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Scan4Reco: Towards the digitized conservation of Cultural Heritage Assets via spatiotemporal (4*D*) Reconstruction and 3*D* Printing

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Abstract

The European Cultural Heritage includes a rich variety of cultural items and a significant amount of resources is devoted to their conservation and dissemination to the public. Living in the era of digitization, these efforts have been significantly facilitated by advances not only in traditional domains (e.g. material science, etc.), but also from more modern ones (i.e. 3D computer graphics & VR simulations). Within this context, the EU funded project Scan4Reco aims to offer low-cost and feasible solutions in the field, as well as to improve existing practices via the automatic digitization and documentation of a wide variety of cultural items. In particular, material identification and visualization will be addressed via multi-sensorial and multi-resolutional material segmentation and data-fusion algorithms, while the problem of the parallel deterioration of the composing materials, given certain environmental conditions will be dealt with via the introduction and fusion of statistical, material-specific ageing models. The conservation dedicated Decision Support System (DSS) of Scan4Reco will be built upon a simulation engine and will suggest optimal conservation methodologies according to different criteria. Last but not least, the Scan4Reco outcomes will be demonstrated through tactile multilayered 3D printed surrogates, while digital surrogates of the cultural items along with their travel in time will be exhibited in a dedicated VR museum. In order to familiarize the reader with Sca4Reco's research novelties and breakthrough innovations, the current paper describes its modules, elaborating on their connection to the project's objectives and to identified user requirements. In addition, we present the overall architecture of the platform commenting on the interdependencies between components and their functionality.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—Digitizing and scanning

1. Introduction

Cultural heritage is highly valued in any modern society allowing people to understand their history and connect to past generations. As a result the interdisciplinary field of cultural heritage management has emerged, that combines techniques and practices from a wide range of domains including history of art, material science, computer graphics and virtual reality. While advances in these domains have certainly fostered progress in cultural heritage management, there is still missing a holistic approach that will allow the automatic documentation and dissemination of cultural heritage assets and at the same time facilitate conservation efforts by providing insight in their past and future state.

If we attempt an overview of past projects, there are several that have exhaustively dealt with the digitization of cultural assets, mainly with respect to their virtual 3*D*-scanning and processing [3DP16] [3DC12], or scanning with more penetrative technologies such as terahertz imaging [INS15]. On the other hand there are projects focussed on the preservation of cultural assets and on raising public awareness. For instance in [DEC14, CUL15] augmented/virtual reality technologies have been deployed to present cultural heritage objects through virtual and augmented reality technologies whereas in [CUL14] an interactive environment has been developed for the exhibition of digital cultural heritage collections. Augmented reality has also been combined with cloud technologies [TAG16] while in [PRE16] geometric-related predictive augmentation technologies are advocated for the digital completion of fragmented/incomplete cultural assets.

Following this brief analysis we can see that past projects have put more effort towards the manual collection or the dissemination of cultural heritage information rather than in its extraction through automated methods that would facilitate both public's accessibility and specialists efforts. To bridge this gap the Scan4Reco project aims to automatically produce digital replicas of cultural heritage assets that will be displayed through a virtual museum but will also be used by a DSS for the selection of optimal conservation strategies. All in all, the main objectives of Scan4Reco are:

- to provide a portable solution, for accurate multi-sensorial 3*D* scanning and efficient automatic digitization of cultural assets, supporting among others material identification and both surface and volumetric diagnosis.

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- to produce a hierarchical 3*D* reconstruction of the object via successive utilization of multi-sensorial data in an order of increasing resolution and infiltration factor, rendering the object in a multi-layered way, that will facilitate its exhibition, conservation and replication via 3*D* printing.
- to apply material analysis techniques, in order to understand the heterogeneous nature of different materials and their degradation mechanisms over time, targeting to extract context-dependent ageing models per material.
- to spatio-temporally (4*D*) simulate uni-material models taking into account environmental parameters, so as to render degradation effects on a digitised cultural object and predict its appearance over time.
- to indicate spots/segments of the cultural object that are in conservation need and to simultaneously provide suggestions through a DSS, regarding the most appropriate conservation method, in a comprehensive way to the conservator via interactive visualization methods.
- to enhance the accessibility of the digitized cultural objects (along with generated metadata) to both the scientific community, the field experts and the general public via the development of a virtual model of a museum where scanned items will be virtually exposed.

In the following paragraphs we will present the architecture of the Scan4Reco platform on a conceptual level commenting on the functionality of individual modules and their connection to the project's objectives as well as to user requirements.

2. Scan4Reco user requirements

To extract concrete user requirements and that will guide technical development, potential end users have been questioned including curators, restorers and conservation scientists. Emphasis has been put on the use cases of Scan4Reco, i.e. metallic objects and paintings. The received feedback can be classified as follows:

- **Documentation process:** End-users have highlighted the importance of systematic documentation and accessibility of all recorded data and analysis results. Computer-based visualization methods must provide adequate information and insight of the property they seek to represent. The platform's design must ensure the safety of the item during the documentation phase and reduce manual interventions to the extent possible.
- **Material and surface characterization:** The acquisition and digital representation of the physical properties of an item's materials both at surface and sub-surface level have been identified as important features.
- **Metallic object analysis:** Another important feature is the processing of local multi-modal measurements on the surface of a metallic object in order to detect any surface of structural changes. These measurements should be further analysed to explore the evolution of metallic objects through spatio-temporal simulation and a DSS should be deployed to help scholars in their restoration interventions. End-users have also shown interest in the replication of metallic objects using 3*D* printing.
- **Painting analysis:** End-users emphasized on the collection of local multi-modal measurements and their registration onto a digital surrogate. Similarly to the case of metallic objects, the platform should allow the spatio-temporal simulation of a painting's ageing process while a conservation-oriented DSS should be available. Positive feedback has been received, regarding the construction of the stratigraphy of visible and non-visible paint layers and the deployment of 3*D* printing to explore real-world replicas of paintings.

3. Scan4Reco High Level architecture

To satisfy these requirements and meet project's objectives, the Scan4Reco system will be able to facilitate measuring through a motorized arm and provide multispectral scanning of a great variety of cultural assets (e.g. wall-paintings, paintings, metallic objects, statues, etc.) non-destructively. Moreover, it will hierarchically process the multi-sensorial input, so as to produce VR models of ascending quality and information according to the demands of end-users or the use-case/application itself, utilizing each time a different set of sensors. This way the complexity and quality of a cultural object's VR model will vary per demand. In addition, Scan4Reco will study and model as many materials as possible corresponding to a variety of cultural assets, putting emphasis on the ones studied in the project's pilots. This way, inter-disciplinary knowledge (e.g. physics, chemistry, history, etc.) will be combined with computer science (e.g. spatiotemporal simulation, 3*D* rendering, visualization etc.). The ultimate goal will be not only the material identification, stratigraphy revealing and automatic, accurate digital 3*D* representation of the object in its current state, but also the automatic inference of both previous states and forthcoming state/shape of the object, leading thus, to a 4*D* representation in Virtual Reality (VR) where 3 spatial dimensions and 1 temporal dimension via simulation are involved.

This way, the scientists but also the public will make good use of the revealed information. The scientific community will benefit from a conservation dedicated DSS that will provide suggestions regarding the conservation process that should be followed via interactive and comprehensive visualization tools. Similarly both scientists and general public will benefit from the digitization and documentation of cultural objects. The massive processing and the derived information will open new horizons for investigation and large amounts of them will become available as multimedia objects, ready to be exhibited in web-based virtual museums or widely accessible digital libraries/databases. In this respect, the most important components to be developed within Scan4Reco are presented in Figure 1 and listed below:

3D Depth Sensor: Low cost visual and depth camera setup for the acquisition of low resolution, rough, global 3*D* of an artwork.
Micro-profilometer: Device that provides quantitative measurements of the surface texture and roughness at micrometric level.
Acoustic Microscopy: 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.
IR 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 ($1-5\mu$m) of a high speed camera. The resulting infrared reflectographic multispectral images reveal the internal stratigraphic structure of the object.

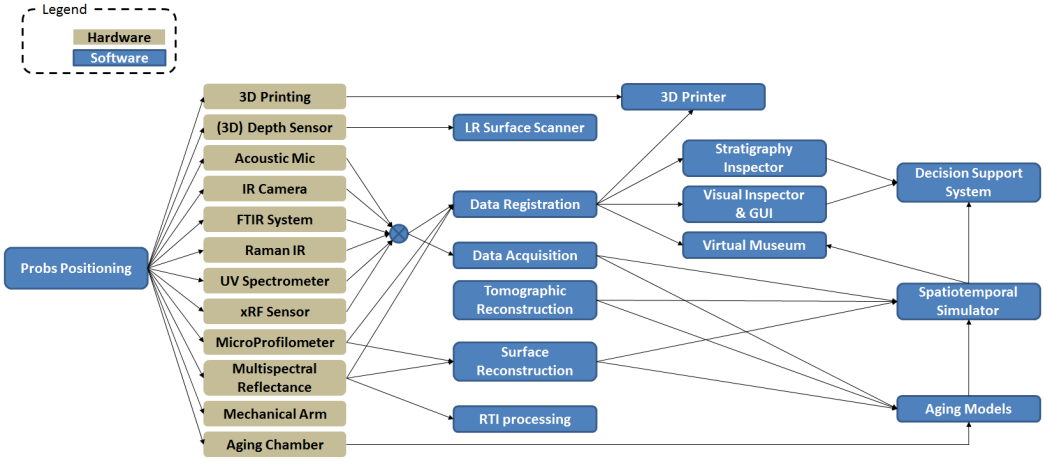

Figure 1: *A high level component architecture of the envisioned the Scan4Reco system.*

FTIR System: Device to acquire data using basic Fourier Transform IR (FTIR) spectrometer in reflectance mode. The data are the spectra of the reflected infrared electromagnetic wave.
Raman IR: 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.
UV Spectrometer: 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.
xRF Sensor: 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.
Multispectral Reflectance: Acquisition device for measurement of surface appearance of material samples for characterization purposes and of visual characteristics of flat areas of cultural objects (e.g. paintings or engravings).
Mechanical arm: Hardware support to assiste measurements of cultural objects, including low-res surface scanning and measurements with probes.
Aging Chamber: Device to speed up the normal aging processes of items under controlled environmental conditions.
3*D* **Printer:** Commercial multimaterial 3*D* printer employing multiple build materials and support material(s) for accurate color reproduction.
LR Surface Scanning: Capture of the low resolution, rough, global 3*D* surface shape of an artwork using the depth sensor and the mechanical arm.
Data Acquisition : 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.
RTI processing: Creation of an integrated representation of small surface patches from a Reflectance Transformation Imaging (RTI) image stack and calibration data.
Surface reconstruction: Computation of derived surface properties and extraction of surface descriptors based on RTI and micro-profilometry data.
Tomographic reconstruction: 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.
Aging model: A software that processes probe measurements and associated semantic descriptors in order to derive parametric and probabilistic material-specific ageing models.
Data registration: Registration of all measurements onto the same reference frame defined by the LR surface scanning component.
Visual inspector & GUI: Visual inspection of measured data, with probe measures positioned on top of low-res surface scan (GIS view).
Stratigraphic inspector: Visual inspection of the stratigraphy of paintings. Tightly integrated with the data registration component.
Spatiotemporal 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.
3*D* **Printing:** The process of creating a low dimensional interim connection space to communicate visual properties for 3*D* printing, and the development of a 3*D* printing workflow to reproduce 3*D* shape and appearance information.
DSS: A system that takes data from the various sensors, ageing models and simulation platform so as to to provide conservators with indications of where and how to apply a certain type of conservation approach, accompanied with a confidence factor.
Virtual Museum: Web-based application for online inspection of cultural objects.

4. Scan4Reco platform

In line with the previous analysis of the conceptual group of Scan4Reco's components, in Figure 2 the component architecture of the platform is depicted. We can identify the following components:

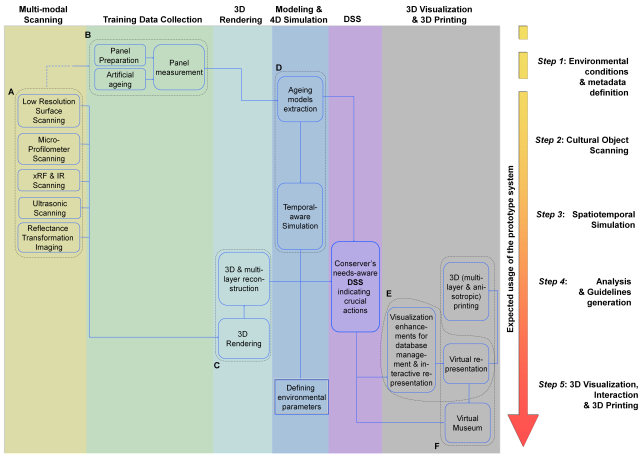

Figure 2: *A categorized view of the modules of envisioned Scan4Reco system. The current illustration can be read in two axis. From left to right, the reader can go through the initially defined categorization of the system's components. From top to bottom the reader can see a possible workflow.*

Core Element I refers to the multi-modal scanning platform and involves the specifications, the development and evaluation of each scanning device, and the integration to the multisensorial platform. *Core Element II* refers to the Training Data Collection and Ageing Models extraction based on an in-depth study of the physiochemical properties of the materials, their corresponding artificial ageing and finally the measurements to be performed via different sensors. *Core Element III* regards the Rendering and 3*D* Reconstruction module of the Scan4Reco system. Thereby algorithms for hierarchical and fast 3*D* data processing, registration and rendering will be implemented so as to deliver a final and intra-registered volumetric 3*D* reconstruction model of the scanned cultural object. *Core Element IV* refers to the 4*D* spatiotemporal simulation of the shape and properties of the previously reconstructed model of the cultural object.

Core Element V refers to the core system of the smart Scan4Reco system, i.e. conservation-oriented Decision Support System (DSS), that has the mission to process all relevant data (i.e. initial 3*D* model, ageing factors, simulated data, etc.), so as to export in a human-comprehensive way the actions needed for the conservation of a cultural object.

Core Element VI deals with the graphical presentation of all outcomes of the previously described Core Elements. In particular, the 3*D* Visualization and 3*D* Printing modules aim at both visually enhancing the presentation of the 3*D* models by enriching them with useful metadata information, but also to provide an interface for Human Machine interaction. 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-coloured 3*D* printings. Last but not least, a virtual museum website will be developed to exhibit the digitized objects, in order not only to increase public awareness but also to receive feedback.

The foreseen formal use of the proposed system is described on the right side of Figure 2 (reading it from top to bottom) in five steps, but is not limited to it. Within Scan4Reco two use cases are specified to evaluate and validate the system's performance.

Paintings pilot: To test mainly the infiltration capabilities of the platform and the volumetric rendering, reconstruction and simulation capabilities of the integrated system, targeting to reveal over-/under-painted drawings, their degradation in time, the 3*D* representation and printing of the underneath layers, as well as the validity of the conservation-related guiding.

Metallic objects pilot: To test mainly the surface exploration and reconstruction of the cultural object, including the infiltration/insight of the system to the first underlying layer, if possible. Certainly, surface rendering and reconstruction capabilities of the integrated system, degradation in time via simulation, 3*D* representation and printing, as well as the validity of the conservation-related guiding, will be tested and evaluated as well.

5. Conclusions

In this paper we gave an overview of the Scan4Reco project. We presented its underlying concept and described its main modules with respect to user requirements extracted from potential end-users of the platform. The block architecture of the system has also been presented with a focus on the core components of the system and its use cases.

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