SPATIAL OBJECT DOCUMENTATION
COSCH WORKING GROUP 2
REPORT ON ACTIVITIES 2012–14

Robert Sitnik [a],*, Miroslav Hain [b]
[a] * WG2 Chair, Warsaw University of Technology, Warsaw, Poland – r.sitnik@mchtr.pw.edu.pl
[b] WG2 Vice-chair, Slovak Academy of Sciences, Bratislava, Slovakia – hain@savba.sk

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ABSTRACT: This interim report covers the activities of the Working Group 2 (WG2) of "Colour and Space in Cultural Heritage" (www.cosch.info), the COST Transdomain Action TD1201, supported by the European Cooperation in Science and Technology between 2012–2016. The report covers the period from 2012 to 2014. The WG2, Spatial Object Documentation, is focusing on two main tasks: identification of the main 3D scanning techniques suitable for cultural heritage (CH) objects; analysis and comparison of different 3D scanning techniques. An overview is provided of the main existing techniques in terms of their practical usage, accuracy and availability. This discussion is illustrated by practical results of comparison of measurements of small fragments of a 17th-century ceramic stove tile with floral decoration in high relief. The main drawback of existing solutions is their limited capacity to measure the variety of surface properties of CH objects, most of which have a complex, composite structure. Further, an overview of multimodal CH objects representation is presented. To achieve this goal two main approaches are developed: software- and hardware-based data measurement and integration.

The members of WG2 conclude that future technologies will be based on multimodal and/or modular measurement systems with the adaptive data processing platform (as proposed by the COSCH WG3). Existing technologies only allow for measurement of one modality at a time, and by a particular system or device. There are some solutions for multimodal measurements. However, they are still not mature enough to be used in everyday 3D measurement practice.

Foreword

The main objective of the Colour and Space in Cultural Heritage (COSCH) Action is to establish an interdisciplinary cooperation, on a concerted European level, and to prepare a novel, reliable, independent and global knowledge base facilitating the use of the state of the art and well-established optical measuring techniques for the documentation of European cultural heritage (CH). As stated in the COSCH Memorandum of Understanding, the key aim is to assure precise and complete documentation of artefacts, which is essential for conservation and preservation of cultural heritage. Other aspects are connected with data processing and visualisation of such data.

In the context of COSCH activities, 'cultural heritage' encompasses two main categories: movable (paintings, sculptures, coins, etc.) and immovable CH (buildings, monuments, archaeological sites, etc.).

COSCH Working Group 2 is focusing on two tasks:

- st2.1 Identification of the main 3D scanning techniques suitable for CH objects,
- st2.2 Analysis and comparison of different 3D scanning techniques.

Work of WG2 is mostly concerned with 3D geometry scanning techniques. However, some hardware solutions for integrated multimodal 3D acquisition of surface properties are also of interest.

1. INTRODUCTION

In order to provide museum professionals and visitors with true and precise representation of 3D surfaces, or even the inner structure of CH object, it is necessary to use proper measurement techniques, perform digitisation processes under the best possible conditions and use correct algorithms for data processing, analysis and visualisation (Ikeuchi, 2007; MacDonald, 2006; Stanco, 2001; Zhou, 2012). WG2 focuses on measurement techniques and the acquisition process under environmental conditions.

There are, however, many factors that influence the choice of an effective measurement technique and, subsequently, a particular device. The most important factors include:

- the dimensions of the CH object;
- the dimensions of the smallest feature that is to be measured;

- surface properties (specular vs diffusive, opaque vs transparent);
- environmental conditions;
- the sampling density and accuracy required or, alternatively, representation of the visual appearance only.

The dimensions of a CH object in relation to the size of the smallest feature to be recorded, directly influence the required spatial sampling (SS) of a digital 3D model. Sometimes it may not be necessary to register the entire surface with equal SS, but it may be sufficient to measure the global 3D geometry and apply more accurate representation locally.

Due to the physical basis of applied measurement methods only subset of existing surfaces can be measured by a single method/device. For example, structured light (Dorsch, 1994; Geng, 2011) or laser triangulation methods are only suitable for diffusive surfaces. Mirror-like, reflective surfaces can also be partially measured, but with lower accuracy (due to lower contrast of the projected raster); locally overexposed areas may provide false information: direct specular reflection of light source, registered on the detector image, in place of the image of projected distorted raster. Another case occurs during terahertz imaging (Jackson, 2011) when only some small portion of water, present in the measured structure, disturbs the measurement result.

Environmental conditions always have to be taken into consideration during the measurement process. Main issues are concerned with the characteristics of the measurement method, and the signal to noise ratio. The impact of characteristics of the measurement method on the quality of final digital data may be explained using the structured light method as an example. In this method the projected pattern is registered by a detector and quality of measurement depends on the pattern contrast in the image. If pattern is projected during direct sunlight exposition then images with a very low contrast of projected raster are captured. The method is not best suited under these conditions; laser triangulation may be a better choice.

Another issue concerns the required format and presentation of the final results. There are methods that offer quantitative results by using metrologically validated systems. Methods are also available that provide valuable results, but their quantitative quality is difficult to assess.

Taking into account all the above constraints, there is a wide choice of different measurement techniques. The most often used and promising techniques include:

- ToF – time of flight (pulse or phase based) (Bohler, 2002);
- Photogrammetry (including structure from motion) (Linder, 2001);
- BRDF – bidirectional reflectance distribution function (including PS – photometric stereo) (Goldman, 2010);
- FS – focus stacking (Ray, 2002);
- LT – laser triangulation (point, line or raster) (Dorsch, 1994);
- SL – structured light (including fringe and Gray codes projection) (Geng, 2011);
- RTI – reflectance transformation imaging (Earl, 2011);
- CT – X-ray Computed Tomography (Kak, 2011);
- THz – Terahertz imaging (Jackson, 2011).

The main drawback of existing solutions is their limited capacity to measure the variety of surface properties of CH objects, most of which have a complex, composite structure. There is no existing solution to recording an object composed of shiny metal, transparent glass, stone or wood in 3D. Such objects can be measured using a number of separate devices then merging all data. This process, however, is problematic due to different formats of data, their representation and lack of stable features for data integration (Simon-Chane, 2013b).

Another approach is based on development of new generation of 3D scanners with extended measurement modalities (Bianco, 2010; Brusco, 2006; Mansouri, 2007; Mączkowski, 2011; Santos, 2014; Simon-Chane, 2013a; Sitnik, 2012; Tonsho, 2011). So, for example, SL and BRDF are performed in a single measurement cycle.

Concluding work of WG2 is focused on the following questions:

- How to select the best measurement technique for my objects, taking into consideration environmental conditions and technical requirements?
- How to compare/integrate results from different techniques/devices?
- Which type of measurement techniques/systems are most promising for the future of CH documentation?

This report partially answers the first question, which is related to st2.1 and st2.2 tasks. The second question will be answered through the ongoing COSCH case studies. The third question is addressed below, in the recommendation section.

2. REVIEW OF EARLIER RESEARCH

In this section a short overview of methods listed above, will be presented. We also refer to some projects that investigate 3D digitisation of CH objects.

Methods:

The ToF method is based on direct measurement of the time of flight impulse generated by a laser or another light source (Bohler, 2002). A recent modification of this technique is based on phase difference in the registered impulse. A good example of implementation of ToF in 3D documentation of CH is registering archaeological sites (Lambers, 2007), architectural documentation (Schreiner, 2008) and large statues (Callieri, 2009). Due to the accuracy limits (> ±2mm) this technique could be applied to large size objects and to non-reflective surfaces.

Photogrammetry (Linder, 2009) generally allows to create a 3D model from images without any additional active lighting. SfM (Szeliski, 2011) technique may be considered as its variation. Photogrammetry may be limited by the resolution of captured images and the lack of characteristic points on the inspected surface. Examples of applications of photogrammetric techniques and comparison of different solutions and devices can be found in (Remondino, 2011).

The BRDF (Goldman, 2010) technique allows measurement of how light reflects from the surface, depending on the angle of illumination and observation. Measurement of spatially varying BRDF is feasible, but mature solutions are still lacking. Although not yet ready to become a common recording tool, the technique is very promising because of its potential for registration of important surface parameters.

The FS (Ray, 2002) technique is based on combining multiple images, captured at different focus distances, to produce one sharp image with greater depth of field. It can be used in optical microscopes or standard photography. An interesting comparison of different techniques is presented in (Brecko, 2014).

LT (Dorsch, 1994) employs the well-known triangulation relationship. The light beam generated by the laser is deflected by a mirror and scanned on the object. A CCD or CMOS sensor is used to digitise the point laser image. The accuracy of measurement mainly depends on the resolution of the detector and triangulation base. Point laser triangulation is very effective in direct sunlight. Some examples of LT results in CH documentation are presented in (Barber, 2011).

SL (Geng, 2011) represents a range of methods whose measurement principle is based on projection of some raster on the surface and further registration of deformed raster, its analysis allowing to obtain 3D coordinates. Amongst these methods the most accurate technique is based on sinusoidal fringe and Gray code projection (Sitnik, 2002). Some exemplary implementation to CH documentation could be found in (Akca, 2011).

RTI (Earl, 2011) is based on acquisition of many images of the object differently illuminated and taken by a camera from a fixed position. It can be used to display a variety of object sizes and types, some of which are difficult or impossible to image with previous methods. Fine details are visible. However, this method lacks accurate representation of geometry and is therefore more a visualisation technique. Some exemplary results are presented in (Mudge, 2010).

CT (Kak, 2011) is a state of the art measurement technique for non-destructive visualisation of the internal structure of objects under study. It combines the principles of X-ray shadow microscopy with the computed tomography CT. During measurement, the object is turned around its rotational axis, step by step, at a small defined angle. After each elementary rotation, one X-ray projection image is recorded by a 2D detector. The 3D volume is reconstructed from the recorded set of X-ray projections by applying the inverse Radon transform; Feldkamp filtered back projection is the most used algorithm. A CT analysis of large Japanese wooden statues was performed and described in (Morigi, 2010).

THz (Jackson, 2011) radiation can penetrate a wide variety of non-conducting materials – it can pass through paper, textile, wood, plastic and ceramics. The penetration depth is typically less than that of microwave radiation and cannot penetrate liquid water or metal. THz time domain spectroscopic (TDS) techniques methods can be used for imaging paintings on canvas or extracting separate information about the parchment, ink and a stain on medieval manuscripts (Fukunaga, 2008).

<u>Selected projects</u>

Information sourced from the project websites

CHARISMA, Cultural Heritage Advanced Research Infrastructures: Synergy for a Multidisciplinary Approach to Conservation/Restoration, FP7 Research Infrastructures programme, 2009–2014, is an integrating activity carried out in the FP7 Capacities Specific Programme Research Infrastructures. The project offers free access to most advanced EU scientific instrumentation and knowledge, allowing scientists, conservators-restorers and curators to enhance their research.

3D-COFORM, Tools and Expertise for 3D Collection Formation, Dec. 2008–Nov. 2012, focused on advancing the state-of-the-art in 3D digitisation and making 3D documentation an everyday practical choice for digital documentation campaigns in the cultural heritage sector.

FING-ART-PRINT, Fingerprinting Art and Cultural Heritage – In Situ 3D Non-Contact Microscale Documentation and Identification of Paintings and Polychrome Objects, Nov. 2005–Apr. 2008, FP6-POLICIES, introduced a prototype system integrating NanoFocus confocal profilometer and ELDIM multispectral camera to uniquely characterise an object.

EPOCH, European Research Network on Excellence in Processing Open Cultural Heritage, Mar. 2004–Mar. 2008, was a Network of Excellence funded by the European Union under the Sixth Framework Programme. The network integrated about a hundred European cultural institutions joining their efforts to improve the quality and effectiveness of the use of Information and Communication Technology for applications to the tangible cultural heritage of monuments, sites and museums.

3D-ICONS, European Commission's ICT Policy Support Programme, Feb. 2012–Jan. 2015, was a pilot project funded under the European Commission’s ICT Policy Support Programme. It brought together partners from across Europe with the relevant expertise to digitise architectural and archaeological monuments and buildings in 3D; to establish a complete pipeline for the production of 3D replicas of archaeological monuments and historic buildings which covers all technical, legal and organisational aspects; to create 3D models and a range of other materials (images, texts and videos) of a series of internationally important monuments and buildings; and to contribute content to Europeana using the CARARE aggregation service.

PRESIOUS, a collaborative three-year STREP project 7FP, Feb. 2013–Jan. 2016, aims to investigate innovative ICT solutions to the following key identified challenges: a) the difficulty and inefficiency of the 3D digitisation process, b) the quantification of stone monument degradation, and c) the reconstruction of objects from large numbers of constituent fragments that may be worn, immovable, dispersed or incomplete. Using a common core of geometric processing, analysis and retrieval methods, PRESIOUS is developing predictive geometric augmentation technologies.

Much other research in this area has been carried out in recent years. Some of the technologies discussed here are well established (LT, CT) and some still rapidly improving (SL, RTI).

3. DISCUSSION OF THE CHOSEN APPROACH AND METHODS

Selecting the best digitisation method

The answer to questions concerning selection of the best measurement method, taking into consideration the properties of the object, measurement conditions and technical requirements of 3D model, is relatively simple when the structure of the object is homogenous. For example, a stone object – within a size of just over 10 meters, the required sampling density equal to 10 mm and accuracy of around 2mm – ToF offers the best technique. SL or LT can be used for the same object, but with the sampling density equal to 1mm and accuracy of around 0.05mm. When only the visual appearance of the surface is important then RTI method is a good choice.

A more complex scenario is required when different parts of the object are to be represented with different sampling densities and accuracies. For example, if the object is inscribed then it is obvious that these local areas have to be measured with higher accuracy, while for the remaining surface more rough recording may be sufficient.

In such a case the optimal strategy may be presented through the following steps:

- rough 3D scanning of the whole object (low accuracy);
- detailed 3D scanning of selected areas (high accuracy);
- data integration within one model (task related to WG3 expertise).

The most complex case, when a composite object is considered for 3D scanning, was discussed in section 1. Each group of sub-surfaces of similar parameters have to be measured separately by setting different parameters or even different methods/devices. Next, these data have to be integrated into one model (WG3 expertise) which, due to lack of overlapping parts, is not a simple task.

WG2 will plan to actively support preparation of guidelines/tools in such processes using materials/methods/results achieved in the course of the COSCH case studies.

Comparing different techniques

In the first two years, WG2 performed comparative measurements of small ceramic fragments of a 17th-century stove tile with floral decoration in high relief, showing a vase with flowers under an arcade.

Fig. 1. Photo of the stove tile from the church of the Holy Saviour and All Saints in Dobre Miasto, Warmia, northern Poland.

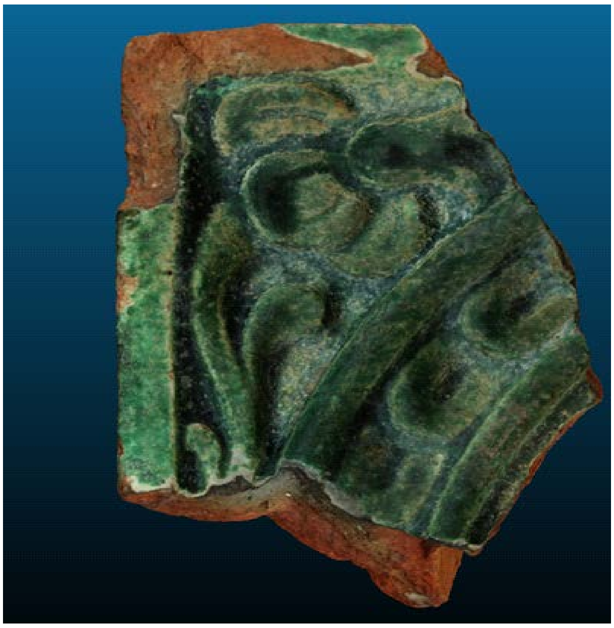

Fig. 2A. A 3D model from measurements of SfM.

The tile comes from the church of the Holy Saviour and All Saints in Dobre Miasto, Warmia, Northern Poland, where it was originally made. The whole panel is presented in Fig. 1. Exemplary measurements of a fragment, using SfM methods, are presented in Fig. 2.

We collected data from a small piece of panel using SfM, SL and CT methods. We also measured it using the Terahertz system; data are being processed to achieve a 3D model.

We propose to compare results obtained by different systems by analysing differences in geometry. Exemplary results of the analysis are presented in Figs. 3–4. Geomagic Control software was used.

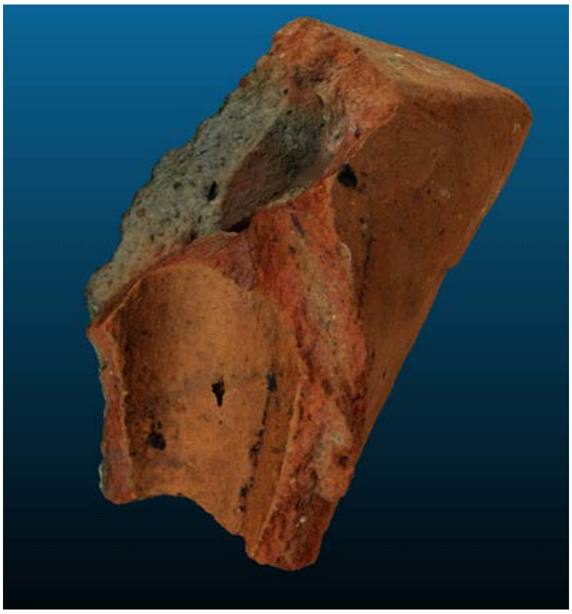

Fig. 2B. A model from measurements of SfM

3D measuring method	Optimal use for	Surface requirements
Time of flight	large size objects and sites (big statues, buildings, archaeological sites, etc) over 10 m	partially diffuse reflection
Photogrammetry, structure from motion	small, middle size and large objects (museum objects, furniture, statues, buildings, archeological sites) made of metal, ceramics, wood, paper, plastic	partially diffuse reflection
Laser triangulation	small and large objects	partially diffuse reflection
Structured light	small and large objects	partially diffuse reflection
Focus stacking	small and middle size objects	partially diffuse reflection
Reflectance transformation imaging	small and middle size objects	partially diffuse reflection
Computed tomography and microtomography	small and middle size objects (1 mm–1 m)	no limitations

Tab. 1. Overview of 3D measuring methods

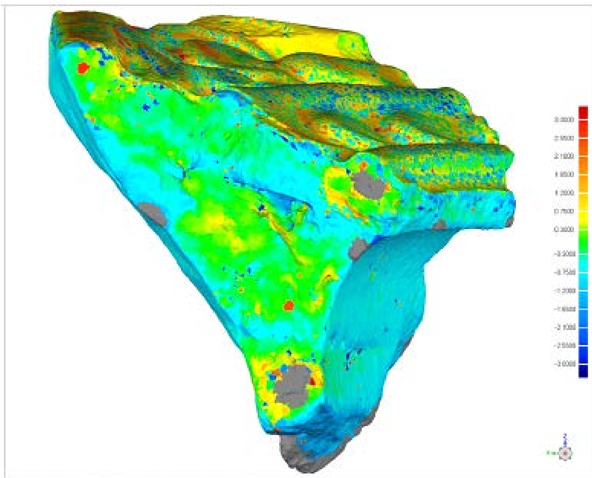

Fig. 3. Visualisation of geometry difference map between µCT and SfM.

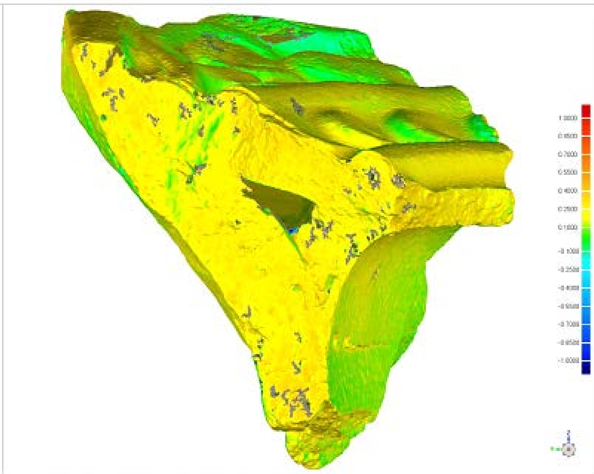

Fig. 4. Visualisation of geometry difference map between SL and SfM.

Although geometry difference comparison is useful, no objective method is yet available to compare results of RTI and BRDF methods.

However, we plan to finalise recommendations on how to compare different techniques, based on results to be achieved through COSCH case studies.

Concluding WG2 investigation, we believe that future systems should allow measurements with more than one modality (geometry or multispectral, or visual, or others) through the same process. This is required due to high diversity of CH objects. The best possible solutions should support optional design of the measurement setup, allowing online selection of modalities actually used with adopted data processing chains (tasks related to WG3).

4. MAIN FINDINGS

Descriptive template for set-ups/systems documenting CH surfaces

In the course of COSCH, WG2 proposed a template (Boochs, 2014) that should be input to any device/system considered for use in documentation of CH objects. The template was discussed with a group of scientists, software and hardware developers, museum professionals and users. An exemplary, completed template was presented to the EuroMed 2014 Conference (Boochs et al., 2014). The proposed template is shown in Tab. 2. We complete such tables during our own research and in the course of the COSCH case studies.

Towards multimodal acquisition

As stated in section 1 we believe that future developments of measurement equipment should be focused on multimodal imaging. Much activity in this area has been observed in recent years, mainly by members of COSCH. The two main approaches are: software- and hardware-based data measurement and integration. Below some hardware solutions will be discussed.

Mansouri (Mansouri, 2007) proposed a combination of SL and seven band multispectral camera as a device for measurement of 3D geometry and spectral reflectance at each point. Such data were used for 3D rendering with arbitrary illumination conditions.

Brusco (Brusco, 2006) proposed a system that integrates LT and spectrograph for texture acquisition. Whole work was oriented towards wall measurements. In this system he achieved a good spectral quality, but poor overall geometry representation.

Tonsho (Tonsho, 2011) developed a setup for goniophotometric acquisition allowing reconstruction of spectral reflectance and specularity on samples of the surface. They use BRDF to separate reflection component from the diffuse one.

Bianco (Bianco, 2010) proposed a combination of SL and multispectral imaging for 3D documentation of historic documents. 3D geometry was used to flatten multispectral images for multispectral reconstruction.

Sitnik (Sitnik, 2012; Mączkowski, 2011) developed a measurement head, which integrates SL, multispectral imaging and BRDF modalities. All these modalities are registered by a shared, single detector, allowing for perfect data integration.

Simon Chane (Simon-Chane, 2013a, Simon-Chane, 2013b) introduced a SL and multispectral camera calibrated together, additionally tracked by photogrammetric system. This solution is very interesting due to the automated alignment of directional 3D scans.

Santos (Santos, 2014) developed a system integrating SfM and SL in application of mass 3D digitisation for museums. System is designed in a modular way, allowing for a relatively easy extension of its modalities.

5. RECOMMENDATIONS FOR THE FUTURE WORK OF COSCH

After two years of meetings, presentations and discussions, WG2 concludes that future technologies will be based on multimodal and/or modular measurement systems with the adaptive data processing platform (as WG3 proposes). Existing technologies only allow for measurement of one modality at a time by a particular system or device. There are some solutions for multimodal measurements. However, they are still not mature enough to be used for everyday 3D measurement.

An important task for future COSCH activities is preparation of guidelines for choosing effective technologies and preparing 3D digitisation process. This task will be fulfilled by all WGs, based on the case studies results.

Questions/answers	**Explanations**
Person producing this form	Name. Affiliation, background
Measurement method principle	
Cost Equipment: Working day: Service:	Cost of the equipment Cost of working day Cost of service
Time constraints	Time of acquisition, processing Time of preparation of the equipment and objects
Preparation: Acquisition: Processing:	
Expected prerequisite expertise of the operator	
Preparation process	Calibration (how often should be done,

	Difficulties, who does it)
Limitations	For objects (min, max dimensions, weight, etc.) Surface limitations (diffusive, transparent, flat, etc.)
List of potential difficulties	This particular system cannot do this This technology cannot do that
Measurement environment limitations (laboratory conditions, outdoor, indoor, in situ etc.)	
Measurement method parameters (resolutions, uncertainties, texture imaging, etc.)	
Resolution: Uncertainty: Working volume (single measurement): Texture imaging: *Other*:	
Example	Measured, evaluated properties of the objects Settings of the equipment Output format, Memory size of the output The name of the project, links
Exemplary results:	
Other important information:	

Tab. 1. Table describing the measurement system/device, with exemplary results and other important characteristics of the CH object.

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