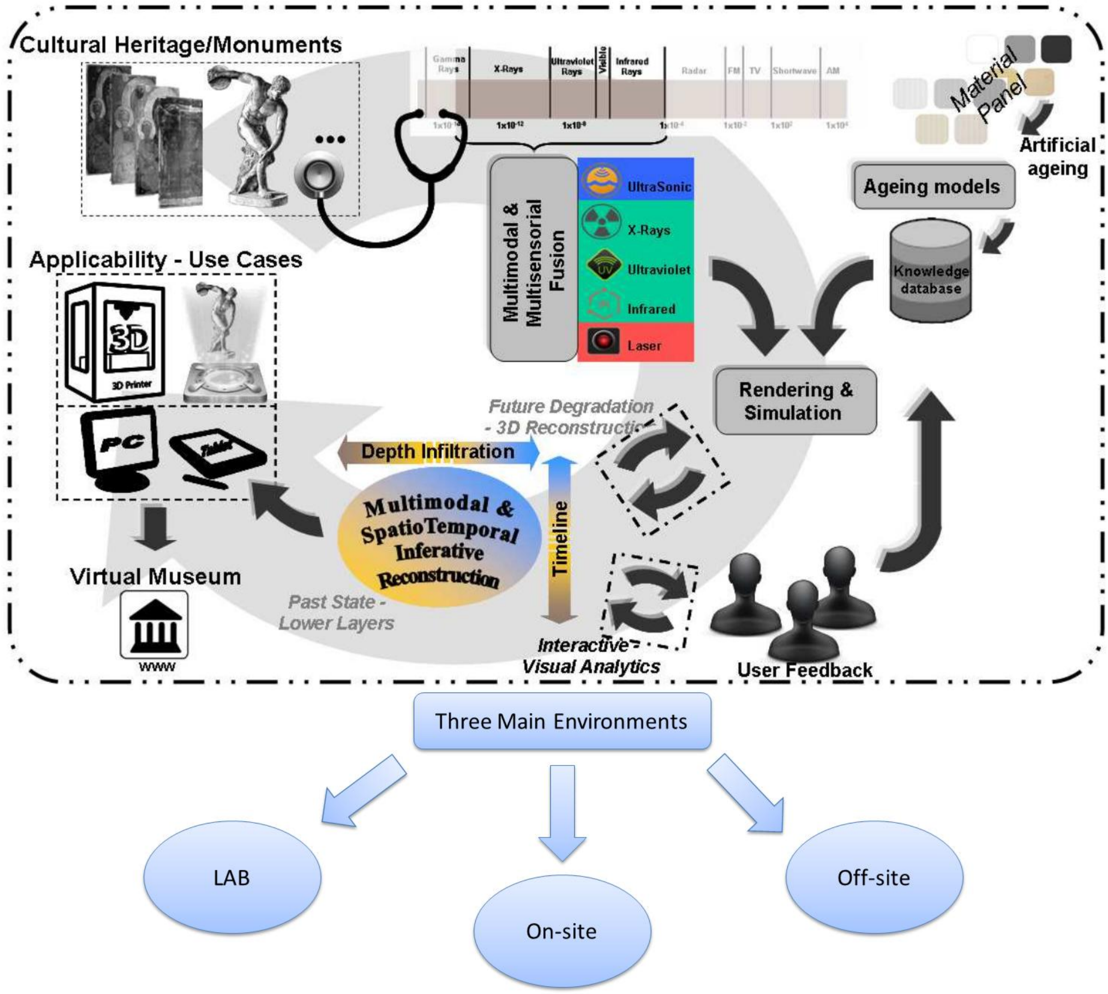

Figure 5 Conceptual architecture breakdown. From end-user requirements analysis it is possible to split the set of system functionalities into three main groups, i.e., three environments in which Scan4Reco activities are done.

4.2 Material and surface appearance characterization

The study of material status and the understanding of its behavior over time in terms of surface appearance and internal structure (EUR/MC/05,EUR/MC/06) is of extreme importance for end-users. For this reason they request to perform the acquisition of some multi-modal signal (EUR/MC/02, EUR/MC/03) on samples/mockups prepared (EUR/MC/04) in a standard and controlled way (EUR/MC/01). This requires a controlled environment (a laboratory) and a controlled and repeatable preparation of the samples/mockups.

All the system components related to "Material and surface appearance characterization" (EUR/MC) must be employed in a laboratory environment (LAB). The end-users demand a standard and controlled manner to prepare and measure the samples/mock-ups.

To study material behavior over time, a list of selected material samples must first undergo a procedure to physically simulate different level of aging or the effects of restoration treatments. This process will produce a set of samples/mock-ups with well-defined aging/restoration conditions, which modify the structure of the surface, its appearance and its chemical-physical properties (EUR/MC/04). This process requires a component to simulate the material degradation.

HW/CHAMBER	*The artificial aging of the samples requires the use of a specific "Artificial Aging Chamber" (HW/CHAMBER), which is a device that speeds up the normal aging process of materials.*

In this phase, the prepared samples/mock-ups must be annotated by attaching information about preparation procedures, and other useful metadata or paradata (EUR/GR/01, EUR/GR/02). This requires a software tool that assists the end-user in this task.

SW/ANNOTATION	*Software tool for annotating (metadata/paradata) the prepared samples/mockups or the chosen artworks being captured and analyzed.*

The prepared samples must be measured to produce a digital representation of surface structure and appearance (EUR/MC/02), and sub-surface physical and chemical properties (EUR/MC/03). From these general material properties, the end-user questionnaire leads to a more specific identification of material measurable features (EUR/MC/02, EUR/MC/03). These measurable features lead to the definition of specific hardware devices for measurements. The first class of features are related to the superficial behaviour of materials (EUR/MC/02), and include 3D microstructure, level of glossiness, micro distortion (bumps, normal maps), and roughness. The following components will respond to the need of an acquisition and analysis of the outmost surface behavior of a material.

HW/MPROF	*The Optical micro-profilometer provides the quantitative measurement of the surface texture and roughness at micrometric level.*

HW/HDMSRI	*A high-density multispectral reflectance imager is used in the LAB environment to provide measurements of surface appearance (e.g., level of glossiness) of material samples and their micro geometric distortions (bumps, normal maps).*
SW/RTIPROC	*This software will be used to create an integrated representation of samples/mock-ups data from the image stack and calibration data produced by the hardware module (HW/HDMSRI).*

HW/UVSPEC	*A UV/VIS spectrophotometer is employed to illuminate an object in the ultraviolet and visible light. Light from one point of the surface is collected and spectrally analyzed to retrieve color properties of the surface. Scanning in two dimensions generates a colour map. The UV light reveals the most external behavior of the surface, or it stimulates particular surface reflectance effects such as fluorescence.*

The other class regards the set of all physical and chemical features, such as molecular and elemental composition of layers, morphology, thickness and number of the layers, adhesion and cohesion of the layers, and the presence of cracks and detachments. These types of features can be acquired and characterized by using different signals, such as ultrasounds, infrared reflectance, Raman scattering and x-ray. This leads to the need and the definition of the following hardware and software components.

HW/ACOUSMIC	*The Acoustic Microscopy System acquires a set of echographs using a*

	piezoelectric transducer which converts an ultrasonic wave into an electrical signal. Each collection contains the structural characteristics of a region of a few mm2. It helps providing information about the volume of the stratigraphy, materials distribution in a stratigraphy and elemental analysis.

HW/IRCAM	*The Infrared camera illuminates an object with an infrared broadband source. The reflection from the surface is imaged by an objective lens onto the focal plane array (1-5μm) of a high speed camera. The resulting infrared reflectographic multispectral images reveal the internal stratigraphic structure of the object. The size of the imaging area depends on the lens used, and usually larger areas are composed by stitching adjacent areas. It provides information of the layers distribution, their number and thickness.*

HW/FTIR	*The Fourier Transform Infrared Spectroscopy System acquires data using basic Fourier Transform IR (FTIR) spectrometer in reflectance mode. The data are the Fourier Transforms (spectra) of the reflected infrared electromagnetic wave. Together with the Raman spectroscopy, it is useful to study the chemical composition of materials.*

HW/RAMAN	*The Infrared laser Raman spectroscopy system acquires a signal produced by a monochromatic laser that excites an object, and captures back on the spectrometer the portion of the electromagnetic wave that contains components attributed to Raman scattering. Together with the Fourier Transform Infrared Spectroscopy, it is useful to study chemical composition of materials.*

HW/XRF	*An X-Ray Fluorescence Spectroscopy system is chosen to perform X-ray fluorescence (XRF) analysis. An XRF elemental analyser includes an X-ray source, the sample holder and the detector, which collects the secondary fluorescence radiation. The elemental analysis is based on the characteristic spectral lines of the elements that appear in specific energy values. It is useful to understand the structure and the status of layers.*

In order to control and combine the various probes, in addition, a coordinating software is needed, especially in the context of multimodal acquisitions and to perform, through a scanning process, area acquisitions from point (or small area) probes.

SW/MMACQ	*This software will be used to acquire data of samples/mock-ups to drive the Infrared Imager (HW/IRCAM), UV/VIS (HW/UVSPEC), Infrared (HW/FTIR, HW/RAMAN), XRF (HW/XRF), and Acoustic Microscopy (HW/ACOUSMIC) modules. It includes parameters that set the direct control of the XYZ moving stages specialized for the above referred modules.*

The captured data required by EUR/MC/02 and EUR/MC/03 will be used to characterize how the material changes over time in terms of surface and sub-surface behavior (EUR/MC/05), and physical and chemical changes (EUR/MC/06). In order to characterize and model different materials in different conditions, we need to use specific software components to extract semantic descriptions out of the raw material data.

SW/SFESURF	*Some semantic features will be extracted and the material model will be reconstructed from surface measurements. The computation of those derived surface properties and the extraction of corresponding surface descriptors will be based on data from Reflectance Transformation Imaging and Optical micro-profilometry.*

SW/SFESTRUCTMTL	*Some semantic features will be extracted and the material model will be reconstructed from material composition and tomographic measurements. The computation of those derived properties and the extraction of the corresponding material descriptors from composition and tomographic measurements will be provided by Acoustic Microscopy, UV/VIS, IR, Raman and XRF datasets. This includes signal processing algorithms related to the (i) mapping images derived by the UV-VIS-IR and Raman spectroscopy, (ii) the time frequency representations for layers and various structural finding in the paint layers.*

These descriptors will be used, through statistical analysis, first principles, and/or a machine learning framework in order to reconstruct a model on how a material changes according to aging factors or restoration treatments (EUR/MC/05, EUR/MC/06). A software component will thus be in charge of modeling the ageing.

SW/AGING	*A software that processes probe measurements and associated semantic descriptors will derive parametric and probabilistic material-specific ageing models.*

4.3 Acquisition of artworks

End-user has defined two types of artworks that represent an important set of CH items for the research of scholars, curators and restores, i.e., metallic objects (EUR/MO) and paintings (EUR/PA). General guidelines about the object dimensions and shape have been already identified by the end-users for metallic objects (EUR/MO/01). Moreover, a description of the types of environments in which these artworks are located has been provided (EUR/MO/01, EUR/PA/01). In order to study these objects, the end-users need to gather a series of local multi-modal measurements of surface, sub-surface, physical and chemical properties across a metallic object and paintings surface (EUR/MO/02, EUR/PA/02). Since the vast majority of artworks are displayed in museums, private collections, churches or monasteries, there is often a preference for in-situ acquisition, especially for large and/or delicate objects which would be cumbersome, risky, or costly to be moved. However, some studies of particular objects, especially small ones, are often performed in laboratories for a variety of reasons (controlled environment, restoration needs, lack of suitable protected areas in display environment, etc.). If there is a need for on-site acquisition, however, the system should be able to support it for the largest practically possible number of modalities compatible with on-site use.

System components related to the acquisition of Metallic objects (EUR/MO) and paintings (EUR/PA) may be employed in an on-site environment (ONSITE).

All the data produced by the acquisition and analysis components will further contribute to the proper documentation of a CH item (EUR/GR/01, EUR/GR/02).

The types of signals acquired for real metallic artworks or paintings are the same measured for samples/mock-ups, in order to use the knowledge obtained from the material characterization for the analysis of a real CH item. Although the types of signal/probes used here is the same, compared to their laboratory version, the configuration for an on-site acquisition will be different to match the constraints of a different environment. For instance, this leads to the introduction of a new component (HW/MSRTI) specifically tailored for on-site acquisition.

HW/UVSPEC HW/ACOUSMIC HW/IRCAM HW/FTIR HW/RAMAN HW/XRF	*All these hardware probes already used (and described) for material and surface appearance characterization are used as well to perform point-wise, local measurements of flat zones across the metallic object and painting surface. These types of measurements provide information about surface structure and appearance of metallic objects and paintings, and their sub-surface, physical and chemical composition.*

SW/MMACQ	*This software will be used to acquire data of metallic objects and paintings from the Infrared Imager (HW/IRCAM), UV/VIS (HW/UVSPEC), Infrared (HW/FTIR, HW/RAMAN), XRF (HW/XRF), and Acoustic Microscopy (HW/ACOUSMIC) modules. It includes parameters that set the direct control of the XYZ moving stages specialized for the above referred modules.*

HW/MSRTI	*A Multispectral Reflectance Transformation Imager is another probe used on-site for the local, point-wise measurements of visual characteristics of flat areas of cultural objects (e.g., paintings or engravings)*

SW/RTIPROC	*This software will process the data acquired with the hardware module used to capture local, punctual RTI measurements of artworks. It will create an integrated representation of the from the image stack and calibration data produced by the component HW/MSRTI.*

Moreover, in the case of artwork acquisition, there is a need not only of local and precise area measurements, but also a global coarse acquisition of the entire CH object (EUR/MO/04, EUR/PA/03). This will be done by a hardware 3D scanner component and a corresponding software tool to drive the capture process.

HW/VISDEPTH	*A scanner of object color and depth will acquire a low resolution, rough, global 3D of a metallic objects and paintings. This global representation (both color and depth) will be used as a geometric prior to position all the local, punctual measurements performed by the other remaining hardware probes.*

SW/SCAN	*This software will drive the capture device (HW/VISDEPTH) for a global, low-resolution scanning of the color and geometry of the metallic object or the painting.*

In order to facilitate the local, punctual acquisitions, and to reduce the manual interventions during the measuring procedure (EUR/GR/03), probes will be mounted on a mechanical device that will assist the positioning and the acquisition operations. This less manual and more controlled operation will increase as well the safety of operations performed on the artworks (EUR/GR/04). The mechanical device will be controlled by a software component that helps its positioning around the artwork.

HW/MECH	*The probes for on-site measurements of objects will be mounted on the coarse positioning system, both for scanning of color and depth (see HW/VISDEPTH), and punctual probe positioning (all the other probes). The mechanical device logically consists of a control unit and the coarse positioning system. The control unit serves mechanical integration.*

SW/MECH	*A firmware is necessary on the HW/MECH component to trigger motor action, such as positioning or reference drives, or provide information on the state of the positioning system.*

SW/PROBPOS	*This is a tool in charge of guiding the mechanical device (HW/MECH) for probe positioning on the metallic object or on the painting, and to perform local point-wise measurements in small flat regions with all the probes.*

In order to fully support a multimodal analysis pipeline, all the local measurements must be registered together and with the global 3D prior captured by the visual scanner (HW/VISDEPTH), as requested by the end-users, explicitly for the paintings (EUR/PA/03) and implicitly for metallic objects inspection (EUR/MO/04, EUR/MO/05, EUR/MO/06). Such a combination is important for a variety of operation, including the creation of a meaningful stratigraphy representation of paint layers (EUR/PA/04). A specific tool should thus be in charge of the multi-modal signal registration onto the global proxy.

SW/REG	*This multi-modal data registration tool will perform the alignment of all measurements of local probes onto the same reference frame defined by the low resolution, rough, global 3D geometry. All the aligned signals are fused in a single data structure stored in the project database and usable by all visualization and simulation components.*

4.4 Analysis of artworks

Given a digital representation of a sample/mock-up or a work of art, end-users require a series of tools to inspect, analyze and study the object features and its preservation condition, and to understand which types of interventions must be undertaken. This analysis is focused on the material features captured and extracted in the previous steps, which give important evidences about surface morphology, texture and surface appearance, as well as compositional features. Although a few of the components in the analysis framework will be used to check the outcomes of the activity in the LAB or ONSITE environments, the vast majority of them may also be used in an OFFSITE environment.

In the scenario of material study, end-users asked for some tools to virtually explore and analyze digital replicas of the acquired samples/mockups (EUR/MC/07). Similarly, in the case of metallic objects, these measurements are used to check possible changes in their surface visual appearance or chemical composition (EUR/MO/03), and the end-user needs a tool to visual inspect those changes by interactively surveying all the signals captured by probes (EUR/MO/04). The interactive exploration is of paramount importance for paintings as well (EUR/PA/05). All the visualization components comply with EUR/GR/01 and EUR/GR/02 regarding the documentation of the CH items. Then, a mandatory component of the Scan4Reco architecture must respond to this visualization need.

SW/INSPECT	*Visual 3D multi-modal inspector of measured data of samples/mock-ups, metallic objects and paintings. The data being visualized will consist in the probe measures positioned (SW/REG) on top of the low-resolution global surface scan (GIS view) provided by HW/VISDEPTH.*

In addition, in the case of samples/mock-ups and mostly for paintings, an important aspect is the visual inspection of the constructed layer stratigraphy obtained with volumetric probes (EUR/PA/04). A separated component will deal with this type of visualization.

SW/SINSPECT	*Visual inspection of the stratigraphy of samples/mock-ups and paintings.*

Given a metallic object made of a single material (e.g., bronze or silver) or a painting, end-users need to understand and foresee how that object will evolve due to some ageing effects or restoration treatments. In order to provide this functionality the aging models developed in the phase of material and surface appearance characterization (SW/AGING) are coupled with the global and local representations obtained in the acquisition steps, and a tool will be implemented for the exploration of the evolution of both single-material metallic objects (EUR/MO/05) and paintings (EUR/PA/06). This tool will show a spatio-temporal simulation of the condition of an artwork.

SW/SIM	*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. It will be applied to both metallic objects and paintings.*

In addition to the virtual inspection of digital representations of artwork, end-users identify as very helpful to also produce real-world 3D printed copies of it (EUR/MC/08,EUR/MO/06 and EUR/PA/07). This can be done by 3D printing the artwork at the current state, at possible level of ageing or after a simulated restoration treatment, by exploiting all the information captured and modeled in the previous steps. From this requirement, the need of a hardware 3D printer and a controlling software component arises.

HW/3DPRINT	*A multimaterial 3D printer employing multiple build materials and support material(s) for accurate color reproduction of samples/mock-ups, metallic objects and paintings.*

SW/3DPRINT	*The process of creating a low dimensional interim connection space to communicate visual properties for 3D printing, and the development of a 3D printing workflow to reproduce 3D shape and appearance information of samples/mock-ups.*

The result of all the requirements so far has produced a very huge amount of data, which is related to samples/mock-ups, metallic objects, and paintings, and is extensible to a generic work of art. The 3D models, the employed ageing factors, the computed models of ageing, all the analytical data about physical and chemical features, the markers of the presence of different artistic materials are all data available to the end-user through interactive virtual visualization and physical replicas. However, the task to derive decision for preservation and restoration from those data remains a challenging issue, due to the complexity of that heterogeneous data. Therefore, end-users can be helped by an oriented Decision Support System (DSS) as a software component that has the mission to organize all this information and provide it in a human-comprehensible way, supporting the decision process concerning the actions needed to be taken for better preservation and conservation of the cultural object under study (EUR/OR/01).

SW/DSS	*A system that takes data from multi-sensorial scanning, ageing models, simulation platform and small database with simple conservation-oriented instructions, and produces decisions/suggestions/results comprehensively to a visualization module, in order to provide conservators with indications of where and how to apply a certain type of conservation approach, accompanied with a confidence factor.*

Finally, for dissemination purposes, there is interest to make available for inspection the results to the general public. End users indicate the interest (EUR/MC/07, EUR/MO/04, EUR/PA/05) for a website where meaningful CH data will be presented and displayed is the most useful manner to reach the vast majority of people from anywhere and at any time.

SW/VMUSEUM	*Web-based virtual museum application for online inspection of cultural objects.*

5. Architecture structure

In Sec. 4, we have analysed end-user requirements, deriving from the important and mandatory functionalities of the Scan4Reco system and the corresponding components (hardware and software) that implement them. Before showing the components and their mutual relationships in detail, we summarize them in a compact view, mapping the identified components to the involved partners and relevant portions of the project work plan.

5.1 Component list

We divide components into two main classes, i.e., hardware and software, and for each component we provide an ID, the name, a brief description, the environment in which it will be employed, the lead (underlined) and other involved partners, and the project tasks related to the component.

HARDWARE					
HW/CHAMBER	Artificial Aging Chamber	Device to speed up the normal aging processes of items under controlled environmental conditions	LAB	<u>OPD</u> OF-ADC	T3.2, T3.3
HW/VISDEPTH	Visual and depth scanner	Low cost visual and depth camera setup for the acquisition of low resolution, rough, global 3D of an artwork.	ON-SITE	<u>CERTH</u> RFSAT	T4.1, T7.2, T7.3
HW/MPROF	Optical micro-profilometer	Device that provides quantitative measurements of the surface texture and roughness at micrometric level.	LAB ON-SITE	<u>UNIVR</u>	T2.1, T3.4, T4.1, T5.2, T7.2, T7.3
HW/ACOUSMIC	Acoustic Microscopy System	Device to acquire a set of echographs using a piezoelectric transducer which converts an ultrasonic wave into an electrical signal. Each collection contains the structural characteristics of a region of a few mm2.	LAB ON-SITE	<u>OF-ADC</u>	T2.1, T3.4, T4.2, T7.2, T7.3
HW/IRCAM	Infrared camera	The object is illuminated with an infrared broadband source. The reflection from the surface is imaged by an objective lens onto the focal plane array (1-5μm) of a high speed camera. The resulting infrared reflectographic multispectral images reveal the internal stratigraphic structure of the object. The size of the imaging area depends on the lens used, and usually larger areas are composed by stitching adjacent areas.	LAB ON-SITE	<u>OF-ADC</u>	T2.1, T3.4, T4.3, T7.2, T7.3
HW/FTIR	Fourier Transform Infrared	Device to acquire data using basic Fourier Transform IR	LAB ON-	<u>OF-ADC</u>	T2.1, T3.4,

	Spectroscopy System	(FTIR) spectrometer in reflectance mode. The data are the Fourier Transforms (spectra) of the reflected infrared electromagnetic wave.	SITE		T4.3, T7.2, T7.3
HW/RAMAN	Infrared laser Raman spectroscopy system	Device to acquire a signal produced by a monochromatic laser that excites an object and captures back on the spectrometer the portion of the electromagnetic wave that contains components attributed to Raman scattering.	LAB ON-SITE	OF-ADC BWTEK	T2.1, T3.4, T4.3, T7.2, T7.3
HW/UVSPEC	UV/VIS spectrophotometer	In ultraviolet and visible spectroscopy, the object is illuminated by an ultraviolet and visible light standard, respectively. Light from one point of the surface is collected and spectrally analysed to retrieve colour properties of the surface. Scanning in two dimensions generates a colour map.	LAB ON-SITE	OF-ADC BWTEK	T2.1, T3.4, T4.3, T7.2, T7.3
HW/XRF	X-Ray Fluorescence Spectroscopy system	Device to acquire data using X-ray fluorescence (XRF) analysis. An XRF elemental analyser includes an X-ray source, the sample holder and the detector, which collects the secondary fluorescence radiation. The elemental analysis is based on the characteristic spectral lines of the elements that appear in specific energy values.	LAB ON-SITE	OF-ADC	T2.1, T3.4, T4.3
HW/HDMSRI	Lab high-density Multispectral Reflectance Imager	Acquisition device for lab measurement of surface appearance of material samples for characterization purposes.	LAB	CRS4 UNIVR	T2.1, T3.4, T4.4, T5.2
HW/MSRTI	Multispectral Reflectance Transformation Imager	Acquisition device for on-site measurement of visual characteristics of flat areas of cultural objects (e.g., paintings or engravings)	ON-SITE	CRS4 UNIVR	T2.1, T4.4, T7.2, T7.3
HW/MECH	Mechanical device	Hardware support to assisted measurements of cultural objects, including low-res surface scanning and measurements with probes. Comprises control unit and coarse positioning system.	ON-SITE	AVASHA OF-ADC BW-TEK	T4.1, T4.2, T4.3, T4.4, T6.3, T7.2, T7.3
HW/3DPRINT	3D Printer	Commercial multimaterial 3D printer employing multiple build materials and support material(s) for accurate color reproduction.	LAB	FHG-IGD	T6.2, T7.2, T7.3

SOFTWARE					
SW/ANNOTATION	Sample and object annotation	Software tool for annotating (metadata/paradata) the prepared samples/mockups or the chosen artworks being captured and analyzed.	OFF-SITE	UNIVR, CRS4	T3.2, T3.4, T7.2, T7.3
SW/MECH	Mechanical device firmware	Firmware for controlling the mechanical device's coarse positioning system for scanning and probe positioning	ON-SITE	AVASHA	T4.1, T4.2, T4.3, T4.4, T7.2, T7.3
SW/SCAN	3D Scanning	Capture of the low resolution, rough, global 3D surface shape of an artwork using the HW/VISDEPTH and the coarse positioning system.	ON-SITE	CERTH AVASHA RFSAT	T2.1, T4.1, T7.2, T7.3
SW/PROBPOS	Probe positioning and local measures	Tool for guiding probe positioning on the artwork and to perform local measurements with probes.	ON-SITE	CERTH AVASHA OF-ADC	T4.1, T4.2, T4.3, T4.4, T7.2, T7.3
SW/MMACQ	Acquisition of data using IR camera, UV/VIS-IR-Raman-XRF spectroscopy, and acoustic microscopy.	Acquisition of datasets using the Infrared Imager, UV/VIS-Infrared- XRF and Acoustic Microscopy modules. Includes parameter setting the direct control of the XYZ moving stages specialized for the above referred modules.	ON-SITE	OF-ADC	T2.1, T3.4, T4.2, T4.3, T7.2, T7.3
SW/RTIPROC	RTI image stack processing	Creation of an integrated representation of small surface patches from a RTI image stack and calibration data	ON-SITE OFF-SITE	CRS4 UNIVR	T2.1, T3.4, T4.4, T5.2, T7.2, T7.3
SW/SFESURF	Semantic feature extraction & reconstruction from surface measurements	Computation of derived surface properties and extraction of surface descriptors based on data from Reflectance Transformation Imaging and micro-profilometry.	OFF-SITE	UNIVR CRS4 BWTEK OF-ADC	T3.4, T4.1, T4.4, T5.2, T7.2, T7.3
SW/SFESTRUCTMTL	Semantic feature extraction & reconstruction from material composition and tomographic measurements	Computation of derived properties and extraction of material descriptors from composition and tomographic measurements provided by Acoustic Microscopy, UV/VIS, IR, Raman and XRF datasets. This includes signal processing algorithms related to the (i) mapping images derived by the UV-VIS-IR and Raman spectroscopy, (ii) The time frequency representations for layers and various structural finding in the paint layers.	OFF-SITE	OF-ADC BWTEK	T3.4, T4.2, T4.3, T7.2, T7.3

SW/AGING	Aging model extraction	A software that processes probe measurements and associated semantic descriptors in order to derive parametric and probabilistic material-specific ageing models.	OFF-SITE	UNIVR CRS4 CERTH OF-ADC	T3.4
SW/REG	Multi-modal data registration	Registration of all measurements of local probes onto the same reference frame defined by the low resolution, rough, global 3D geometry. All the aligned signals are fused in a single data structure stored in the project database, and usable by all visualization and simulation components.	ON-SITE OFF-SITE	OF-ADC UNIVR RFSAT AVASHA	T3.4, T5.1, T7.2, T7.3
SW/INSPECT	3D multi-modal inspector	Visual inspection of measured data, with probe measures positioned on top of low-res surface scan (GIS view)	ON-SITE OFF-SITE	CERTH RFSAT	T6.4, T7.2, T7.3, T7.4
SW/SINSPECT	Stratigraphic inspector	Visual inspection of the stratigraphy of paintings. Tightly integrated with SW/REGISTRATION.	ON-SITE OFF-SITE	OF-ADC	T6.4, T7.2, T7.3, T7.4
SW/SIM	Spatio-temporal simulation	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.	OFF-SITE	CERTH RFSAT UNIVR	T5.3, T5.4, T7.2, T7.3
SW/3DPRINT	3D printing Software	The process of creating a low dimensional interim connection space to communicate visual properties for 3D printing, and the development of a 3D printing workflow to reproduce 3D shape and appearance information.	OFF-SITE	FHG-IGD	T6.2, T7.2, T7.3
SW/DSS	Decision Support System	A system that takes data from multi-sensorial scanning, ageing models, simulation platform and small database with simple conservation-oriented instructions, and produces decisions/suggestions/results comprehensively to a visualization module, in order to provide conservators with indications of where and how to apply a certain type of conservation approach, accompanied with a confidence factor.	OFF-SITE	CERTH OF-ADC FHG-IGD	T5.5, T6.1, T7.2, T7.3, T7.4
SW/VMUSEUM	Virtual Museum	Web-based application for online inspection of cultural objects.	OFF-SITE	CERTH	T6.4, T7.2, T7.3, T7.4

5.2 High-level architecture structure

The presented set of required components are logically organized into groups based on functionalities and main data flowing between them, giving a high-level representation of the designed architecture (Figure 6).

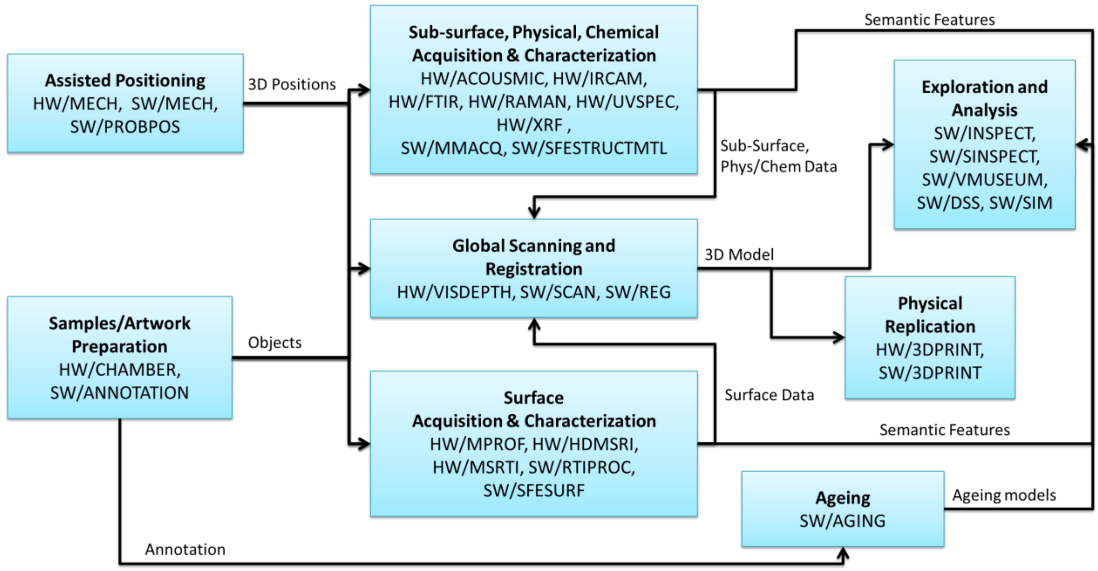

Figure 6 Groups of components and data flow in a high-level architecture representation.

The main groups of components are thus the following:

- **Samples/Artwork Preparation**. This group is devoted to the preparation of both samples for material characterization and the objects for data capture. The component HW/CHAMBER will be used to simulate the artificial ageing so that the other acquisition probes can measure the same signals from samples at different conditions. The software component SW/ANNOTATION will assist end-users in producing metadata/paradata associated to both samples and objects.
- **Assisted Positioning.** On mechanical device (HW/MECH) all the probes and the 3D scanner will be mounted, in order to assist the data capture of artworks in the ONSITE environment. The mechanical device will be controlled by a low-level firmware (SW/MECH), and a software tool SW/PROBPOS will control the device and will produce a set of 3D positions of the other hardware modules.
- **Sub-surface, Physical, Chemical Acquisition & Characterization.** This group concerns all the hardware and software modules involved in the physical and chemical acquisition and characterization of the materials (including surface and subsurface measurements), and the acquisition of a volumetric representation of samples/mock-ups and artworks (HW/ACOUSMIC, HW/IRCAM, HW/FTIR, HW/RAMAN, HW/UVSPEC, HW/XRF). The input of this group is the object to be acquired and, in the case of onsite acquisition, it will be positioned in the space following the 3D positions computed by the module SW/PROBPOS. The software SW/MMACQ will drive the various probes and produce the raw acquired data, while in the processing step (SW/SFESTRUCTMTL) semantic features will be extracted from raw data.
- **Surface Acquisition & Characterization.** Similarly to the physical and chemical acquisition and characterization, this group of components (HW/MPROF, HW/HDMSRI, HW/MSRTI) focus instead on capture and

processing of data related to the outmost, superficial layer of a sample/mock-up or an artwork. The input of this group is the object to be acquired and, in the case of onsite acquisition, it will be positioned in the space following the 3D positions computed by the module SW/PROBPOS. The software SW/RTIPROC will process the raw input to allow for a meaningful handling of the data. SW/SFESURF will process the data from HW/MPROF, HW/HDMSRI, and HW/MSRTI to characterize surface behaviour by extracting relevant semantic features.

- **Global Scanning and Registration.** The module HW/VISDEPTH is in charge to retrieve a global low-resolution geometric and chromatic representation of the artwork being analyzed. It is controlled both by the mechanical device (HW/MECH) for its positioning around the object (SW/PROBPOS), and by the internal scanning software SW/SCAN, which performs the actual capture. The component SW/REG within this group will collect data from SW/SCAN and from the other acquisition groups and perform a registration of the local, punctual measurements done in the small flat regions around the object surface onto the global 3D low-resolution geometrical proxy.
- **Ageing.** The single component SW/AGEING here will take all the semantic features extracted from acquired data (SW/SFESURF, SW/SFESTRUCTMTL) and the metadata/paradata information (SW/ANNOTATION) to find parameters that can model the behaviour of a material over time or as an effect of a restoration process.
- **Exploration and Analysis.** The ultimate goal of the pipeline is to provide scholars in CH with a tool that helps them to analyze the status of an artwork and to decide what to do for its preservation and conservation. This is the main aim of this group of components, which will use visualization techniques (SW/INSPECT, SW/SINSPECT) to explore the acquire data, and to present a series of simulation of the material behaviour (SW/SIM). These simulations, coupled with a Decision Support System tool (SW/DSS) will help CH people in analysing the artworks and prevent its degradation. In order to increase the accessibility of the cultural heritage assets to a broader audience, a web-based virtual museum (SW/VMUSEUM) will be developed to allow researchers, scholars and the general public to remotely explore captured data and project's results.
- **Physical Replication.** These components (HW/3DPRINT,SW/3DPRINT) will take the 3D model with the attached multi-modal signals and produce a multi-material physical replica of it. By taking inputs from the exploration and analysis group, also illustrative 3D printing procedures might be employed, to tangibly represent the volumetric structure of the material.

5.3 Information flow

Each of the macro-blocks identified in the high-level architecture contains components with a well-defined information flow inside and outside of the macro-block. In Figure 7 we present the same main blocks of functionalities, but with the explicit connections between all the components within them.

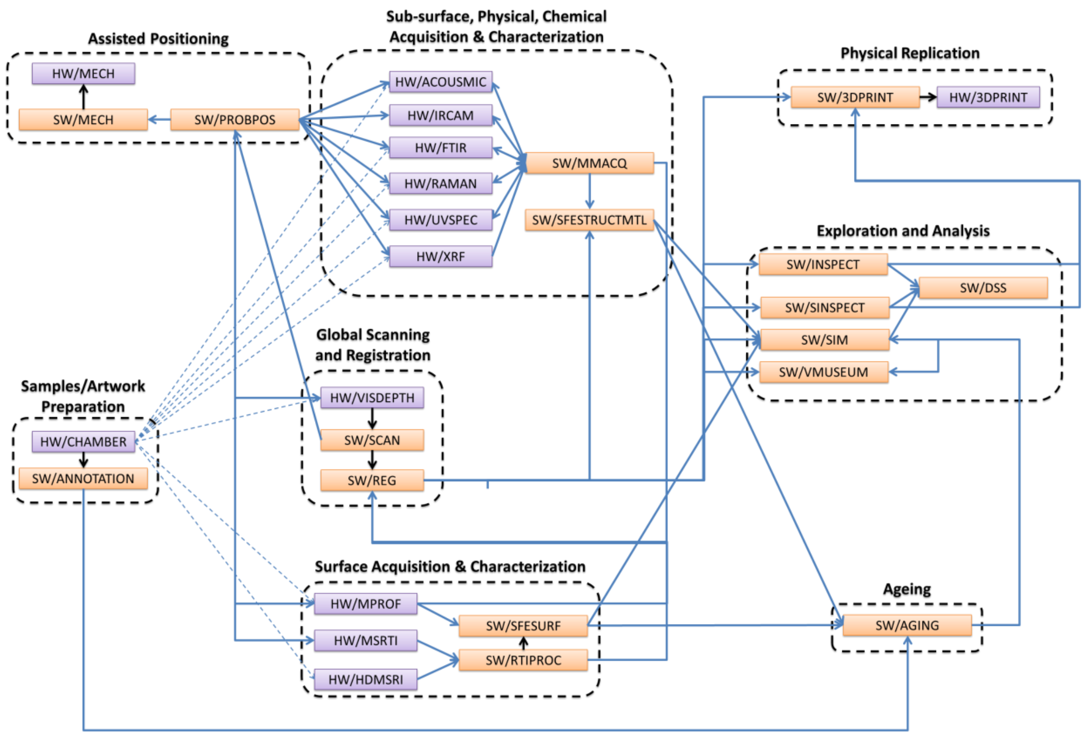

Figure 7 Scan4Reco Architecture Diagram

In the figure, the hardware components are depicted in light violet, while the software components are in orange. Dotted lines coming out of HW/CHAMBERS indicate the production of physical samples for lab analysis. All the other arrows indicate the information flow.

5.4 Modularity and project objectives

From the high-level structure of the architecture, its subdivision into macro-groups, and the data flowing between them, it is clear that the system architecture has been designed to be highly modular and to **respond to the major scientific and technological objectives** of the Scan4Reco project. Their realization is required to respond to the **end-user needs,** but also to perform **requested use cases and validation** with their set of actions and steps for artwork capturing, analysis and interpretation (for details see section 8).

In the following, we briefly analyse how the various components can be mixed and matched to fulfil the project objectives set out in the grant.

Objective 1	*...to **provide an integrated, portable solution** based on a **modular** architecture, for accurate (i.e. via a dedicated motorized **mechanical device**) **multi-sensorial 3D scanning** and **efficient automatic digitization of a big variety of cultural/heritage assets even in situ**, supporting among others **material identification** and both **surface and volumetric diagnosis**.*

The **mechanical device** (HW/MECH and SW/MECH) and all the mounted **multi-sensorial** (HW/MPROF, HW/ACOUSMIC, HW/IRCAM, HW/FTIR, HW/RAMAN, HW/UVSPEC, HW/XRF, HW/HDMSRI, HW/MSRTI) and **3D scanning** modules (HW/VISDEPTH) **provide an integrated, portable solution**, and the architecture design has been made to decrease strong dependencies between them and to increase the toolbox view and **modular** behaviour of the entire system. The probe positioning (SW/PROBPOS) and the controlling software for scanning (SW/SCAN) will enable an **efficient automatic digitization of a big**

variety of cultural/heritage assets even in situ. The characterization of the data acquired through the extraction of semantic features (SW/SFESURF, SW/SFESTRUCTMTL), and their analysis and modelling (SW/AGING), will be the basis for a tool of **material identification** and **surface and volumetric diagnosis** (SW/SIM, SW/DSS).

Objective 2	*…to apply a* ***hierarchical approach for 3D reconstruction of the object*** *via the successive collection and utilization of the* ***multi-sensorial data*** *in an order of* ***increasing resolution*** *and* ***infiltration factor****, making thus, possible, to* ***render the object*** *in a* ***multi-layered*** *way, so as to facilitate its deployment in* ***analysis*** *and* ***3D printing procedures***

Objective 3	*…to create* ***high precision*** *and* ***realistic digital surrogates of the cultural assets*** *by also providing* ***detailed insight regarding both the surface but also the volumetric structure, material composition and shape and structure of the underlying materials****,* ***so as to render them visible to the unaided eye*** *either via occlusion capable visualization techniques or* ***via transparent multi-material*** *3D printing.*

By coupling low-resolution global scanning (HW/VISDEPTH, SW/SCAN) and the capture of localized **multi-sensorial data** through point probes or probes that acquire small flat regions of the artworks (HW/MPROF, HW/ACOUSMIC, HW/IRCAM, HW/FTIR, HW/RAMAN, HW/UVSPEC, HW/XRF, HW/HDMSRI, HW/MSRTI, SW/MMACQ, SW/RTIPROC), the architecture provides **a hierarchical approach for 3D reconstruction of the object** under study, and helps to obtain a **realistic digital surrogates of the cultural assets**. Punctual/local probes will produce **increasing resolution** data at **high precision** in small selected areas determined of interest by the end users, and the use of surface (HW/MPROF, HW/UVSPEC, HW/HDMSRI, HW/MSRTI) and sub-surface (HW/ACOUSMIC, HW/IRCAM, HW/FTIR, HW/RAMAN, HW/XRF) measurements will convey, in the selected regions of interest, **multi-layered** representation of the CH object and a **detailed insight regarding both the surface but also the volumetric structure, material composition and shape and structure of the underlying materials**. This high **infiltration factor** will facilitate the **analysis** (SW/SIM, SW/DSS) of the artwork and will allow the scholars to **render the object** (SW/INSPECT, SW/SINSPECT) and to inspect hidden properties **so as to render them visible to the unaided eye**. Further, the architecture will enable researchers to produce real-world replicas of the artwork by **3D printing procedures** (HW/3DPRINT, SW/3DPRINT), and to physically print volumetric stratigraphy **via transparent multi-material** rapid prototyping.

Objective 4	*…to apply* ***systematic study*** *and methodical* ***material analysis*** *through state-of-the-art* ***laboratory*** *techniques, so as to* ***understand the heterogeneous nature and complex structures****, to identify the broad and varied class of materials and to* ***understand their degradation mechanisms over time****, targeting to the* ***extraction of the appropriate parameters*** *able to* ***accurately describe context-dependent ageing models per material****.*

A group of components is devoted to the **systematic study** of **material analysis**. They take the annotations (SW/ANNOTATIONS) made on prepared samples together with probe measurements done in a controlled **laboratory** environment (HW/MPROF, HW/ACOUSMIC, HW/IRCAM, HW/FTIR, HW/RAMAN,

HW/UVSPEC, HW/XRF, HW/HDMSRI, SW/MMACQ, SW/RTIPROC), and extract descriptors (SW/SFESURF, SW/SFESTRUCTMTL) in order to **understand the heterogeneous nature and complex structures** of materials. The modelling of the ageing factors of materials will give scholars a tool to **understand their degradation mechanisms over time**, and the **extraction of the appropriate parameters** will be used to **accurately describe context-dependent ageing models per material** (HW/CHAMBER, SW/ANNOTATION, SW/AGING).

Objective 5	*…to* ***spatiotemporally (4D)*** *simulate* ***uni-material models*** *individually* ***based on certain environmental phenomenon modeling*** *(i.e. context-dependent), so as to collectively* ***render imminent degradation effects*** *on the multi-material cultural objects in an attempt* ***to predict and to recreate the appearance of the cultural object in specific times in the future*** *or even to perform reverse engineering so as to achieve the automatic restoration, reaching even back to its original shape.*

Objective 6	*…to indicate, the* ***invisible to an unaided eye****, spots/segments of the cultural object that are in eminent conservation need and require special care, while to simultaneously provide suggestions by* ***a dedicated Decision Support System (DSS)****, regarding* ***the most appropriate conservation method that should be followed, in the most comprehensive and analytic way*** *to the conservator via* ***enhanced interactive visualization methods, for both gaining from human intelligence and allowing metadata collection/updating***

The 3D reconstruction (HW/VISDEPTH, SW/SCAN, HW/MECH, SW/PROBPOS, SW/REG), the local measurements (HW/MPROF, HW/ACOUSMIC, HW/IRCAM, HW/FTIR, HW/RAMAN, HW/UVSPEC, HW/XRF, HW/HDMSRI, HW/MSRTI, HW/MECH, SW/PROBPOS, SW/MMACQ, SW/RTIPROC), the knowledge about materials and how they degrade over time (HW/CHAMBER, SW/ANNOTATION, SW/SFESURF, SW/SFESTRUCTMTL, SW/AGING), and the capability to render them in a meaningful way (SW/INSPECT, SW/SINSPECT), will be all employed for two main tasks, i.e., **spatiotemporally (4D)** simulation of **uni-material models** (SW/SIM), and **a dedicated Decision Support System (DSS)** for guidelines generation (SW/DSS). **Based on certain environmental phenomenon modelling** (SW/AGING), the spatiotemporal simulation will **render imminent degradation effects** in order **to predict and to recreate the appearance of the cultural object in specific times in the future**. The possibility of doing reverse ageing will be also evaluated. On the other hand, the component SW/DSS will assist curators by suggesting **the most appropriate conservation method that should be followed, in the most comprehensive and analytic way**, based on the analysis of digital data about the elements that are **invisible to an unaided eye** (HW/ACOUSMIC, HW/IRCAM, HW/FTIR, HW/RAMAN, HW/XRF). The SW/DSS will be tightly linked to the system visualization tools (SW/INSPECT, SW/SINSPECT,SW/SIM) that use **enhanced interactive visualization methods, for both gaining from human intelligence and allowing metadata collection/updating** (SW/ANNOTATION).

Objective 7	*…****to validate the aforementioned actions*** *on* ***real case scenarios*** *involving* ***heterogeneous objects of various sizes and materials****, as well as to identify* ***probable research challenges for the future***

The artworks that can be captured, analysed, and visualized by the proposed architecture and the Scan4Reco system are **heterogeneous**. The high modularity and the toolbox nature of the proposed architecture proved to be a very flexible acquisition setup (HW/MECH, SW/MECH, SW/PROBPOS) and allows for a wide range of possible analysis, since the set of multi-modal probes (HW/MPROF, HW/ACOUSMIC, HW/IRCAM, HW/FTIR, HW/RAMAN, HW/UVSPEC, HW/XRF, HW/HDMSRI, HW/MSRTI, HW/MECH, SW/MECH, SW/PROBPOS, SW/MMACQ, SW/RTIPROC) can deal with a wide spectrum of materials. Among all these **objects of various sizes and materials**, end-users have identified two broad classes of **real case scenarios** that represent the two main use cases (pilots) **to validate the aforementioned actions** and for the architecture and system testing. They are the metallic objects (EUR/MO) and the paintings (EUR/PA).

Objective 8	*…to **enhance the accessibility of the digitized cultural objects** (along with the **outcomes of the project**) to both **the scientific community, the field experts and the general public** via the development of a **virtual** model of a **museum where all scanned artifacts will be virtually** exposed*

Finally, data will be released in a **virtual museum** (SW/VMUSEUM), **where all scanned artifacts will be virtually** available to **the scientific community, the field experts and the general public**. This will both **enhance the accessibility of the digitized cultural objects**, and provide the community with the relevant **outcomes of the project.**

6. Component description

For the purpose of the architecture definition, we provide a description of each of the components that have been identified. The level of description is consistent with the current level of advancement in the specification of each component. Following the iterative project design guidelines, the component description will be iteratively refined during project evolution to reflect the evolution of the state-of-the-art, as well as the improved understanding of end user needs and of their technological implications. In particular, Deliverables D2.4 and D2.5 will present the evolved System Specification.

Each component has been described with a fixed, common structure, in order to convey a clear and standard overview of its nature, functionalities and dependencies. The format starts with a short header:

{HW,SW}XX	**Name**
Partners:	LEAD-PARTNER, other partners
Environment:	{LAB, ON-SITE, OFF-SITE}
Receives input from:	{HW,SW}XX – …
Produces output for:	{HW,SW}XX – …

- **ID** is the unique ID of the component {HW,SW,PR}XX, where:
  - HW: hardware
  - SW: software
  - XXXX: evocative abbreviation of the component
  - Example: ID for the micro-profilometer component HW/MPROF
- **Name** is the name of the component;
- **Partners** lists the lead partner (underlined) and the other involved partners;
- **Environment** is the place in which the component will be used, e.g., LAB, ON-SITE or OFF-SITE;
- **Receives input from** is the list of component IDs that produces the input for this component;
- **Produces output for** is the list of component IDs that use the output produced by this component;

Then a brief section **"Purpose"** explains the abstract functionality of the component and its relationships with the end-user requirements. The purpose of the component is accompanied, in this pubic version of the deliverable by a **"Data"** section iwith the description of the types of data used by the component and its format, i.e., Name, Description and Format ID.

- ***Name*** is the identifier of the dataset used as input, output, or for other purposes (e.g., temporary storage, internal repository, …)
- ***Description*** is a brief description of the contents of the dataset
- ***Format ID*** refers to the data format in which this particular dataset is stored. There might be multiple formats here in case multiple options apply. The ID refers to an entry in the data format description table (see section 7). It could be a standard format or a custom one developed for the project.

6.1 Hardware components

In the following, we summarize the description of the hardware components of the system. These can be subdivided into:

- the chamber for samples/mock-ups preparation (HW/CHAMBER);
- the capture component of the global scanning device (HW/VISDEPTH);
- all the surface and sub-surface measurement probes (HW/MPROF, HW/ACOUSMIC, HW/IRCAM, HW/FTIR, HW/RAMAN, HW/UVSPEC, HW/XRF, HW/HDMSRI, HW/MSRTI);
- the mechanical device onto which on-site probes/scanners will be mounted (HW/MECH);
- the multi-material 3D printer (HW/3DPRINT).

HW/CHAMBER	Artificial Aging Chamber
Partners:	OPD, OF-ADC
Environment:	LAB
Receives input from:	NONE
Produces output for:	HW/VISDEPTH, HW/ACOUSMIC, HW/IRCAM, HW/FTIR, HW/RAMAN, HW/UVSPEC, HW/XRF, HW/MPROF, HW/HDMSRI

Purpose

The artificial aging chambers are devices to speed up the normal aging processes of items under controlled environmental conditions. For each kind of objects, the factors which most affect their ageing path will be taken into account in order to plan a proper aging experiment. Hence, conditions pretending both indoor and outdoor display environments will be selected and reproduced.

Data

None.

HW/VISDEPTH	Visual and depth scanner
Partners:	CERTH, RFSAT
Environment:	ON-SITE
Receives input from:	HW/CHAMBER, SW/PROBPOS
Produces output for:	SW/SCAN

Purpose

The depth sensor will provide colour and depth data that will be used to extract a coarse estimation of a cultural object's 3D structure and appearance. The data produced by the sensor will contribute to the proper documentation of a CH item (EUR/GR/01, EUR/GR/02) and will accelerate the measuring process (EUR/GR/03) by identifying regions that require further processing and facilitating the positioning of the various probes on salient regions both for metallic objects (EUR/MO/02) and for paintings (EUR/PA/02).

Data

Input	-	None besides control flow	
Output	Depth maps set	Set of depthmaps, in form of a PNG image sequence, corresponding to different views of a CH item	PNG
	RGB images set	Set of color images, in form of a JPEG image sequence, corresponding to different views of CH item	JPEG
Other	-	-	-

HW/MPROF	**Optical micro-profilometry**
Partners:	UNIVR
Environment:	LAB, ON-SITE
Receives input from:	HW/CHAMBER, SW/PROBPOS
Produces output for:	SW/REG, SW/SFESURF

Purpose

Optical micro-profilometry provides a quantitative estimation of the surface texture and roughness at micrometric level through a direct measurement of the surface profile. The 3D representation obtained by this device is mandatory to convey the proper information about the material roughness level and the regularity of micro-3D structures (EUR/MC/02). The use of data from micro-profilometer local measurements (EUR/MO/04) of mock-ups (EUR/MC/01) and metallic object (EUR/MO/04) provides objective insights about surface structure and appearance (EUR/MC/02) in order to characterize and model different materials (EUR/MC/05). This will enable scholars to understand the variation of material geometry and appearance after properly induced changes (EUR/MC/04, EUR/MO/06, EUR/MO/07, EUR/MO/08). The information about roughness and micro-scale structure is helpful as well to model the geometry of metallic object for 3D printing purposes (EUR/MC/08, EUR/MO/09).

Data

Input	-	None besides control flow and parameter setting	
Output	Microprofilometer data patch	The data format for microprofilometer data will include metadata and pixel level values	MPFDATA
Other	-	-	-

HW/ACOUSMIC	**Acoustic Microscopy System**
Partners:	OF-ADC
Environment:	{LAB, ON-SITE}
Receives input from:	HW/CHAMBER, SW/PROBPOS, SW/MMACQ
Produces output for:	SW/MMACQ

Purpose

Acoustic microscopy constitutes a powerful non-destructive testing (NDT) technique which provides quantitative structural information of an object at micrometric level. Primarily, this HW component will support the acquisition of structure and appearance of the surfaces and sub-surfaces (EUR/MC/02, EUR/MC/03) of either metallic (EUR/MO/02) or painting (EUR/PA/02) objects. Moreover, it will contribute to the proper measurement documentation (EUR/GR/01, EUR/GR/02). Secondarily, the data set that will be produced by this component will be used by the respective SW components in order to support the characterization, the modelling, the visualization and the replication of CH item (EUR/MC/05, EUR/MC/06 EUR/MC/07, EUR/MC/08, EUR/MO/04, EUR/MO/05, EUR/MO/06, EUR/PA/03, EUR/PA/05, EUR/PA/06, EUR/PA/07).

Data

Input	ADC Acquisition Parameters	The parameters of ADC cards, e.g. sampling rate, gate, triggering type, etc.	ADCPARAMS
Output	Echographs Stack	A set of A-scan signals with their index in the region of interest.	ECHOSTACK
Other	-	-	-

HW/IRCAM	**Infrared camera**
Partners:	OF-ADC
Environment:	{LAB, ON-SITE }
Receives input from:	HW/CHAMBER, SW/PROBPOS, SW/MMACQ
Produces output for:	SW/MMACQ

Purpose

The infrared images produced by the method provide qualitative and quantitative analysis of the physical and chemical properties of a CH item, as well as, information about a state of the item. Hence, the HW component will support the acquisition of physical and chemical properties of the surfaces and sub-surfaces (EUR/MC/02, EUR/MC/03) of either metallic (EUR/MO/02) or painting (EUR/PA/02) objects. Moreover, it will contribute to the proper measurement documentation (EUR/GR/01, EUR/GR/02). Secondarily, the data set that will be produced by this component will be used by the respective SW components in order to support the characterization, the modelling, the visualization and the replication of CH item (EUR/MC/05, EUR/MC/06 EUR/MC/07, EUR/MC/08, EUR/MO/04, EUR/MO/05, EUR/MO/06, EUR/PA/03, EUR/PA/05, EUR/PA/06, EUR/PA/07).

Data

Input	IR Imaging Acquisition Parameters	The parameters of IR imaging,	IRIMAGPARAMS
Output	IR Imaging Stack	A set of images with their index position.	IRIMAGSTACK
Other	-	-	-

HW/FTIR	**Fourier Transform Infrared Spectroscopy System**
Partners:	OF-ADC
Environment:	{LAB, ON-SITE }
Receives input from:	HW/CHAMBER, SW/PROBPOS, SW/MMACQ
Produces output for:	SW/MMACQ

Purpose

FTIR spectroscopy is useful in identifying unknown material, determining the quality or the consistency of a sample and/or determining the amount of components in a mixture. Primarily, this HW component will support the acquisition of physical and chemical properties of the surfaces and sub-surfaces (EUR/MC/02, EUR/MC/03) of either metallic (EUR/MO/02) or painting (EUR/PA/02) objects. Moreover, it will contribute to the proper measurement documentation (EUR/GR/01, EUR/GR/02). Secondarily, the data set that will be produced by this component will be used by the respective SW components in order to support the characterization, the modelling, the visualization and the replication of CH item (EUR/MC/05, EUR/MC/06 EUR/MC/07, EUR/MC/08, EUR/MO/04, EUR/MO/05, EUR/MO/06, EUR/PA/03, EUR/PA/05, EUR/PA/06, EUR/PA/07).

Data

Input	FTIR Acquisition Parameters	The parameters of FTIR measurement, i.e. spot size, scan time and spetral region of measurement.	FTIRPARAMS
Output	FTIR Spectra Stack	A set of FTIR spectra with their index in the region of interest.	FTIRSTACK
Other	-	-	-

HW/RAMAN	Infrared laser Raman spectroscopy system
Partners:	OF-ADC, BWTEK
Environment:	{LAB, ON-SITE}
Receives input from:	HW/CHAMBER, SW/PROBPOS, SW/MMACQ
Produces output for:	SW/MMACQ

Purpose

Raman spectroscopy is used in identifying unknown material and determining the quality and the consistency of samples. Primarily, this HW component will support the acquisition of physical and chemical properties of the surfaces (EUR/MC/02) of either metallic (EUR/MO/02) or painting (EUR/PA/02) objects. Moreover, it will contribute to the proper measurement documentation (EUR/GR/01, EUR/GR/02). Secondarily, the data set that will be produced by this component will be used by the respective SW components in order to support the characterization, the modelling, the visualization and the replication of CH item (EUR/MC/05, EUR/MC/07, EUR/MC/08, EUR/MO/04, EUR/MO/05, EUR/MO/06, EUR/PA/03, EUR/PA/05, EUR/PA/06, EUR/PA/07).

Data

Input	Raman Acquisition Parameters	The parameters of Raman measurement, i.e. integation time and laser power.	RAMANPARAMS
Output	Raman Spectra Stack	A set of Raman spectra with their index in the region of interest.	RAMANSTACK
Other	-	-	-

HW/UVSPEC	**UV/VIS spectrophotometer**
Partners:	OF-ADC, BWTEK
Environment:	{LAB, ON-SITE}
Receives input from:	HW/CHAMBER, SW/PROBPOS, SW/MMACQ
Produces output for:	SW/MMACQ

Purpose

UV/Vis spectroscopy is useful in measuring the reflective ability/permeability and the color of a sample. Primarily, this HW component will support the acquisition of physical and chemical properties of the surfaces (EUR/MC/02) of either metallic (EUR/MO/02) or painting (EUR/PA/02) objects. Moreover, it will contribute to the proper measurement documentation (EUR/GR/01, EUR/GR/02). Secondarily, the data set that will be produced by this component will be used by the respective SW components in order to support the characterization, the modelling, the visualization and the replication of CH item (EUR/MC/05, EUR/MC/07, EUR/MC/08, EUR/MO/04, EUR/MO/05, EUR/MO/06, EUR/PA/03, EUR/PA/05, EUR/PA/06, EUR/PA/07).

Data

Input	UV/Vis Acquisition Parameters	The parameter of UV/Vis measurement, i.e., the integration time	UVVISPARAMS
Output	UV/Vis Spectra Stack	A set of UV/Vis spectra with their index in the region of interest.	UVVISSTACK
Other	-	-	-

HW/XRF	**X-Ray Fluorescence Spectroscopy System**
Partners:	OF-ADC
Environment:	{LAB, ON-SITE}
Receives input from:	HW/CHAMBER
Produces output for:	SW/MMACQ

Purpose

X-ray fluorescence (XRF) spectroscopy allows the qualitative and quantitative analysis of the sample. Moreover, it is a multi-element analysis method, as it allows the simultaneous determination of several chemical components. The X-ray fluorescence spectroscopy finds application in the analysis of a plurality of different kind of samples and often the requirements for the preparation of the sample is small. This HW component will support the characterization and modelling of different materials (EUR/MC/05, EUR/MC/06) and the acquisition of physical and chemical properties of CH items (EUR/MO/02, EUR/PA/02). Moreover, it will contribute to the proper measurement documentation (EUR/GR/01, EUR/GR/02).

Data

Input	-	None besides control flow	
Output	XRF Acquisition Stack	A set of XRF spectra along with respective metadata.	XRFSTACK
Other	-	-	-

HW/HDMSRI	**Lab high-density Multispectral Reflectance Imager**
Partners:	CRS4, UNIVR
Environment:	LAB
Receives input from:	HW/CHAMBER
Produces output for:	SW/RTIPROC

Purpose

This hardware module acquires multispectral reflectance data of samples/mock-ups (and possibly very small flat objects) in a controlled laboratory setup. It responds to the end-user need of surface appearance characterization (EUR/MC). In particular, it contributes to the acquisition and digital representation of surface structure and appearance of material samples/mock-ups (EUR/MC/02). Its raw output will be used directly as input by the RTI processing step (SW/RTIPROC), and this signal will be useful for the tasks of characterization and modelling of different materials or material states based on surface appearance (EUR/MC/05).

Data

Input	-	-	-
Output	Image stack	Set of images corresponding to different lighting conditions	RAW/TIFF+XML
Other	-	-	-

HW/MSRTI	Multispectral Reflectance Transformation Imager
Partners:	CRS4, UNIVR
Environment:	ON-SITE
Receives input from:	SW/PROBPOS
Produces output for:	SW/RTIPROC

Purpose

This hardware module acquires multispectral reflectance data of small, flat region of metallic objects and paintings. It operates on-site for local, punctual probing of artworks. It responds to the general end-user requirements regarding the metallic objects and paintings analysis (EUR/MO, EUR/PA), and in particular to the need of gathering a collection of a series of local multi-modal measurements across a metallic object surface (EUR/MO/02) and across paintings (EUR/PA/02). Its raw output will be used directly as input by the RTI processing step (SW/RTIPROC). This hardware will be mounted on the mechanical device (HW/MECH).

Data

Input	-	None besides control flow	
Output	Image stack	Set of images corresponding to different lighting conditions	RAW+XML
Other	NA	NA	NA

HW/MECH	Mechanical device
Partners:	AVASHA, OF-ADC, BW-TEK
Environment:	ON-SITE
Receives input from:	SW/MECH
Produces output for:	NONE

Purpose

Mechanical device is a generic term for all hardware involved in the Scan4Reco system for on-site measurements, except for the hardware which is part of a sensor. On a logical level, the mechanical device breaks down into two components, namely the control unit and the coarse positioning system. Physically, these two components might form an integrated system, or may have to be split into even more than two parts.

The purpose of the control unit is to provide the electro-mechanical framework to host those hardware and software components of the on-site system which are neither a sensor probe or the coarse positioning system. To achieve modularity, compactness and marketability, standardization of the electrical and mechanical properties of sensor controller devices will be a key aspect. In the proposal, the role of the control unit is covered under the topic of "mechanical integration" (D6.3).

The purpose of the coarse positioning system is to position the sensor probes relative to the cultural heritage object for measurements. This will be done by moving the probe and/or the object. This positioning serves to support scanning of the coarse object geometry via HW/VISDEPTH and performing local measurements near the object surface with the probes of HW/MPROF, HW/ACOUSMIC, HW/IRCAM, HW/FTIR, HW/RAMAN, HW/UVSPEC and HW/MSRTI. The coarse positioning system corresponds to the "motorized mechanical arm" (part of D5.1) in the proposal.

Consequently, the capabilities of HW/MECH should support efforts leading to an integrated and portable device (project objective 1), the reduction of manual intervention (EUR/GR/03), safety of operation (EUR/GR/04), use also outdoor and on scaffolds (EUR/MO/01), the need to support registration within a single reference frame for various measurements (EUR/MO/02 and EUR/PA/03), the system ease of use (EU/PA/02) and the ability to perform measurements for the geometries of the test cases for metallic objects and paintings.

It should be noted that registration task here does not refer to fine multimodal registration of acquired data (which is handled by SW/REG), but to providing support for positioning of probes in a shared reference frame at a sufficient resolution.

Data

Input	-	None besides control flow and parameter setting	-
Output	-	-	-
Other	-	-	-

HW/3DPRINT	3D Printer
Partners:	FHG-IGD
Environment:	LAB
Receives input from:	SW/PRINT
Produces output for:	NONE

Purpose

A multimaterial 3D printer for reproducing shape and appearance of 3D scans of artwork / sculptures and scientific renderings/simulations visualizing hidden layers, material compositions or aging. The device is required to respond to the need for replication of single-material metallic objects (EUR/MO/06) as well as for the exploration of paintings (EUR/PA/07).

Data

Input	BMP stack	Each slice is specified by N 1bit BMPs specifying the droplet positioning of the resin materials (N = 3 for the Connex3 and N=6 for the J750 printer).	BMPstack
	Voxelprint Configuration	Config file for Voxelprint specifying the print mode and the path to the BMP Stack	VPTXT
Output	-	-	-
Other	-	-	-

6.2 Software components

In the following tables we summarize the description of the software components of the system. These can be subdivided into:

- an annotation tool to produce metadata/paradata related to the prepared samples/mock-ups and the artwork being acquired (SW/ANNOTATION);
- the tools to drive the mechanical device (SW/MECH and SW/PROBPOS);
- the tools for performing holistic scanning (SW/SCAN) and multimodal acquisition (SW/MMACQ);
- the tool for multimodal registration (SW/REG);
- the processing tools to extract information and features from local probe data (SW/RTIPROC, SW/SFESURF, SW/SFESTRUCTMTL) and the corresponding ageing model (SW/AGEING);
- tools to visually explore the acquired datasets (SW/INSPECT, SW/SINSPECT, SW/VMUSEUM);
- the simulation, analysis and guidelines generation software (SW/SIM, SW/DSS);
- the 3D printing software module (SW/3DPRINT).

SW/ANNOTATION	Sample and object annotation
Partners:	UNIVR, CRS4,
Environment:	{OFF-SITE}
Receives input from:	HW/CHAMBER
Produces output for:	SW/AGEING

Purpose

The purpose of this software component is to allow for a standard annotation of the sample and artworks for analysis and model training. The produced metadata will be the first piece of information that will be attached to a sample/mock-up or an artwork, in order to respond to the end-user need of a clear documentation throughout all the system pipeline (EUR/GR/01,EUR/GR/02).

Data

Input	-	-	-
Output	META	DICOM-like format for the basic object information and ageing conditions	META
Other	-	-	-

SW/MECH	Coarse Positioning Controller Firmware
Partners:	AVASHA
Environment:	ON-SITE
Receives input from:	SW/PROBPOS
Produces output for:	SW/PROBPOS, HW/MECH

Purpose

The firmware of the coarse positioning system is installed on its motion controller. It executes commands received via a serial interface. The commands will trigger motor action, such as positioning or reference drives, or provide information on the state of the coarse positioning system and its axes.

Data

Input	POSCMD	Command to coarse positioning controller via serial interface	SPOSCMD
Output	POSOUT	Result of command execution sent by coarse positioning controller via serial interface	SPOSCMD
Other	-	-	-

SW/PROBPOS	Probe positioning and local measures
Partners:	CERTH, AVASHA, OF-ADC
Environment:	ON-SITE
Receives input from:	NONE
Produces output for:	SW/MECH, HW/ACOUSTIC, HW/IRCAM, HW/FTIR, HW/RAMAN, HW/UVSPEC, HW/XRF, HW/MPROF, HW/MSRTI

Purpose

The purpose of this software component is to control the mechanical device (HW/MECH), through its driver SW/MECH, in order to position probes on the artworks for performing global and local measurements. It contributes to the need for multi-modal capture of metallic objects (EUR/MO/02) and paintings (EUR/PA/02, EUR/PA/03). It also responds to end-user requirements of a reduced manual intervention in measuring (EUR/GR/03) by facilitating the positioning of the capturing devices, with a high attention on the safety of operation (EUR/GR/04).

Data

Input	-	None besides control flow and parameter setting	-
Output	-	None besides control flow and parameter setting	-
Other	-	-	-

SW/SCAN	3D Scanning
Partners:	CERTH, AVASHA, RFSAT
Environment:	ON-SITE
Receives input from:	HW/VISDEPTH
Produces output for:	SW/REG

Purpose

This software component will produce a 3D digital replica of the original CH item using the data captured by the HW/VISDEPTH sensor. The computed digital surrogate will provide a coarse approximation of the items surface and appearance. It will contribute to the proper documentation of the CH item (EUR/GR/01, EUR/GR/02). The generated proxy will enable end users to virtually explore the surface and structure of the CH item (EUR/MC/07) and to visualize the analysis results on specific regions (EUR/MO/04, EUR/PA/05). The generated models will be also used to initialize the spatiotemporal simulation process (EUR/MO/05, EU/PA/06).

Data

Input	Depthmaps set	Set of depthmaps corresponding to different views of a CH item	PNG
	RGB images set	Set of color images corresponding to different views of CH item	JPEG
Output	3D model	Assembled 3D object	3MF, OBJ, STL
Other	-	-	-

SW/MMACQ	Acquisition of data using IR camera, UV/Vis-IR-Raman-XRF spectroscopy, and acoustic microscopy
Partners:	OF-ADC
Environment:	{ON-SITE}
Receives input from:	HW/ACOUSMIC – HW/IRCAM – HW/FTIR – HW/RAMAN – HW/UVSPEC – HW/XRF – SW/PROBPOS
Produces output for:	HW/ACOUSMIC – HW/IRCAM – HW/FTIR – HW/RAMAN – HW/UVSPEC - SW/SFESTRUCTMTL – SW/REG – SW/PROBPOS

Purpose

This software component is the software interface of the HW components, i.e. IR camera, spectroscopies and acoustic microscopy. The main objective of this component is to efficiently collect and save the data produced by these various sensors. Hence, this SW component will support the acquisition of structure and appearance of the surfaces and sub-surfaces (EUR/MC/02, EUR/MC/03) of either metallic (EUR/MO/02) or painting (EUR/PA/02) objects. It will contribute to the proper measurement documentation (EUR/GR/01, EUR/GR/02). Also, the data set that will be produced by this component will be used by the other SW components in order to support the characterization (SW/SFESTRUCTMTL), the modelling (SW/REG), and will be useful for the later tasks of visualization and replication (SW/INSPECT, SW/SINSPECT, SW/3DPRINT) of CH item (EUR/MC/05, EUR/MC/06 EUR/MC/07, EUR/MC/08, EUR/MO/04, EUR/MO/05, EUR/MO/06, EUR/PA/03, EUR/PA/05, EUR/PA/06, EUR/PA/07).

Data

Input	Echographs stack	A set of A-scan signals with their index in the region of interest.	ECHOSTACK
	FTIR Spectra Stack	A set of FTIR spectra with their index in the region of interest.	FTIRSTACK
	IR Imaging Stack	A set of images with their index position	IRIMAGSTACK
	UV/Vis Spectra Stack	A set of UV/Vis spectra with their index in the region of interest.	UVVISSTACK
	Raman Spectra Stack	A set of Raman spectra with their index in the region of interest.	RAMANSTACK
	XRF Acquisition Stack	A set of XRF spectra along with respective metadata.	XRFSTACK
Output	Acoustic Microscopy Dataset	Acoustic microscopy system data format.	MODEL-ACS

	Spectroscopic Data Point Table	Data point table with the spectra from UV/Vis, Raman, FTIR and XRF spectroscopy	MODEL-DPT
	IR Images	Picture format for IR images.	IRIMAGE
Other	ADC Acquisition Parameters	The parameters of ADC cards, e.g. sampling rate, gate, triggering type, etc.	ADCPARAMS
	FTIR Acquisition Parameters	The parameters of FTIR measurement, i.e. spot size, scan time and spetral region of measurement.	FTIRPARAMS
	IR Imaging Acquisition Parameters	The parameters of IR imaging.	IRIMAGPARAMS
	UV/Vis Acquisition Parameters	The parameter of UV/Vis measurement, i.e., the integration time.	UVVISPARAMS
	Raman Acquisition Parameters	The parameters of Raman measurement, i.e. integation time and laser power.	RAMANPARAMS
	XRF Acquisition Parameters	The parameters of XRF measurement, i.e. integation time.	XRFPARAMS

SW/RTIPROC	**RTI image stack processing**
Partners:	CRS4, UNIVR
Environment:	ON-SITE, OFF-SITE
Receives input from:	HW/HDMSRI, HW/MSRTI
Produces output for:	SW/REG, SW/SFESURF

Purpose

The software component SW/RTIPROC will process the output image stack captured by the multi-spectral reflectance imagers (HW/HDMSRI, HW/MSRTI) and produce an integrated and manageable per-point representation of the reflectance data. It responds to the need of a digital representation of surface structure and appearance of material samples/mock-ups (EUR/MC/02), and the resulting signal is important for the characterization and the modelling of the material surface appearance (EUR/MC/05). Of course this software module will also process all the collection of reflectance data taken locally from small flat patches of metallic objects and paintings, so it is important for end-user needs related to artworks analysis (EUR/MO/02, EUR/PA/02).

Data

Input	Image stack	Set of images corresponding to different lighting conditions	IMSTACK
Output	Appearance profiles	The custom data format for RTI data will include metadata and pixel level values	RTISTACK
Other	-	-	-

SW/REG	Multi-modal data registration
Partners:	OF-ADC, UNIVR, RFSAT, AVASHA
Environment:	{ON-SITE, OFF-SITE}
Receives input from:	SW/SCAN - SW/MMACQ – HW/MPROF – SW/RTIPROC
Produces output for:	SW/INSPEC – SW/SINSPEC – SW/VMUSEM – SW/SIM – SW/3DPRINT

Purpose

This SW component supports the registration of all measurements of local probes onto the same reference frame defined by the low resolution, rough, global 3D geometry. Hence, it provides a 3D digital representation of the surface and the sub-surfaces of samples (EUR/MC/02, EUR/MC/03, EUR/PA/04). All the aligned signals are fused in a single data structure stored in the project database and usable by all visualization (EUR/MC/07, EUR/MO/04, EUR/PA/05) and simulation components (EUR/MC/05, EUR/MC/06, EUR/MO/05, EUR/PA/06).

Data

Input	Acoustic Microscopy Dataset	Acoustic microscopy system data format.	MODEL-ACS
	Spectroscopic Data Point Table	Data point table with the spectra from UV/Vis, Raman, FTIR and XRF spectroscopy	MODEL-DPT
	IR Images	Picture format for IR images.	IRIMAGE
	Microprofilometer data patch	The data format for microprofilometer data will include metadata and pixel level values	MPFDATA
	Appearance profile	The custom data format for RTI data will include metadata and pixel level values	RTISTACK
	3D model	Coarse 3D model from 3D scanning	3MF, OBJ, STL
Output	Registration data	3D model information of a CH item along with the registered measurements	PROJ
	3D model	3D model format for export and 3D printing	3MF, OBJ, STL
Other	-	-	-

SW/SFESURF	Semantic feature extraction & reconstruction from surface measurements
Partners:	UNIVR, CRS4, BWTEK, OF-ADC
Environment:	{OFF-SITE}
Receives input from:	HW/MPROF - SW/RTIPROC
Produces output for:	SW/AGING, SW/SIM

Purpose

The purpose of this software component is the extraction of semantic features from surface measurements performed with micro-profilometer and RTI software. These methods are required to derive surface features of material and surface characterization (EUR/MC), and in particular for the characterization and modeling of different materials and material states based on descriptors from superficial measurements (EUR/MC/05). The generated descriptors will be useful for other SW components, i.e. SW/INSPECT for the virtual interactive exploration of the samples (EUR/MC/07, EUR/MO/04, EUR/PA/05), SW/AGING and SW/SIM for modelling the aging procedure (EUR/MC/05, EUR/MC/06, EUR/MO/05, EUR/PA/06) and later for SW/DSS for creating a Decision Support System (EUR/OR/01).

Data

Input	Microprofilometer data patch	The data format for microprofilometer data will include metadata and pixel level values	MPFDATA
	Appearance profile patch	The custom data format for RTI data will include metadata and pixel level values	RTISTACK
	Semantic features	Values of labels and numerical features derived by statistical processing of patch data	FEATDATA
Other	NA	NA	NA

SW/SFESTRUCTMTL	Semantic feature extraction & reconstruction from material composition and tomographic measurements
Partners:	OD-ADC, BWTEK
Environment:	{ OFF-SITE}
Receives input from:	SW/MMACQ, SW/REG
Produces output for:	SW/AGING, SW/SIM

Purpose

This component supports the computation of derived properties and extraction of material descriptors (EUR/MC/05, EUR/MC/06) from composition and tomographic measurements provided by Acoustic Microscopy, UV/VIS, IR, Raman and XRF datasets. This includes signal processing algorithms related to the (i) mapping images derived by the UV-VIS-IR and Raman spectroscopy, (ii) The time frequency representations for layers and various structural findings in the paint layers. The generated descriptors will be useful for other SW components, i.e. SW/SINSPECT for the virtual interactive exploration of the samples (EUR/MC/07, EUR/MO/04, EUR/PA/05), SW/AGING and SW/SIM for modelling the aging procedure (EUR/MC/05, EUR/MC/06, EUR/MO/05, EUR/PA/06) and later for SW/DSS for creating a Decision Support System (EUR/OR/01).

Data

Input	Acoustic Microscopy Dataset	Acoustic microscopy system data format.	MODEL-ACS
	Spectroscopic Data Point Table	Data point table with the spectra from UV/Vis, Raman, FTIR and XRF spectroscopy	MODEL-DPT
	IR Images	Picture format for IR images.	IRIMAGE
Output	Semantic features	Values of labels and numerical features derived by statistical processing of material composition and tomographic measurement data	FEATDATA
Other	-	-	-

SW/AGEING	Ageing model extraction
Partners:	UNIVR, CRS4, CERTH, OF-ADC
Environment:	{OFF-SITE}
Receives input from:	SW/ANNOTATION, SW/SFESURF, SW/SFESTRUCTMTL
Produces output for:	SW/SIM

Purpose

The purpose of this software component is the use of prior knowledge and the training of parametric and statistical models for the development of different models of the ageing processes specific of specific materials in specific conditions as a function of pointwise features extracted from the multimodal acquisitions of Scan4Reco. The generated model will be useful for other SW components, i.e. SW/INSPECT and SW/SINSPECT for the virtual interactive exploration of the samples (EUR/MC/07, EUR/MO/04, EUR/PA/05), SW/SIM for simulating the aging process (EUR/MC/05, EUR/MC/06, EUR/MO/05, EUR/PA/06) and SW/DSS for creating a Decision Support System (EUR/OR/01).

Data

Input	Semantic features	Values of labels and numerical features derived by statistical processing of patch data	FEATDATA
	Metadata	DICOM-like format for the basic object information and ageing conditions	META
Output	Model	Ageing model description	AGEINGMODEL
Other	-	-	-

SW/INSPECT	3D multi-modal inspector
Partners:	CERTH, RFSAT
Environment:	{ON-SITE, OFF-SITE}
Receives input from:	SW/REG
Produces output for:	SW/DSS

Purpose

SW/INSPECT will be responsible for the visualization of the various stages of a CH item's analysis to the end user. Based on the generated 3d digital surrogate of the item SW/INSPECT will allow users to virtually explore the surface of a CH item and inspect the various local measurements from different sensors. Consequently, SW/INSPECT is related to EUR/MC/07 as it allows the virtual inspection of a CH item's replica as well as EUR/GR/01 and EUR/GR/02, since it helps end-users visualize and understand the recorded measurements and general state of the object. Additionally, SW/INSPECT satisfies EUR/MO/04 and EUR/PA/05, enabling end users to interactively explore the analysis results for both paintings and metallic objects. Finally, SW/INSPECT is related to EUR/MO/05 and EUR/PA/06 through the visualization of results of the spatio-temporal simulation process.

Data

Input	Registered 3D object	A custom file format following an XML structure that will include the 3D model of an item along with any related measurements and annotations.	PROJ
Output	Registered 3D object	A custom file format following an XML structure that will include the 3D model of an item along with any related measurements and annotations.	PROJ
	3D model	3D model format for export and 3D printing	3MF, OBJ, STL
Other	-	-	-

SW/SINSPECT	**Stratigraphic inspector**
Partners:	OF-ADC
Environment:	{ON-SITE, OFF-SITE}
Receives input from:	SW/REG
Produces output for:	SW/DSS

Purpose

This component supports the visual inspection of the stratigraphy of paintings (EUR/MC/02, EUR/MC/03, EUR/PA/04). It is also strongly related to SW/REG component (EUR/MC/07, EUR/MO/04, EUR/PA/05).

Data

Input	Registered 3D object	A custom file format following an XML structure that will include the 3D model of an item along with any related measurements and annotations.	PROJ
Output	Registered 3D object	A custom file format following an XML structure that will include the 3D model of an item along with any related measurements and annotations.	PROJ
	3D model	3D model format for export and 3D printing	3MF, OBJ, STL
Other	-	-	-

SW/VMUSEUM	Virtual Museum
Partners:	CERTH
Environment:	OFF-SITE
Receives input from:	SW/REG, SW/SIM
Produces output for:	N/A

Purpose

The interactive Virtual Museum will enable the general public to view in detail the 3D model of a digitized CH item through a dedicated website. The digitized surrogates will capture the texture and appearance of the original object and will be enhanced with metadata on certain regions of the CH item, e.g. visualizing its stratigraphy. SW/VMUSEUM complies with EUR/GR/01 and EUR/GR/02 regarding the documentation of the CH items. It will also allow the virtual exploration of CH items (EUR/MC/07) and the interactive exploration of analysis results for metallic objects (EUR/MO/04) and paintings (EUR/PA/05).

Data

Input	PROJ	Object and annotation information from other components	PROJ
Output	3D model	3d model for export and 3D printing	3MF, OBJ, STL
	Document	Document with information regarding the historical origins of an object	PDF
Other	-	-	-

SW/SIM	Spatio-temporal Simulation
Partners:	CERTH, RFSAT, UNIVR
Environment:	{LAB, ON-SITE, OFF-SITE}
Receives input from:	SW/REG – SW/SFESTRUCTMTL – SW/SFESURF – SW/AGING
Produces output for:	SW/VMUSEUM – SW/DSS

Purpose

The purpose of this software component is the exploration of a CH item's deterioration and ageing process through spatiotemporal simulation both for single-material metallic objects (EUR/MO/05) and for paintings (EUR/PA/06).

Data

Input	PROJ	XML-based 3D data format	3MF
	Semantic features	Values of labels and numerical features derived by statistical processing	FEATDATA
	Ageing model	Ageing model description	AGEINGMODEL
Output	Screen	Images of simulated future appearance	-
Other	-	-	-

SW/DSS	Decision Support System
Partners:	CERTH, OF-ADC, FHG-IGD
Environment:	ON-SITE, OFF-SITE
Receives input from:	SW/SINSPECT, SW/INSPECT, SW/SIM
Produces output for:	SW/SINSPECT, SW/INSPECT

Purpose

The aim of the Decision Support System (SW/DSS) is to process all the extracted multi-modal data of the Scan4Reco platform and to produce a probability based ranking of items from a dedicated database of conservation instructions. This will help conservators/restorers in deciding the right intervention for a a specific CH item (EUR/OR/01). These data include the measurements from the various sensors of the system, the ageing models and the outcome of spatiotemporal simulation. The generated suggestions will be visualized through a user interface.

Data

Input	PROJ	A custom file format following an XML structure that will include the 3D model of an item along with any related measurements and annotations.	PROJ
Output	DSS	A custom file format containing the suggestions of the DSS and the simulated states of the item at specified time instants.	DSS
Other	-	-	-

SW/3DPRINT — 3D Printing Software

Partners:	FHG-IGD
Environment:	OFF-SITE
Receives input from:	SW/REG, SW/INSPECT, SW/SINSPECT
Produces output for:	HW/3DPRINT

Purpose

The purpose of the 3D printing software is to enable accurate reproductions of 3D models by multi-material 3D printers. To achieve this, the software transforms geometry and annotated optical material properties / appearance correlates (e.g., color, translucency) of the 3D model into an appropriate arrangement of printing materials used to control a multi-material 3D printer. The input 3D models cover appearance 3D scans of artwork / sculptures and scientific renderings/simulations to visualize hidden layers, material compositions or aging. In particular, 3D printing is required to respond to the need for replication of single-material metallic objects (EUR/MO/06) as well as for the exploration of paintings (EUR/PA/07).

Data

Input	3d model	Printable 3D model in a standard file format	PLY, OBJ, WRL, PSET, STL, 3MF
	3d printing parameters	Text file specifying the 3D printing components and parametrization (a default JSON is always provided)	TXTJSON
Output	BMP Image Stack	Stack of 1bit BMP images, for n slices and N materials (currently we support 6 materials: cyan, magenta, yellow, black, white and clear)	BMPSTACK
	Voxelprint configuratio n	Config file for Voxelprint specifying the print mode and the path to the BMP Stack	VPTXT
Other	-	-	-

7. Data formats

In order to respond to the high modularity paradigm of the architecture, an important role in linking components and in the communication among them is played by the nature of data shared throughout the process pipeline. To make the development of each module as independent as possible, and to make constraints more loose, we rely, when possible, on standard data formats, while custom file formats will be designed only for representations specifically tailored to the project action field.

This list of file format is important not only for the communication between hardware and software components, but also to provide accessibility of captured and processed data for exchanging them either among the partners of the project or between the consortium and third parties, such as researchers in CH or the general public. These data formats will be used for making datasets and project results will be available for sharing and re-use [27].

7.1 Standard formats

Here we provide a list of standard file formats used by the architecture components. For each of them we define a unique format ID, we give a brief description, and we list the components that make use of it.

Format ID	Description	Components
BMP	BMP is a widely used image encoding format. It will be used to produce the slices for 3D printing. Each slice is specified by N 1bit BMPs specifying the droplet positioning of the resin materials (N = 3 for the Connex3 and N=6 for the J750 printer).	HW/3DPRINT SW/3DPRINT
JPEG	JPEG is a widely used image encoding format. It will be used to produce colored views of objects.	HW/VISDEPTH SW/SCAN SW/MMACQ SW/REG SW/SFESTRUCTMTL
PNG	PNG s a widely used image encoding format. It will be used to produce depthmaps for different view of objects.	HW/VISDEPTH SW/SCAN
RAW	A camera raw image file that contains the minimally processed data from the image sensor.	HW/HDMSRI HW/MSRTI SW/RTIPROC
TIFF	TIFF is a computer file format for storing raster graphics images. The standard defining it is ISO 12639:2004 / Amd. 1:2007	HW/HDMSRI HW/MSRTI SW/RTIPROC
3MF	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. 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. http://3mf.io Note: The 3MF file format shall be enhanced in this project to support the low-dimensional interim connection space that stores visual material attributes beyond color (e.g. gloss, translucency). This interim connection space shall be developed in this project.	SW/SCAN SW/REG SW/INSPECT SW/SINSPECT SW/VMUSEUM SW/3DPRINT

OBJ	A 3D model format geometry definition file format first developed by Wavefront Technologies 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. http://www.wvfront.com	SW/SCAN SW/REG SW/INSPECT SW/SINSPECT SW/VMUSEUM SW/3DPRINT
PLY	3D file format mainly used in the graphics community, can store basically arbitrary data, such as custom vertex attributes and faces of arbitrary number of vertices. Common vertex attributes (beyond position x-, y- and z-coordinates) are colors (r, g, b) and normals. Both ASCII and binary formats	SW/3DPRINT
PSET	Oriented point cloud data. Used in computer vision community	SW/3DPRINT
STL	STL (STereoLithography) is a file format native to the CAD software created by 3D Systems. 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. http://www.wvfront.com	SW/SCAN SW/REG SW/INSPECT SW/SINSPECT SW/VMUSEUM SW/3DPRINT
WRL	3D file format mainly used in the graphics community and virtual reality communities. Can contain multiple textures (incl. transparencies using an alpha channel) and multiple objects. ASCII and binary format that can store basic geometry along with transformation hierarchies	SW/3DPRINT
JSON	Text file specifying the 3D printing components and parametrization (a default JSON is always provided)	SW/3DPRINT
PDF	Portable Document Format. http://www.adobe.com	SW/VMUSEUM
TXT	Config file for Voxelprint specifying the print mode and the path to the BMP Stack.	HW/3DPRINT SW/3DPRINT

The two major groups of formats are standard formats are image formats (BMP, JPEG, PNG, RAW, and TIFF) and 3D model formats (3MF, OBJ, PLY, PSET, STL, and WRL). The image formats are used in selected subgroup of components for special needs, and will all be supported. The mentioned 3D model formats are all supported by the 3D printing components, but possibly a selected subset of them will be used for the Scan4Reco project. At present, 3MF, OBJ, PLY, and eventually STL are the major candidates for an implementation in the Scan4Reco tools.

7.2 Custom formats

Here we provide a list of custom file formats used by the architecture components. For each of them we define a unique format ID, we give a brief description, and we list the components that make use of it.

The aim is to reduce as much as possible the number of custom formats, which typically are a modification of standard data formats useful for specific project requirements. When needed, and possible, some of these formats might become the objects of a standardization activity during the project, so that they will be inserted in identified best practices within project domain, and they will increase the data interoperability with respect to use cases and scenarios selected in Scan4Reco.

We list here only the formats where some permanent storage is envisioned, and not formats related to low-level communication with hardware, which are mentioned in the individual components. These low level formats are referred to, in particular, as SPOSCMD for communication with HW/MECH, ADCPARAMS for the parameters of ADC cards, and IRIMAGPARAMS, FTIRPARAMS, RAMANPARAMS for the parameters of the various acquisition modalities.

Format ID	**Description**	**Components**
META	DICOM-like format for the basic object information and ageing conditions	SW/ANNOTATION SW/AGEING
PROJ	This custom format will have and XML structure and will contain the 3D model information of a CH item along with the registered measurements. Any annotations for specific regions will also be included.	SW/REG SW/INSPECT SW/SINSPECT SW/DSS
DSS	A custom file format containing the suggestions of the DSS and the simulated states of the item at specified time instants	SW/DSS
MPFDATA	Microprofilometer data. Raw data will include depth and Signal to noise ration and will be coupled with metadata related to the probe, probe settings, scanning stage, resolution, the sample (unique ID, name, materials and treatments); creators, date, ageing and treatments; acquisition date, time and operator	HW/MPROF SW/SFESURF
RTISTACK	Original data consists of stacks of RAW photographic images of the imaged samples and (eventually) of calibration targets. Derived data will be stored, as well, as appearance profiles data, including per-pixel information about illumination direction and intensity, estimated reflectance and color components. A specific folder structure will be designed to store raw data as well as metadata and processed information. Metadata include information regarding: the sample (unique ID, name, materials and treatments); creators, date, ageing and treatments; the acquisition setup (camera and light parameters); the acquisition protocol; acquisition date, time and operator	SW/RTIPROC SW/REG SW/SFESURF
FEATDATA	A common structure for all the features associated to local surface characterization. It includes a vector of local values or annotated semantic labels.	SW/SFESURF SW/AGEING
ECHOSTACK	A stack of raw data produced by the acoustic microscope. It consists of a set of echographs (1D signals) each of which represents the reflected wave from a spot of measurement.	HW/ACOUSTIC SW/MMACQ
IRIMAGSTACK	A stack of raw data produced by the IR camera. It consists of a set of images (2D signals) each of which is taken from a region of measurement.	HW/IRCAM SW/MMACQ
FTIRSTACK	A stack of raw data produced by the FTIR	HW/FTIR

	spectroscope. It consists of a set of spectra each of which represents the reflected electromagnetic from a spot of measurement.	SW/MMACQ
RAMANSTACK	A set of Raman spectra with their index in the region of interest.	HW/RAMAN SW/MMACQ
UVVISSTACK	A set of UV/Vis spectra with their index in the region of interest.	HW/UVSPEC SW/MMACQ
XRFSTACK	A set of XRF spectra along with respective metadata	HW/XRF SW/MMACQ
MODEL-ACS	All raw data from acoustic microscope are written in a same file using a compression method. Along with the raw data, a set of metadata are also incorporated in the same file as a header. These metadata consists of parameters of the measurement.	SW/MMACQ SW/REG SW/SFESTRUCTMTL
MODEL-DPT	All raw data from a spectroscopy (FTIR, UV/VIS, Raman, XRF) are written in a same file as data point tables. Along with the raw data, a set of metadata are also incorporated in the same file as a header. These metadata consists of parameters of the measurement.	SW/MMACQ SW/REG SW/SFESTRUCTMTL

8. Use cases and pilots

The architecture has been designed to satisfy the important, general requirement of a high modularity, with well-defined blocks that loosely constrain one another and that can be mixed and matched to accomplish specific tasks.

The fact that each block can alone solve a need of the end-users in cultural heritage, and that the same is valid for small groups of blocks or for the entire Scan4Reco system, makes the proposed architecture a powerful general solution for use cases involving artwork capture, analysis and investigation. It both conveys quantitative knowledge of the artwork properties through digital measurements, and also gives insights for future, operational interventions on the artwork undertaken by restorers and conservators. All these functionalities result in a very flexible, helpful toolbox, where the architecture components can be mixed and matched depending on the particular CH application and/or the object under study.

The architecture proves to realise the breakthrough vision of the Scan4Reco purpose in a concrete and general system, well-fitting all the project's scientific ambitions, and widely applicable to several use case scenarios. The general scope of the project will be put in practice by enabling and facilitating, with the designed components, the tasks of preservation, conservation, and restoration through a series of actions, such as the acquisition of multi-modal scanning (HW/MPROF, HW/ACOUSMIC, HW/IRCAM, HW/FTIR, HW/RAMAN, HW/UVSPEC, HW/XRF, HW/HDMSRI, HW/MSRTI, HW/MECH, SW/PROBPOS, SW/MMACQ, SW/RTIPROC), the material exploration (SW/INSPECT, SW/SINSPECT, SW/SIM, SW/DSS), the material identification and modelling (HW/CHAMBER, SW/ANNOTATION, SW/SFESURF, SW/SFESTRUCTMTL, SW/AGING), the 3D reconstruction (HW/VISDEPTH, SW/SCAN, HW/MECH, SW/PROBPOS, SW/REG), the presentation to the general public and scholars with a virtual museum (SW/VMUSEUM), and the creation of tactile multi-layered surrogates (HW/3DPRINT, SW/3DPRINT).

8.1 Use cases for the system

The Scan4Reco modules (a single, a subset or all of them) will be employed in a wide range of possible use cases. In fact, not all them must always be applied to get results of value to scholars, since intermediary solutions are of their own interest (e.g., material characterization), and some phases can be applied by using data from other pipeline (e.g., 3D printing). Among all use cases, it is worth noting that each main phase of the Scan4Reco pipeline (see Sec. 4 for more details) can be seen itself as an isolated use case, with results that could often be used standalone and independently from all the other phases. These use cases are: *"Environmental conditions & metadata definition"*, *"Cultural Object Scanning"*, *"Spatiotemporal Simulation"*, *"Analysis & Guidelines generation"*, and *"3D Visualization, Interaction & 3D Printing".* The modularity of the architecture or the system makes it possible to mix and match components to achieve partial results without the problems of a monolithic approach.

In the following, we provide information on how analysis phases are applied, and on how they offer use cases for the applications of component subsets.

8.1.1 Environmental conditions & metadata definition

This is the laboratory preparation phase, where environmental conditions of artwork degradation and the corresponding type of restoration intervention will be defined and studied. A panel of materials will be prepared based on a wide but well defined set of artworks. While the process rationale is generally applicable to any material, this step will focus on metallic objects and materials in paintings. The main activity here is the training data collection and the extraction of ageing models. The end-users will prepare a panel with a set of samples/mock-ups at different level of ageing and restoration treatments (HW/CHAMBER). The laboratory probes will be employed to perform digital acquisition of these samples (HW/MPROF, HW/ACOUSMIC, HW/IRCAM, HW/FTIR, HW/RAMAN, HW/UVSPEC, HW/XRF, HW/HDMSRI, SW/MMACQ, SW/RTIPROC) and processing tool for data analysis (SW/SFESURF, SW/SFESTRUCTMTL) will characterize the surface and sub-surface nature of them. After the panel measurements and data characterization, an ageing modelling engine (SW/AGING) will perform analysis and synthesis of the parameters that describe material degradation over time. In addition, this is the phase in which the metadata associated with materials and ageing factors will be produced (SW/ANNOTATION).

The laboratory environment with all the corresponding activities in this project phase can be viewed as a single use case, when scholars in CH need to study not a particular artwork, but the characteristics of a specific material, and/or possibly its behaviour over time. In Figure 8 we show the subset of components required for this laboratory use.

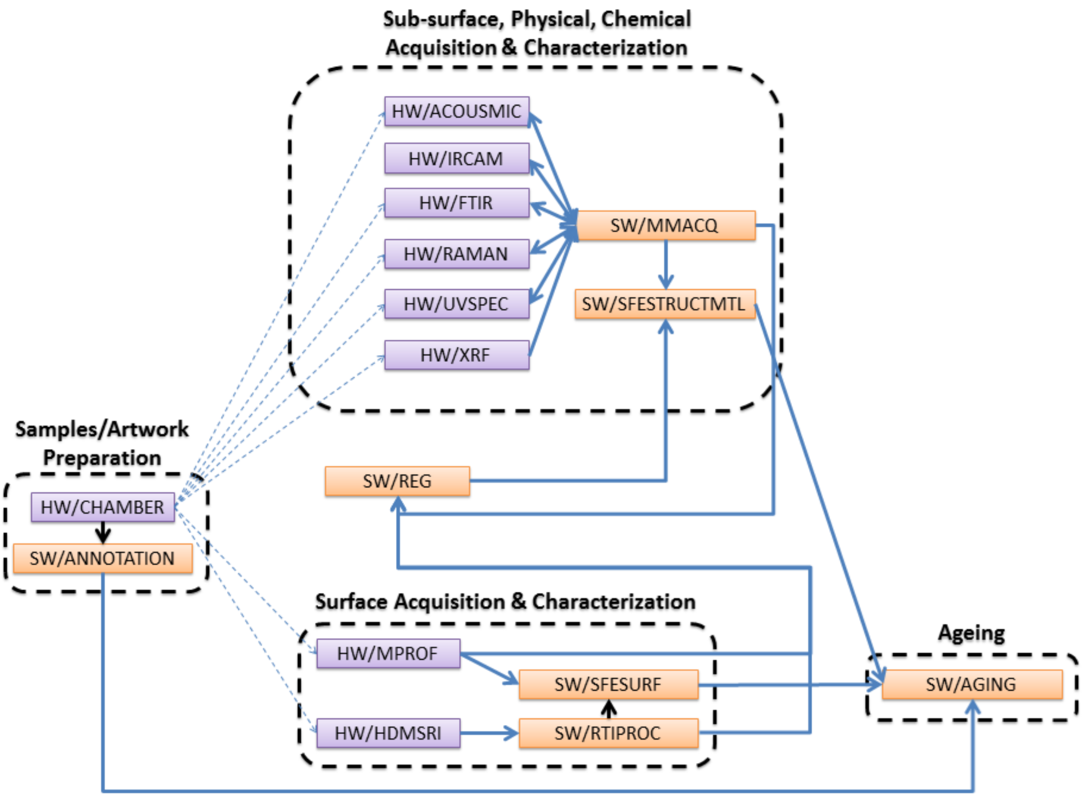

Figure 8 Group of components used in the use case „Environmental conditions & metadata definition"

8.1.2 Cultural Object Scanning

This is the on-site phase of the Scan4Reco project, where a selected artwork will be digitally acquired. Outside the Scan4Reco context, cultural object scanning is often a typical use-case, often applied in isolation for documentation purposes.

First, a global low-resolution digital representation of the object will be provided (HW/VISDEPTH, SW/SCAN), both in terms of geometry and colour. Then, all the local punctual probes will acquire multi-modal signals of small, flat areas on the object surface (HW/MPROF, HW/ACOUSMIC, HW/IRCAM, HW/FTIR, HW/RAMAN, HW/UVSPEC, HW/XRF, HW/MSRTI, SW/MMACQ, SW/RTIPROC). All of them will be registered on the global geometric proxy in order to provide a referenced frame to navigate all the data afterwards in a meaningful way (SW/REG). The capture process will be assisted by a mechanical device (HW/MECH, SW/PROBPOS), onto which all the probes and the global scanning devices will be mounted. Artwork scanning is one the most frequent activities when technology is applied to CH research, due to documentation, archiving, preservation, didactic and visualization purposes. This phase/use case of the Scan4Reco pipeline will provide scholars with a standalone multi-modal tool to acquire digital information of an object under study. Figure 9 presents the components involved in this on-site use case.

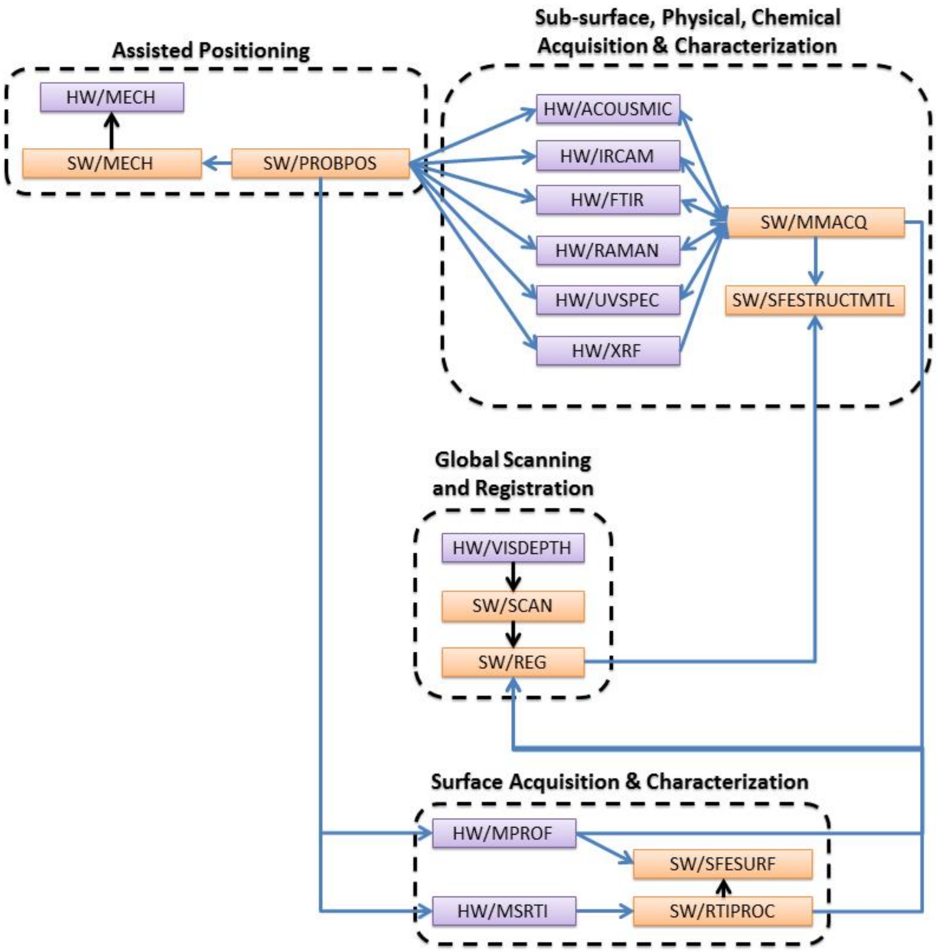

Figure 9 Group of components used in the use case scenario „Cultural Object Scanning"

8.1.3 Spatiotemporal Simulation

Virtually simulating the evolution of a cultural object condition over time, in order to make reliable prediction on the object behaviour and the effect of the restoration treatments, is of primary importance in the CH domain.

In the context of Scan4Reco, this is achieved by a spatiotemporal simulation engine (SW/SIM), which takes as input material information as well as object information. Material information consists in material ageing models and how some materials behave under the effect of restoration treatments. Object information in this phase consists on the global low-resolution geometry and colour of an artwork, combine with the measurements of specific interesting points on its surface.

Of course, all the visual capabilities of the system will be exploited to convey the most useful simulation (SW/INSPECT, SW/SINSPECT). Coupled with those visualization capabilities (see Figure 10) this Scan4Reco phase can be seen as an isolated tool, usable also independently from the project pipeline, to visualize and study how a particular artwork changes over time under a series of different environmental conditions.

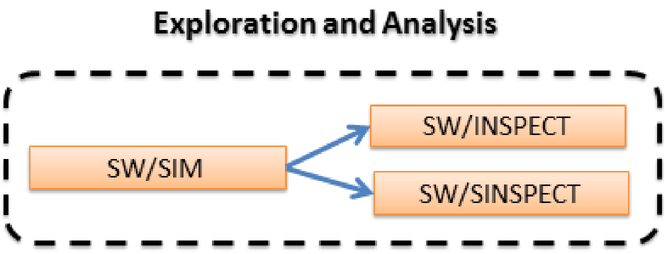

Figure 10 Group of components used in the use case scenario „Spatiotemporal Simulation"

8.1.4 Analysis & Guidelines generation

The spatiotemporal simulation will give scholars only with a rendered object in a particular conservation status. Conversely this use case will be devoted to the analysis of this retrieved digital representation, and to the task of using this analysis to provide curators and restorers with a rendering-based help to take the right operational strategy. An oriented Decision Support System (SW/DSS) will take the 3D and multi-layered reconstruction, the output of simulation, and, in general, all the data that so far will have been related to a work of art throughout the system pipeline, and it will present this data in a human-comprehensive, readable way, and extract complex conservation related options. It will use a database of simple conservation instructions and select a sub-set of them in a combinatorial way to produce the desired outcome. As in spatiotemporal simulation, the visualization capabilities of the system will be exploited to visually help while using the DSS (SW/INSPECT, SW/SINSPECT). By giving the proper data of a 3D model and the digital information of its behaviour over time, the components in Figure 11 can be used standalone to support the daily decisional activity of conservators and restorers.

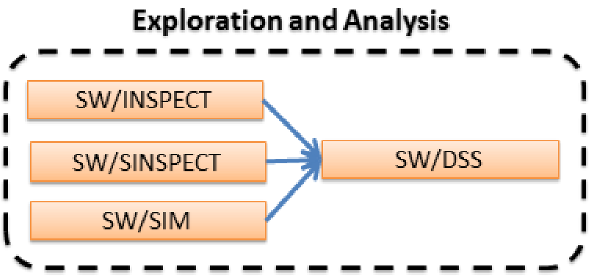

Figure 11 Group of components used in the use case scenario „Analysis & Guidelines generation"

8.1.5 3D Visualization, Interaction & 3D Printing

Presenting information on a cultural object is one of the main applications of digital technology in cultural heritage, both for professional application and for dissemination purposes. Apart from their great utility within the project framework, these tasks by themselves are very useful for scholars, which can provide digital models as input for them from a wide variety of different pipelines. Thus, both specialized rendering tools tools (SW/INSPECT, SW/SINSPECT) and tools for the general public (SW/VMUSEUM) are important for this use case. Pure digital representation is complemented by the generation of real-world replicas of the artworks or parts of them, produced through multi-material 3D printing (HW/3DPRINT, SW/3DPRINT). The toolbox of visualization tools, both virtual and physical, allows for a real-time, easy interaction between the end-users, scholars, curators and general public, and the cultural heritage assets. The scope of this phase is to facilitate and increase the accessibility to CH content and facilitate their analysis. Figure 12 shows the components involved in this use case and the relationships among them.

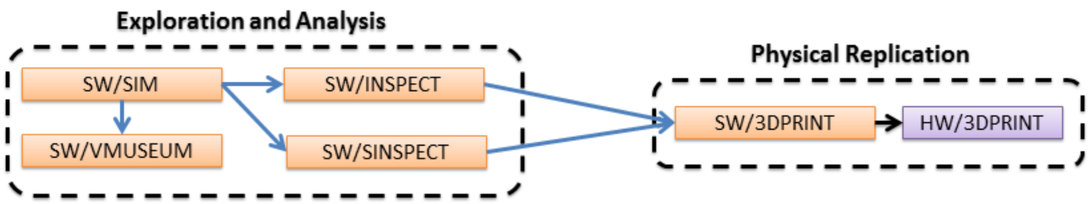

Figure 12 Group of components used in the use case scenario „3D Visualization, Interaction & 3D Printing‟

8.2 The pilots

Among all the possible use cases, and in order to validate the Scan4Reco pipeline, end-users have identified two validation pilots, which refer to two classes of CH objects, i.e., metallic objects and paintings:

- **Metallic objects.** This pilot mainly aims at testing the capabilities of the Scan4Reco system in terms of surface exploration and reconstruction. A minor aim, when possible, will be to test the infiltration/insight capabilities of the system to the first underlying layer. In this pilot it is of great interest to measure and analyse the surface morphology at multiple scales, which might reveal 3D features related to the way the artefact has been created or the results of a conservation intervention. The acquired information about material roughness will provide crucial insights about corrosion, degradation, and, in general, about the effects due to aging or to other cleaning and protective treatments. The pilots will study the appearance of the object (reflectance, glossiness, multi-spectral colour), whose features are related to aesthetic aspects and material stability of an artwork. All these measurements from all the punctual techniques are useful to guide the conservation by providing possible alarm of alterations.
- **Paintings.** The painting pilot has the purpose of investigating the infiltration capabilities of the proposed system. The volumetric acquisition, coupled with the rendering and simulation tools, will reveal over-/under-painted drawings, their degradation in time and will provide a validation instrument for conservation-related tasks. Conservation scientists and conservators will use the data provided by the system to get cues about visible and non-visible parts of the artwork, which can guide hypothesis about the time of creation of the painting, the phases of its creation and development, former conservation attempts and also environmental conditions the painting has been subject to. The volumetric stratigraphy helps to understand the art school of the painting as well.

Of course the validation activity and the tests done in those pilots will provide scientists and scholars with useful insights about **probable research challenges for the future**.

9. Conclusions

This deliverable has presented the overall designed architecture of the Scan4Reco project.

We have shown how it responds to end-user requirements and to the initial conceptual idea of the system pipeline.

The definition of the architecture components has been derived from the breakdown of the conceptual architecture into a series of high-level functionalities and system requirements (technical, functional, operational) that map the conceptual core elements to end-user needs.

Its high level of modularity makes the architecture a very flexible toolbox-like system, which can be employed in a wide range of different CH applications, including artwork capture, analysis and investigation. It is also able to convey quantitative knowledge of the artwork properties through digital measurements, and also gives insights for future, operational interventions on the artwork undertaken by restorers and conservators.

Although the presented architecture has a well-defined structure, which gives the proper guidelines for project development, the design process won’t end with this document. Scan4Reco consortium will continue in following a cyclic process that exploits an iterative methodology that goes from the end-user feedbacks, through the analysis of the components and their links, to a continuous architecture refinement. In this way, during the life of the project, until month 24, the system requirements and architecture specifications will evolve according to both the constraints set in this deliverable, and the future on-going needs.

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