Design and implement a reality-based 3D digitisation and modelling project

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Abstract—**3D digitisation denotes the process of describing parts of our physical world through finite measurements and representations that can be processed and visualised with a computer system. Reality-based 3D digitisation is essential for the documentation, conservation and preservation of our Cultural Heritage. This article composes a critical review of the digitisation pipeline, ranging from sensor selection and planning to data acquisition, processing and visualisation.**

Keywordsð Digitisation, 3D, Planning, Acquisition, Modelling

I. INTRODUCTION

For more than a decade reality-based 3D digitisation and modelling have been applied in many fields. Beside industrial design, prototyping, entertainment and medicine, 3D digitisation is considered as common practice in the Cultural Heritage (CH) domain [1]. 3D provides solutions for several CH needs such as documentation, preservation and conservation and is an efficient medium for digital archiving and dissemination of exceptional artefacts and monuments to future generations [2]-[8]. Currently, there is a significant variety of 3D acquisition methodologies [9]. Despite the method being used, one of the fundamental properties of the collected data is the sampling resolution, i.e. the minimum distance between two consecutive measurements. For image-based methods, this is given by the image Ground Sampling Distance (GSD), while for range-based methods, it is defined by the instrument's specifications and actual performance. Thus, the 3D shape of a physical object can be digitally reconstructed and defined using only a discrete number of points in the 3D space.

Many people often perform 3D digitisation with results inferior to those initially expected. This is due to the fact that no 3D data collection technique can be correctly performed without understanding its behaviour and potential and also without knowing what accuracy and data quality is attainable under certain conditions. A proper way to decide which technique suits better for a particular situation should be followed. A correct methodology to predict and measure the quality of the output should also be designed and applied.

Just like in any other project that offers an end- product; the 3D digitisation pipeline consists of phases such as design planning, implementation and delivery. During the latter, the client evaluates whether the product meets its requirements specification and purpose of use. Of course it is a prerequisite that the financial aspect of the project makes sense for both the *contractor* and *contracted*. Thus, the main objective is to produce an optimal digitisation and implementation plan that takes under consideration not only the specifications of the desired output (e.g. 3D model or other suitable representation that meets desired accuracy and resolution) but also the minimisation of both costs and execution duration. Both design and implementation planning require not only the expertise in several disciplines but also an understanding of the application and its environment. However this is not an easy task to perform when it comes to CH 3D digitisation since aspects of the technology being used are still in research labs and have not sufficiently matured or offered commercially.

This paper summarises the digitisation design process and optimal implementation of a reality-based 3D modelling project, i.e. a project that aims to create 3D data starting from field measurements performed with active or passive sensors - range-based modelling (RBM) or image-based modelling (IBM), respectively [10]-[13]. It is intended to be a guide for selecting the appropriate techniques, their configurations, the related design variables and processing methods in order to meet project requirements. We draw upon our own experience and a large number of research works. This provides a statistically adequate sample of which important conclusions can be drawn. Figure 1 depicts a generalised version of the phases found in a 3D digitisation project. In particular, the actions that have to be planned, designed and implemented in order to satisfy a project's requirements are:

1. Site overview and planning or object examination;
2. Selection of the appropriate technology and parameters, or combination of multiple technologies.
3. Data collection positions planning and configuration design.
4. Data acquisition workflow based on best practice.
5. Selection of data processing tools, 3D model representation method and suitable file formats.
6. Selection of software tools able to handle all processing and visualisation needs.

The first three components can be grouped under the *project design phase*. Design (Fig. 2) is an iterative process that often involves trade-offs between competing performance criteria.

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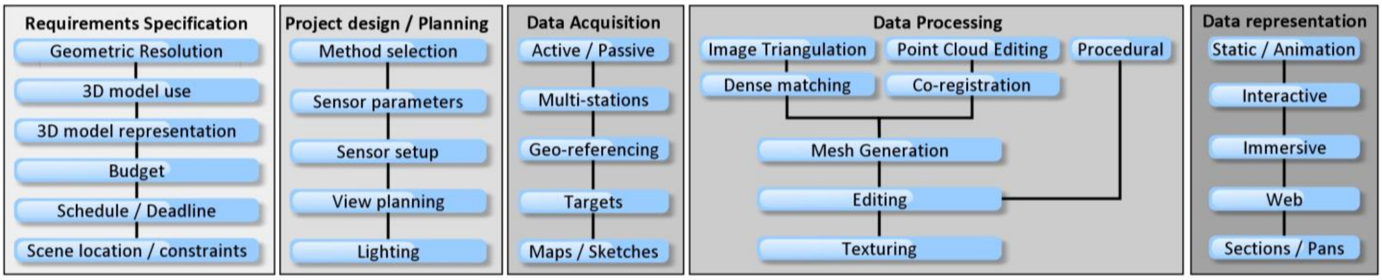

Fig. 1: Overview of a 3D surveying and modelling project: specification definition, planning, data acquisition, processing and representation.

As the design process progresses, the initial objectives, requirements and constraints are often altered in order to achieve a viable solution. But without knowing the exact outcome of an algorithm or a given technology under real project constraints, one cannot properly execute the digitisation design process. The iterative alteration of the project design phase is in most cases unavoidable as after performing a preliminary on-site data collection and data processing, the design needs to be tweaked again. It is sometimes not feasible to take into account all the parameters even with a sound prediction function available. Thus, even after all data are captured and integrated, there is a chance of recapturing some parts using a different acquisition configuration. In some cases, going back to the requirements specification and make some changes once the data has been processed is another possibility.

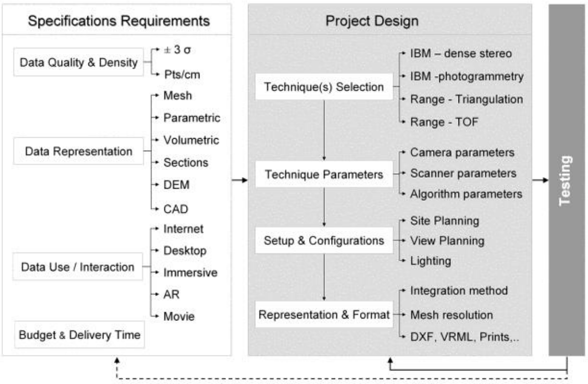

Fig. 2: Project design cycle.

II. SITE OVERVIEW

A thorough reconnaissance tour on the site is one of the first tasks undertaken. During this visit, one should make sketches, take notes, pictures, videos and perform some initial measurements. Both sketches and notes should also cover the surrounding area. All these contribute in creating valuable information sources that can influence decisions related to the digitisation equipment, its set-up and data collection, as well as in addressing safety issues (especially when dealing with old structures and ruins), movement and positioning constraints. It will also determine the crew size and equipment required on-site for the various operations and the way to transfer the equipment particularly in sites where wheeled cases are impossible to use. It is important when planning the acquisition viewpoints to consider the site's layout, the scene's materials and the terrain where it is located. Some sites impose strict access times and restrictions to certain areas, which inevitably have an impact on the data collection phase. It is imperative to ensure that a power source is also accessible.

Some digitisation methodologies require the placement of elements such as targets, scale bars or laser-scanning registration spheres, securely placed in the appropriate positions before the data acquisition phase. They are of great importance in large scale projects as they assist in data registration and geo-referencing accuracy verification and to avoid shape deformation.

In addition, the digitisation team has to ensure access to morphologically complex areas by building temporal scaffoldings, use stable cranes or unmanned aerial vehicles (UAVs), or acquire access to nearby building or higher spots from which data acquisitions can be executed. The use of mirrors should be taken under consideration for many objects and sites that have surfaces that are occluded or cannot be directly accessed by the sensor [14]. Surface material, fragility, lighting conditions and other properties must be observed during this phase. In case of a single small artefact, it is important to find out whether it can be moved to a lab or it has to be digitised in its current location.

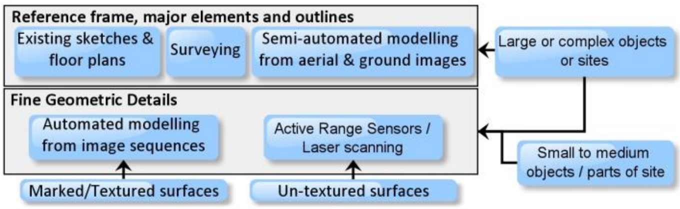

Fig. 3: The appropriate approach and technique for a given task.

III. SELECTION OF 3D DIGITISATION METHOD AND SENSOR

The selection of a single or multiple technologies to collect any types of data is another key step in the project design phase. Figure 3 provides a quick guideline of which technique is the most appropriate. Selecting an unsuitable technology may lead to failure in achieving the project requirements. This is one of the main reasons why 3D digitisation has not yet reached its maximum potential. [15] reports as rule of thumb that point spacing in range scanning (i.e. lateral resolution) should equal *5%* of the feature size. So a tool mark measuring *10 mm* will require at least *0.5 mm* point spacing to be clearly visible and adequately digitised. This is also linked with the accuracy of the employed scanner. For example, a scanner with

5 mm measurement uncertainty should be avoided when the resolution has to be near *2 mm*. Obviously the scanner's measurement uncertainty should be smaller than the required resolution by at least a factor of two. The same applies to imaging where the GSD should be at least *2-3* times smaller than the smallest geometric detail to be captured. One should also consider the fact that recording large objects and sites in high resolutions will result long acquisition times and an unmanageable amount of data.

Choosing between a passive indirect 3D technique (IBM) or an active direct technique (RBM) is an important decision that is based on several factors:

1. Object size and geometric details: for small objects, range-based techniques can provide accurate details at a high degree of automation. Image-based techniques may suffer from focus, lack of texture or depth of field problems [16].
2. Cost: digital cameras used in IBM are standard and of low cost consumer products that can be used for a wide range of projects (both objects and scenes). Active / range sensors are still considered specialised equipment and thus they remain costly especially in cases where more than one sensors of different capabilities are needed. Since a range sensor is designed to give the optimum accuracy at a specific range, a project that includes objects of different sizes or approachable from widely different ranges may require multiple types of sensors. The data/images captured in IBM can always be reused when newer algorithms will be developed. For active systems the data need to be recaptured as technology advances and that leads to additional costs.
3. Portability: most active sensors, although branded as portable equipment, are not efficient for long travels or remote locations when compared to digital cameras. This can be a decision factor for some projects.
4. Data collection speed: photo shooting remains more efficient and fast than range scanning. But range sensors provide directly 3D points while IBM techniques require further elaborations (and ground truth information for scaling purposes) that may lengthen the processing sessions.
5. State of the art: both RBM and IBM are capable of producing photorealistic models with high geometric accuracy. The issues that remain unsolved in IBM are the inability to capture details on low-featured or texturless surfaces producing high levels of noise. Laser scanners are able to handle a broader range of surfaces. Nevertheless, many commercial systems have problems with specific types of surfaces (e.g. translucent surfaces) or bad illumination (only for triangulation-based systems). Both techniques need to deal with occlusions, specular surfaces and edges. Hence, they both require a significant amount of post-processing in order to create a photorealistic result.
6. Tools availability: both IBM and RBM techniques have matured to the point that all the necessary hardware and software are available as open-source or as commercial products.

Several recent publications compared the two technologies based on factors such as accuracy and resolution [17]-[19]. We argue that both technologies are capable of providing similar accuracy and resolution when supported by a well-designed digitisation plan. Thus, before selecting between the two, one must determine the design parameters for each technique to match the required accuracy and resolution. The six factors previously described should be consulted in order to define the most suitable.

The next step is to select the specific digital camera or active sensor model or brand which matches the project's requirements. It will not be constructive to compare brands and styles or models in this paper since 3D technology is advancing fast and product models and specifications are constantly changing, usually for the better. The reader could consult good and reliable online resources that are well maintained and kept up-to-date [e.g. www.dpreview.com, www.geo-matching.com, www.ceti.gr/3d-icons/tools, www.laserscanning-europe.com].

Regarding digital camera's hardware specifications, the important parts are the sensor's (CCD/CMOS) size, its resolution, image quality and availability of RAW format, lens quality and focal length, metering and focusing accuracy, performance or speed, low light or high ISO performance, its actual weight and interfacing when used on UAVs.

On the other hand, the critical parts of laser scanners specifications are the accuracy, lateral resolution at the intended scanning range, speed, field of view (horizontal and vertical), the minimum/maximum useful operating distances including the ambiguity interval and power supply requirements [11]. Calibration certificate and vendor brochures should always be validated and proved [20]. It is also mandatory to have a proof of effective temperature and humidity compensation and whether the sensor can operate under the given environment conditions.

IV. SENSOR POSITIONING

The next step is to set up the chosen sensor and acquire the data in the best possible way to ensure the successful operation of the applied post-processing algorithms. An efficient planning of sensor positioning still remains an active research area [21]. Its main scope is to ensure optimum (i.e. lowest number) sensor positions and, at the same time, to achieve *(i)* complete object coverage, with sufficient overlap for partial scans registration and *(ii)* the required geometric accuracy of the complete model. The sensor positioning can be implemented by following two general approaches:

1. Multi-view Planning (MVP) [22]-[24]: it requires the knowledge of the scene's structure (at least a coarse one) and computes all positions simultaneously in an optimised way;
2. Next Best View (NBV) planning [25]-[27]: it determines the next position and orientation given each previous viewpoint, generally with no requiring a complete object model. In most practical applications, and particularly for large sites and complex objects, NBV is the most applicable approach.

In [28] it is proposed an evaluation methodology for the comparison of reconstructions based on different NBV algorithms achieved with different techniques and various kinds of sensors using a known object as reference.

A. Camera positioning

The subject has been extensively studied in target or feature-based photogrammetry [28]-[31], based mainly on the B/D (*image Base – Distance to object*) ratio. However, in addition to the known requirement of strong B/D ratio [32], sufficient similarity between images and small occlusions for dense matching has to be met [33]-[35]. A good B/D ratio ensures high depth accuracy, however the resulting significant dissimilarity and occlusions will lead to limited matching's success for Structure from Motion (SfM) methods or dense reconstruction algorithms. The acceptable B/D ratio to achieve high accuracy has been reported in various publications and ranges from *0.16* to *0.5* or even higher. Generally the depth error increases significantly when the B/D ratio decreases below *0.3*. An approach to reduce the absolute error in the *XYZ* coordinates is to have a smaller image point error [36]. Using high precision image observations (mainly *0.1* pixel precision or better) may allow smaller baseline and yet achieve good depth *(Z)* accuracy [37]. Simulation is a cost effective way to measure the effect of each parameter or a combination of parameters and any sensor configuration [38].

B. Range sensor positioning

The correct positioning of range sensors guarantees good coverage, lack of occlusions and enough overlap for accurate (maybe automated) registration of the partial scans. Issues like *scanning angle in relation to the surface* should be taken into consideration since the accuracy decreases proportionally to the angle size. Sensor's performance varies based on the operating environment (indoors, outdoors, airborne or terrestrial). If the general geometry of the surveyed scene is known, the positioning planning is rather simple and can be determined at once (i.e. MVP) rather than NBV. On the other hand, if the scene's geometry is unknown, the problem becomes harder to solve and a NBV is the only option.

In cases where sensor positioning planning is not an option, great experience by the digitisation crew is required. An adequate number of viewpoints that completely cover the object must be decided in a limited time while in-situ, without taking into account the quality of the final produced mesh, except the sampling density. In such cases a few extra capturing positions may always help.

V. DATA COLLECTION

Different research efforts are made to formalise data collection best practices and guidelines for CH applications [35][39]-[41]. Such efforts are often covering also metadata aspects. Before presenting in detail the data collection pipeline, some general remarks are recalled:

1. Collected data must be stored, labelled and associated with a possibly known position (e.g. for geo-referencing purposes). A meaningful data storage folder naming and structure should also be adopted. Such details, improve the post-processing phase especially in case of large sites.
2. Assemble an effective and experienced team on the site to optimally handle all operations, especially if there are strict time constraints for on-site work.
3. Carefully checked and calibrated beforehand the instruments having in mind the project's requirements.
4. Store (and preserve) the acquired data in their *raw* formats. This will allow going back to the acquired data when more powerful tools become available or when changes in the requirements occur. Moreover, as 3D modelling is a lossy procedure, it might be necessary to re-use some of the original data. Storing the raw data in proprietary, non-standard and non-documented formats should always be avoided [42].

A. Digital Camera Data Collection

Recent works demonstrated the possibility to derive dense 3D information from Web-based image sets or tourists shots or videos [43]-[45]. The accuracy and object coverage cannot be guaranteed or predicted with such approaches. To deliver results that meet specific requirements, one must plan the image collection phase and follow best practice guidelines. We have adapted and modify the *3x3 rules* [46] by taking under consideration the digital era and the new software developments (Table I).

TABLE I. THE MODIFIED 3X3 RULES FOR PHOTOGRAMMETRIC DOCUMENTATION USING DIGITAL CAMERAS.

GEOMETRIC	PHOTOGRAPHIC	ORGANISATIONAL
Acquire control / ground information	Keep a constant interior geometry of the camera	Make proper sketches
Multiple & convergent image coverage with adequate B/D ratio	Keep homogeneous illumination	Write proper protocols and keep metadata
Separate calibration & orientation	Select a stable combination of large format camera & lenses	Perform a final check

Using Table I as a starting point, the following guidelines are applicable to any IBM project:

1. Pre-calibrate the camera and keep the calibration valid throughout the acquisition phase by not adjusting optics parameters (e.g. zooming) as they change the camera's internal geometry. Although current algorithms allow to simultaneously calibrate the camera and orient images (i.e. Structure from Motion), it is always better to keep the two procedures separated in order to achieve better accuracies [47]. Simultaneous determination of all the unknown parameters might lead to incorrect results [48] as the image's spatial topology that is ideal for calibration is different from the one used for 3D reconstruction. Moreover, it is important to that the calibration software employs the same mathematical model (e.g. Brown) as the one used for bundle adjustment and dense matching in order to avoid conversion and terminology errors.

2. Images should not be *geometrically* altered (e.g. crop, rescale, use of image stabiliser), or compressed. For texturing reasons, it might be worth to acquire high dynamic range (HDR) images.
3. For large scale reconstructions, use large depth of field settings on views with significant depth variation since dense matching algorithms requires all pixels - from the most distant to the closest - being in focus. This is achieved by setting high *f*-values (e.g. *f11-f14* thus small aperture) and where possible using a tripod due to slow shutter speed.
4. Although noise levels depend on the quality of the camera, it is generally preferable not to use high ISO values although most professional cameras are nowadays able to produce almost noise-free images at high ISO values (800). There are three variables that affect how the sensor responds to light presented (in the order they should be prioritised): aperture, shutter speed and ISO. The goal is to achieve minimum noise at maximum sharpness/focus on all surfaces of interest at any given lighting condition. Low-end consumer cameras should be avoided as they do not offer adequate control over these variables and because of the artefacts produced by the JPEG format compression.
5. If there are no restrictions on where to place the camera in relation to the object, a medium focal length (equivalent to *50 mm* on a full frame camera) is the most favourable one. This reduces possible foreshortenings that distort perspective. These lenses produce less geometric distortion and create scenes close to what the human eyes see. If it is necessary to use a wide angle lens then practise a larger overlap between images in order to avoid low quality reconstruction in the parts of the image that are near the frame edges.
6. Make sure colour settings are the same between successive imaging sessions. It is a good practice to use *(i)* a photometer to control ambient lighting, *(ii)* a standard colour chart to check colour consistency and *(iii)* a standard grey card (18% grey) placed in the scene for correcting the white balance. Setting white balance manually is a better approach as an automatic setting can provide erroneous values due to different light sources.
7. Outdoor acquisitions should be performed, when possible, in diffuse or flat lighting (white sky) conditions as they provide unified colour intensities and unburdens the digitisation crew to synthetically produce such conditions (e.g. ambient occlusion shadowing) during the texture map post-processing phase. Imaging in flat lighting is particularly important when other objects or buildings are too close and may cast strong shadows on the object of interest. On the other hand, indoor imaging can be affected by specular reflections of artificial lights which effects can be avoided by using polarised filters.
8. Plan the image GSD in accordance with the project needs and employed sensor and taking into consideration that the smallest image element (pixel) is normally not sufficient to reconstruct entirely and correctly an object’s detail.
9. In the absence of ground control points (total station or GNSS surveying with accuracy 3-4 times better than the image GSD), a scale bar of precisely known length should be placed in some images to establish the scale. If the model is required to be geo-referenced, at least three surveyed points (four is recommended) have to be used and be clearly visible in the images. The scaling operation must be performed during the image triangulation step (bundle adjustment) and not a-posteriori (once the 3D model is obtained) otherwise possible image block or model deformations cannot be compensated [48].

B. Range Sensor Data Capturing

Some related works on best practices for 3D data acquisition with active sensors were presented in [40] and [49]. Even if a sensor’s positioning is properly planned in advance, visualisation feedback, (e.g. labelling / flagging points that don’t meet uncertainty requirements), should be provided immediately after each scan to ensure that the proper coverage and desired accuracy meet the previously planned design. This could also be integrated with fast on-site scan registration (perhaps with a reduced density dataset) before moving the instrument or leaving the site in order to verify that no large gaps exist or there are no other problems with the data. This is referred as *real-time modelling* in [50] or *interactive modelling* in [51]. The on-line checking and registration of the acquired scans is not only important for inspecting the data quality and completeness, but it can also be used to determine the next best view (NBV).

VI. DATA PROCESSING

A. Image data processing

Camera calibration and image orientation are two fundamental procedures required for all image-based reconstructions. Both are based on perspective or projective methods [52][53], starting from a set of common features visible in as many images as possible [54] followed by a bundle adjustment procedure, i.e. a non-linear optimisation procedure that attempts to minimise an appropriate cost function (Gauss-Markov, Gauss-Newton or Levenberg-Marquardt methods). The employed bundle adjustment algorithm must be robust, able to handle possible outliers and provide statistical outputs in order to be able to validate its results. Once the camera interior and exterior parameters are found, the successive surface measurement and feature extraction steps is performed mainly using manual or semi-automated approaches - as still much more reliable and precise - in particular for complex architectural scenes, man-made objects, detailed city modelling and cartographic applications at large scale. Nevertheless the latest developments in automated dense point cloud generation [34][55]-[59] demonstrated high versatility and results in the generation of high quality 3D data of complex scenes. Such methods have led to open-source and commercial solutions able to deliver 3D point clouds of similar quality to the active sensors.

B. Range data processing

In order to create a complete 3D model, several partial scans have to be captured. Once a partial scan (range map or a point cloud) is acquired from a specific viewpoint, it is defined in a coordinate system with its origin located on the range sensor. This approach denotes the collection of 3D data that represent the same geometry in different reference systems whose mutual orientation is generally unknown. Thus, it is necessary to align all partial scans into a common coordinate system by means of a similarity (Helmert) transformation. The process can be achieved in three different ways [60][61]:

1. Use a complementary devices like CMM;
2. Use reference targets/points surveyed with an independent technique (e.g. total station) in order to define a global reference system where such targets are represented;
3. Apply an Iterative Closest Points (ICP) method [62] i.e. an iterative process for minimising the average distance between two datasets, starting from an approximate alignment not too far from the optimised one. The initial approximations are normally provided with manual intervention although automated methods based on distinctive and repeatable 3D keypoint detectors and descriptors are also available [63].

VII. FURTHER DATA PROCESSING AND VISUALISATION

Once a point cloud is obtained, a polygonal model is usually produced with ad-hoc algorithms [64]. Although some research is still being performed to improve the performance of such algorithms, this process is already available in several 3D modelling software packages and consists of several steps that can be completed in a different order depending on the 3D data source – namely structured or unstructured point clouds [65]. There are different ways to design the data structure or representation (e.g. point-based [66], exact/parametric surface-based splines [67], direct meshes [68], polyharmonic radial basis functions (RBF) [68], etc.). Each one has its advantages and disadvantages and should be considered as part of the project requirements and specifications. Once a polygonal 3D model is created, it can be visualised in wireframe, shaded or textured mode. A textured (photo-realistic) geometric model is probably the most desirable 3D object documentation by most since it gives, at the same time, a full geometric and appearance representation and allows unrestricted interactive visualisation and manipulation at a variety of lighting conditions. For the visualisation and interaction with a 3D digital model, various methods are currently available (Figure 4). A photo-realistic 3D model offers the user the freedom to choose viewpoints with different lighting conditions, unlike pre-rendered animations or movies where the viewpoints and lighting conditions are static and predefined. On the other hand, a model may be simplified for real-time interaction while a movie, being rendered off-line, can make use of the highest level of details offered by the data and by visual enrichments in terms of shadowing, lighting and surface properties that are still impossible to be rendered in real-time due to their increased computational demands. A movie or an animation offers also the possibility to hide missing or less detailed parts of the model. Some applications, particularly for large sites, architecture or city models may also require 2D drawings, such as cross sections or plans, or orthoimages or 2.5D representation (such as DEM or contours). In cases of rapid prototyping, a watertight model in the STL format is usually required.

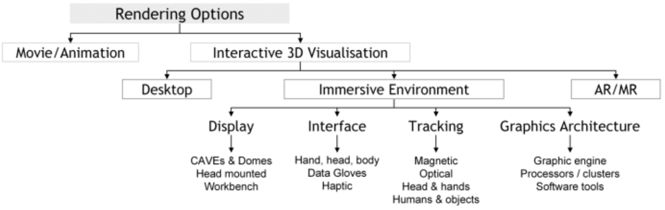

Fig. 4: Possible rendering and visualisation options.

VIII. CONCLUSIONS

The paper reviewed the state-of-the-art in reality-based 3D surveying and modelling, based on imaging and ranging data. The survey's planning and design, its implementation on the field and the successive data processing steps were analysed. Guidelines and best practices were reported from our experience and with a large collection of publications. These will help a non-expert reader to select the appropriate technique and product, use them in the best way and identify the design parameters to meet project requirements. Nevertheless guidelines and standards are still missing for the sensor technology and vendors are using different terminologies and names which can confuse users.

The continuous development of new sensors, data capture methodologies, multi-resolution 3D representations and the improvement of existing 3D recording methods is significantly contributing to the documentation, conservation and presentation of heritage and to the growth of research in the heritage field. Aerial and terrestrial active sensors are still the most common 3D recording technique in the heritage field but the image-based approach (photogrammetry) is definitively out of the shadow and is once again an active research area. The richness of image content information cannot be matched by any active acquisition device and many examples demonstrate the potential of the image-based methodology. Of course, the two techniques should be considered as complementary given all their advantages and disadvantages. Despite all the potentials offered by 3D recording and modelling techniques and the constant pressure of international heritage organisations, a systematic and targeted use of 3D data in the CH field is still not yet employed as a default approach. Moreover when a 3D model is produced, it is often subsampled or reduced to a 2D drawing due to a lack of software or knowledge for the proper handling of 3D data by non-experts. But it is clear that the availability and correct use of 3D metric data opens a wide spectrum of further applications and allows new analyses, studies, interpretations, conservation policies or digital restoration.

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