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Original article

Portable solution for high-resolution 3D and color texture on-site digitization of cultural heritage objects

Roland Ramm[a,*], Matthias Heinze[a], Peter Kühmstedt[a], Andreas Christoph[b], Stefan Heist[a], Gunther Notni[a,c]

[a] Fraunhofer Institute for Applied Optics and Precision Engineering IOF, Albert-Einstein-Str. 7, 07745 Jena, Germany
[b] Thüringer Universitäts- und Landesbibliothek Jena ThULB, Bibliotheksplatz 2, 07743 Jena, Germany
[c] Technical University Ilmenau, Gustav-Kirchhoff-Platz 2, 98693 Ilmenau, Germany

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ABSTRACT

A peculiar characteristic of cultural heritage objects is their uniqueness. This results in an enormous importance for their preservation against aging, accidents, destruction etc. Although not replacing physical preservation, one way is the digitization of the objects in their current state by modern scanning technologies. This research describes a new method to combine 3D shape and color texture data acquired without contact to achieve high-resolution 3D representations. The method was basis of a portable 3D digitization system. The portable character allows its application on-site, which is essential for sensitive and non-transportable objects. A structured-light 3D sensor and a photo camera are used to capture the object from various overlapping perspectives. Then, the 3D shape and photographic data are processed and merged into a complete textured 3D model. Resolution and accuracy of the final model are in the range of 0.1 mm. Beyond preservation, the models can be used to make museum objects digitally available for experts or visitors worldwide e.g. in the form of online databases or virtual museums. A first utilization of the presented technology was realized with historic globes, especially with a Schöner globe dating from 1515 as highlight. The used method can be extended beyond RGB texture acquisition using multi-/hyperspectral sensors leading to an increased information content about the objects.

Introduction

Aging, accidents, or deliberate destruction represent constant danger for unique objects of cultural heritage [1–4]. For that reason, many museum objects are not publicly accessible. Instead they are stored safely in archives [5,6]. Digital copies in high quality are one way to preserve information on cultural heritage objects [7,8]. They also open new ways for the public or experts to access them [9–16].

The digitization of objects is closely related to optical measurement technologies. These contactless and non-invasive technologies are especially advantageous for sensitive objects. Photography and 2D scanning are established methods, e.g. Google Books collection or Wani et al. [8]. Technologies which capture complete objects in their three-dimensional (3D) shape are of growing interest [17–21]. A combination of 3D shape with photographic acquisition is demanded because surfaces can contain meaningful texture information, such as with vases, statues, globes. Singular examples are found in the literature which use 3D measurement technologies to create digital 3D models of museum objects [22–27]. A broad usage on a large number of objects, called mass digitization, is not apparent [30].

The presented research focuses on portable and automated digitization of museum objects. Transportability is important, because the digitization systems should be brought on-site to the sensitive objects and not vice versa. The transport of objects to a digitization lab (e.g. [32]) is not favored by curators. In archeological applications, some objects cannot be transported at all [33]. Automated processing allows the application to a large number of objects without high personnel effort. The research had the further aim to provide high data quality, including 3D shape and photographic data, to create authentic digital representations of the objects.

Structure-from-Motion (SfM) and active triangulation by structured-light are the most relevant optical 3D measurement technologies for museum objects [21,34,35]. Laser scanning is common for large structures such as building sites (e.g. [36–39]) but close range laser scanners can be applied for medium sized museum objects as well [40]. These are based on the photogrammetric triangulation principle and are closely related to

* Corresponding author.
E-mail address: roland.ramm@iof.fraunhofer.de (R. Ramm).

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structured-light systems [41]. In this article, laser scanners on the basis of triangulation are also considered structured-light systems, e.g. the Konica-Minolta Vivid 910 was used by Menna et al. [27].

SfM is the most frequently used method to get 3D models of cultural heritage. The advantage is the simple equipment. Only a digital photo camera is required, although for professional purposes sophisticated lightning equipment is used as well. For SfM the object is photographed from a large number of perspectives, typically many hundreds. Software packages then reconstruct a textured 3D model, some well-known are Metashape (https://www.agisoft.com) and VisualSFM (https://ccwu.me/vsfm). In a photogrammetric calculation the camera parameters, camera positions and 3D coordinates of object surface points are determined [42,43]. The principal requirement to apply SfM is the occurrence of texture features (e.g. corners, edges, points) on the object surface as these are the basis for the whole photogrammetric calculation. The quality and resolution of the 3D data depends strongly on the object texture [28,29]. Furthermore, the 3D models must be scaled into the correct metric size by a known dimensional distance in the scene, e.g. a ruler. Automated SfM systems exist but have limited transportability [31].

Structured-light systems project structured patterns onto the surface. Laser scanners based on active triangulation use laser line(s) or dot(s) patterns in contrast to structured-light systems [44–47]. The shape is reconstructed by triangulating the pattern features using one camera or two calibrated stereo cameras [47,48,35]. The achievable 3D data quality and resolution of structured-light systems depend on the sensor specifications and not on the object texture. The digitization of a complete object requires data capturing from different perspectives but the required number of acquisitions for a complete 3D model is typically much lower in comparison to SfM as each single acquisition already represents a surface patch of the complete model. In subsequent processing, these patches, i.e. single 3D point clouds, need to be registered. An overview of registration methods is given in [47]. The most common methods are: (1) alignment by iterative closest point (ICP) algorithm [49], (2) tracking of coded or non-coded registration markers on or beside the measurement object [50,51], (3) alignment by an accurate, calibrated turntable [52]. In cases of symmetrical geometrical surfaces such as on symmetrical vases or spherical globes, ICP is not robust and can fail. ICP often requires the user to prealign the 3D point clouds. The usage of adhesive markers is not applicable for sensitive cultural heritage objects. Notni et al. [53] describes a method using virtual registration markers. It requires additional external cameras and a stable environment. The usage of a turntable requires extra effort for calibrating the rotation axis, reduces the portability of the whole setup and is only applicable for movable objects up to the maximum allowed weight of the specific table.

Structured-light systems acquire basically pure shape information of the object surface. Photographs from an additional camera must be registered to the 3D point clouds. SfM includes color information implicitly when a color camera was used. One way is to add a fixed photo camera to the structured-light sensor and calibrate its relative position [53–55]. Most commercial systems have integrated a photo camera directly into the sensor unit itself and make the photo-to-3D-data registration automatically, e.g. Artec Eva or Microsoft Kinect. This registration requires an accurate calibration of the cameras and a stable mounting. These are sensitive requirements for a transportable system. Further there is no easy way to use an alternative photo camera. Another method for photo-to-3D-data registration uses geometrical features in the 3D-data to fit photographs, which requires distinctive edges in the 3D data [56,57]. Siepmann et al. [58] used a color camera, which directly captured the structured patterns of the white light structured-light system and thus achieved a pixel synchronous registration of the color data without any known calibration. The internal monochrome cameras of structured-light sensors can obtain pixel synchronous color data by illuminating the scene subsequently with colored light, e.g. through RGB projection [59].

The combination of SfM and structured-light achieves both high 3D data quality together with high-resolution photo-realistic texture. [27,60–63] used one 3D model reconstructed by pure SfM from a set of color photographs and a second 3D model reconstructed by pure ICP of 3D point clouds from a structured-light system. In an interim step, both 3D models were registered. [61] demonstrated an automatic approach for this purpose. Afterwards, the photo camera positions are known relative to the structured-light 3D model and can be used to blend the photographic texture onto the model surface. This method works well if the object has sufficient texture for SfM and enough geometrical features for ICP. In case of insufficient texture and/or geometry, additional aids are required, e.g. registration markers or a calibrated turntable. The large differences in terms of scale and quality of both 3D models can cause errors or demand manual corrections by an operator. In [64] a workflow for digitizing spherical globe balls was demonstrated, where triangulation based laser scanning and photographic acquisition were performed independently. No fusion of both data sets was realized. ICP was used to register the single point clouds, based on small geometric features on the surface. [24] digitized the Behaim globe by pure SfM and filled afterwards small gaps in the resulting 3D model by data from a close range laser scanner.

The method presented in this research uses a new approach to the fusion of structured-light 3D scanning data and SfM data on the basis of the camera images and not on the subsequent 3D data. Thereby, additional camera images from the structured-light sensor are incorporated. The registration of the single 3D point clouds from the structured-light sensor falls away with the fusion process as a byproduct, so that ICP is not necessary. The realization of a simpler sensor setup suited for applications directly on the spot, together with a completely automatic data processing software was achieved in that method. Beneficial features from previous projects, e.g. cross-polarization photography [26] and masked photo blending [70], were integrated into the system as well. Promising results on challenging objects with limited texture or geometrical features were demonstrated. Overall, the system has potential to be used for mass 3D digitization of museum objects on-site.

Research aim

In this research, a new method for the 3D digitization of museum objects was developed. The method is based on a portable sensor setup which is used on-site, e.g. directly at museums or excavation sites. The 3D scanning techniques of structured-light and Structure-from-Motion are combined. Thus, high data quality in terms of resolution and accuracy was achieved. Output of the digitization are authentic 3D representations, including 3D shape and photographic texture from the originals. Those digital replications preserve the original object in terms of visual appearance and are resistant to aging, damage or deliberate destruction. Further, they allow experts to devise new methods to analyze the objects. Virtual museums could present the 3D models to visitors.

Material and methods

3D digitization procedure

The new procedure for 3D digitization of objects requires a stereo camera based structured-light 3D sensor and a digital photo camera. It is assumed that the 3D sensor outputs, in addition

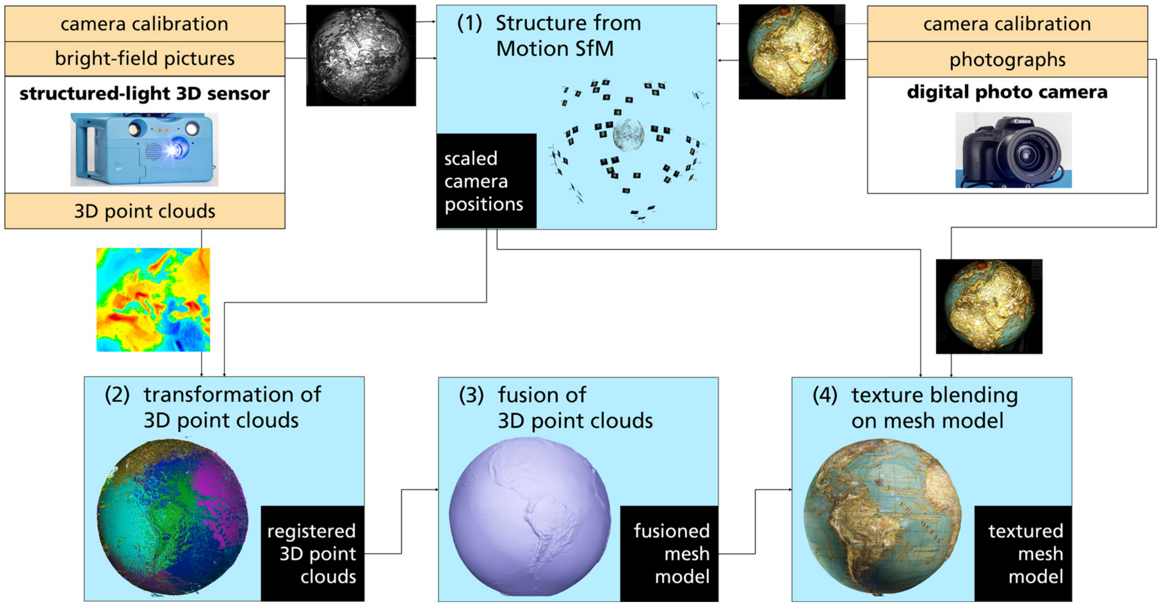

Fig. 1. Flowchart of the 3D digitization procedure.

to the 3D data, bright-field pictures of the scene captured by its stereo cameras and that the 3D data is in a known coordinate system relative to the stereo cameras. Each acquisition with the 3D sensor consists of one 3D point cloud or 3D mesh and the two stereo camera bright-field pictures.

In this context bright-field pictures refer to camera images under uniform illumination, i.e. without any structured pattern. Those may be provided through the structured-light projector itself, an additional ring light or an ambient light source. Therefore, every structured-light or close range laser scanner is suited to be used by the described 3D digitization procedure, provided it consists of a stereo camera setup and can output bright-field pictures with each 3D acquisition.

The 3D sensor and the photo camera are used to capture a set of acquisitions from different perspectives from one scan object. It is pointed out that the 3D sensor acquisitions can be performed independently from the photographic acquisitions. The exact positions of the camera and 3D sensor as well as their total number can be different. Of course, a certain overlap between the perspectives must be respected.

The 3D digitization process consists of four main steps which are presented schematically in Fig. 1. One set of 3D point clouds and stereo camera bright-field pictures is available as well as one set of photographs from the scan object. Furthermore, the calibration data of the stereo cameras and, optionally, of the photo camera are given. First, the bright-field pictures of the 3D sensor stereo cameras together with the captured photographs are processed by known SfM methods. The 3D point clouds are completely neglected in the first step. The main result of this calculation is a photogrammetric camera network consisting of the camera orientations for the pictures and photographs. A sparse 3D point cloud based on the distinctive texture features on the object surface ("tie points") is determined as well but for the presented procedure this coarse point cloud is not of interest. Optionally, intrinsic camera calibration parameters (principal distance, principal point, distortion) are determined. For the stereo cameras those are already given, so that they are used as additional input to the photogrammetric calculation. For the used photo camera, those parameters can be inputted as well, although it is not mandatory. However, it is preferable in case only a small number of photo acquisitions is applied, e.g. < 10. As the baseline of the stereo camera pair is part of the calibration, the complete photogrammetric network including all camera orientations can be scaled to metric size. The 3D digitization procedure could be extended to single camera structured-light or laser scanners by using a metric scale bar in the scene.

Second, the determined orientations of the stereo cameras are taken from the previous step. Each single 3D point cloud is transformed from the original sensor coordinate system into the photogrammetric camera network by using the scaled orientations of the stereo cameras. After this step, all 3D point clouds are registered into one coordinate system together with the photo camera orientations which will be of use in the last step.

Third, the registered 3D point clouds are merged and meshed into one model. In the last step, the photographs are mapped onto the mesh model by blending algorithms. The result is a mesh model based on the structured-light 3D data with a texture layer based on the photographic data, e.g. texture atlas.

The described 3D digitization procedure has the following advantages against pure SfM and structured-light methods:

- The 3D data quality, in terms of accuracy and resolution, is determined by the 3D sensor used and is independent from the object surface texture. Texture features are only required to register the single 3D point clouds and the photographs in the initial SfM step.
- The registration of the single 3D point clouds does not depend on shape features as it is required for the ICP algorithm. This enables the application of the method on objects with smooth or symmetrical shape, e.g. vases, globes. The method also requires no registration markers or a calibrated turntable.
- 3D data and photographic acquisition are independent from each other, specifically no precalibration between 3D sensor and photo camera is required. The process can be extended to the use of multiple 3D sensors and / or multiple photo cameras. In case no photo camera is used, the bright-field pictures of the 3D sensor can be blended onto the mesh model.
- The number of required perspectives is smaller compared to SfM. Therefore, a shorter processing time for the 3D digitization can be realized. Nevertheless, the required number of perspectives is still dependent on the complexity of the object and its amount of texture features. The implementation of the 3D

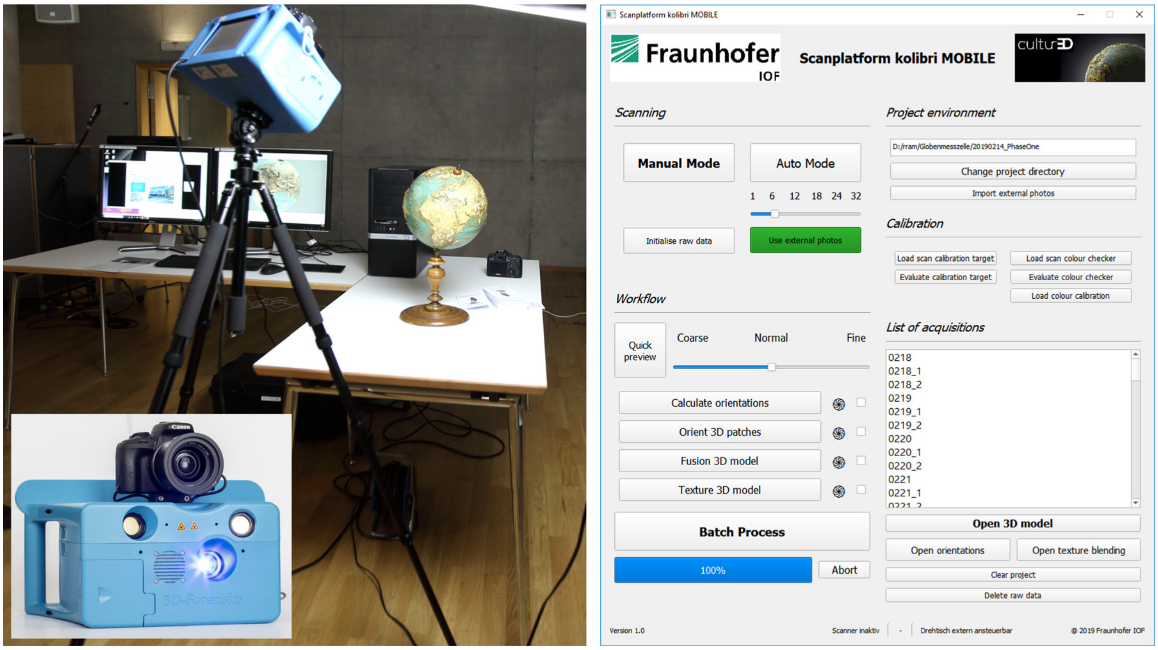

Fig. 2. Sensor unit standalone and mounted on a tripod (left) and data processing software GUI of the system kolibri MOBILE (right).

Fig. 3. Suppressing of specular highlights in the photographs by cross-polarization ring flashlight (left) in comparison to a standard ring flashlight (center) and the usage of external soft box illumination (right).

digitization procedure described below allows the quick reconstruction in a preview mode which can help to decide during acquisition whether further perspectives are required.

Portable system equipment

The procedure described in the previous chapter was the basis of a new 3D digitization system with a focus on portability. The workflow in Fig. 1 was implemented in the system kolibri MOBILE. The system consists of a structured-light 3D sensor unit [55], an attached DSLR camera and a data processing software on a separate workstation (Fig. 2). The workstation can be a laptop so that the complete system is transportable, e.g. for usage in-house in museums or at excavation sites.

The 3D sensor unit includes a stereo camera setup and a digital structured light projector (DLP). The shape measurement is based on fringe projection [48]. Hereby, a sequence of gray code and sinus fringe patterns is projected onto the object surface and triangulated between calibrated stereo cameras. The DSLR camera is mounted on top of the 3D sensor unit, although a fixed mounting is not mandatory for the 3D digitization procedure. The relative position between the 3D sensor and the DSLR is not part of the data processing. The software also allows the import of photographs from one separate photo camera.

The 3D sensor from [55] was taken for kolibri MOBILE because it is already designed as a self-contained device with an integrated processing unit, touchscreen and battery. This enables its flexible usage on-site. In contrast to the original design from Ramm et al. [55] the DSLR camera is replaced by a Canon EOS 5D Mark IV with greater pixel count. Analogous to [26] and [27], cross-polarization is used to suppress specular highlights in the photographs which would cause artefacts in the texture blending (Fig. 3). The DSLR camera is equipped with a Canon Macro Ring Lite MR-14EX II and a cross-polarization filter Polar_eyes.

Use of the sensor unit on a tripod results in the best 3D and photograph quality. Only in specific situations where concealed parts on the object are hard to reach by tripod, handheld scans should be taken as compromise. Table 1 shows technical specifications of the sensor unit.

The sensor unit is used to capture single acquisitions from the scan object from different perspectives. Each acquisition includes one 3D point cloud, two stereo camera bright-field pictures and one photograph. The bright-field pictures are generated by projecting a uniform image with the DLP projector. The photographs of the DSLR camera are saved in raw format. Previews on the touch-

Table 1
Technical specifications of the sensor unit according to [65] (GSD - ground sample distance).

Pixel count stereo cameras	2048 × 1280
Pixel count DLP projector	940 × 1140
Pixel count DSLR camera	6720 × 4480
Scanner-to-object distance	455 mm
Field of view (horizontal x vertical)	35.5° × 23.7°
	325 × 200 mm² @ 455 mm
Depth of field	100 mm
GSD 3D sensor	0.15 ... 0.20 mm
GSD photographs	0.05 ... 0.10 mm
Accuracy 3D (VDI 2634 [66])	0.05 mm (single acquisition)

screen allow the user to check each acquisition. The processing described in Fig. 1 takes place on the workstation after the acquisition is finished. The files can be transferred remotely by a local WiFi network or by USB stick. The data processing software kolibri MOBILE requires an installation of a SfM software package, more precisely Metashape Professional from Agisoft and BINGO (https://bingo-atm.de) are used.

Implementation of the 3D digitization procedure

The workflow is split into two phases: (1) 3D data and photographic acquisition and (2) 3D model processing.

Data acquisition process

The 3D digitization of an object starts with the capturing of 3D and photographic data. The scan object must be placed on a base that allows accessibility from all required viewing perspectives. As some objects tend to change their physical shape under movement, e.g. a globe sphere can move within its frame, it is preferred to keep the object still on its base and to move the sensor unit around it. In case there is low risk for changes in shape, e.g. with vases, it is also an option to put the object on a turntable and to keep the sensor unit in a fixed position. The 3D digitization procedure requires neither a calibration of the turntable rotation axis nor the knowledge of the exact angular position. A base with a textured surface is beneficial in case the object itself does not have easily detectable texture.

The sensor unit is mounted on a standard tripod with a tilt head. The scan object is captured from different perspectives with the goal to have data from all accessible regions of its surface. Fig. 4 shows as an example the captured perspectives visualized in the calculated photogrammetric camera network. Their exact position or sequence is not important. However, the images from the acquisitions must have a certain overlap, whereby 50% is good practice.

An extra illumination setup is not required for data acquisition. Illumination takes place through the structured-light projector and the DSLR camera ring flashlight. Very strong external light sources, i.e. direct sun light, must be avoided. When on-site, the sensor unit can be checked in terms of scale accuracy by a calibrated marker board and in terms of color reproduction by a color checker. Scale and color reproduction can be corrected in the later data processing, if required. Setting up the system equipment takes less than ten minutes.

3D model processing

The 3D model processing described above was implemented in the software tool of kolibri MOBILE (Fig. 2 right). Each 3D model reconstruction is handled in a dedicated project structure. Input to the process are the acquired data from the sensor unit and, optionally, from a further separate photo camera. The four processing steps described in Fig. 1 are fully automated and require no user interaction, although expert users have the possibility to enter and edit intermediate results of the process, e.g. masking the base out of the 3D model, optimize the registration of the 3D point clouds by ICP, etc. The raw data is never changed by the software, so that each process step can be undone.

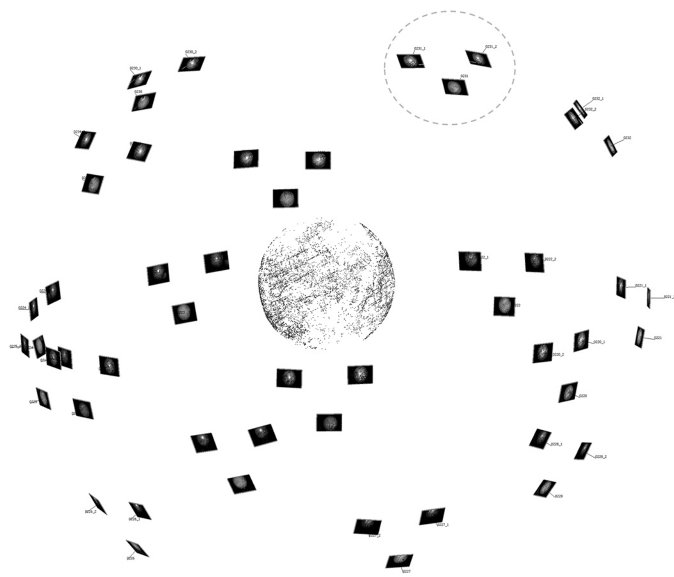

Fig. 4. Example of acquisition positions for a globe. The sparse point cloud in the center consists of the tie points used for orientating the cameras. The triplets of oriented cameras (e.g. inside the marked circle) represent each a set of two stereo camera bright-field pictures and one photograph.

In step 1, the orientations of all cameras are calculated. For this purpose, kolibri MOBILE uses the SfM software packages Metashape and, optionally, BINGO. The orientations are used in step 2 to register all 3D point clouds. At this step it is optionally possible to refine the registration by global ICP alignment. In step 3 the points clouds are converted into meshes and fused by the screened Poisson surface reconstruction algorithm described in [67]. In the last step the fused mesh model is loaded together with the photo camera orientations into the Metashape software. Here the texture blending is performed using a blending algorithm (e.g. [68,69]).

Before the final blending, kolibri MOBILE processes the photographs. According to [70], photo masking is applied. As the distance and orientation of each camera pixel to the 3D model surface are known, pixels which are out of depth of field or pixels which see the surface under a large inclination angle, can be masked out automatically. Further, if the DSLR camera was used with a ring flashlight, a normalization of the photographs based on Lambert's cosine law is made [71]. The texture blending profits from the earlier suppression of specular highlights through cross-polarization.

The user can select between five accuracy levels which change a set of parameters in all intermediate processing steps influencing the resolution of the model and the processing time. An additional preview option reconstructs quickly a very coarse 3D model based on the sparse point cloud outputted by the camera orientation process step. This is designed to be used on-site in between the data acquisition to check the progress and to identify gaps in the digital 3D model.

One advantage of the presented method is that it can be extended to multiple photo cameras and / or 3D sensors. For this, an option in the kolibri MOBILE software was implemented to import photographs from a further separate photo camera into the workflow. Such photographs can be added or can replace the photographs acquired by the sensor unit DSLR camera.

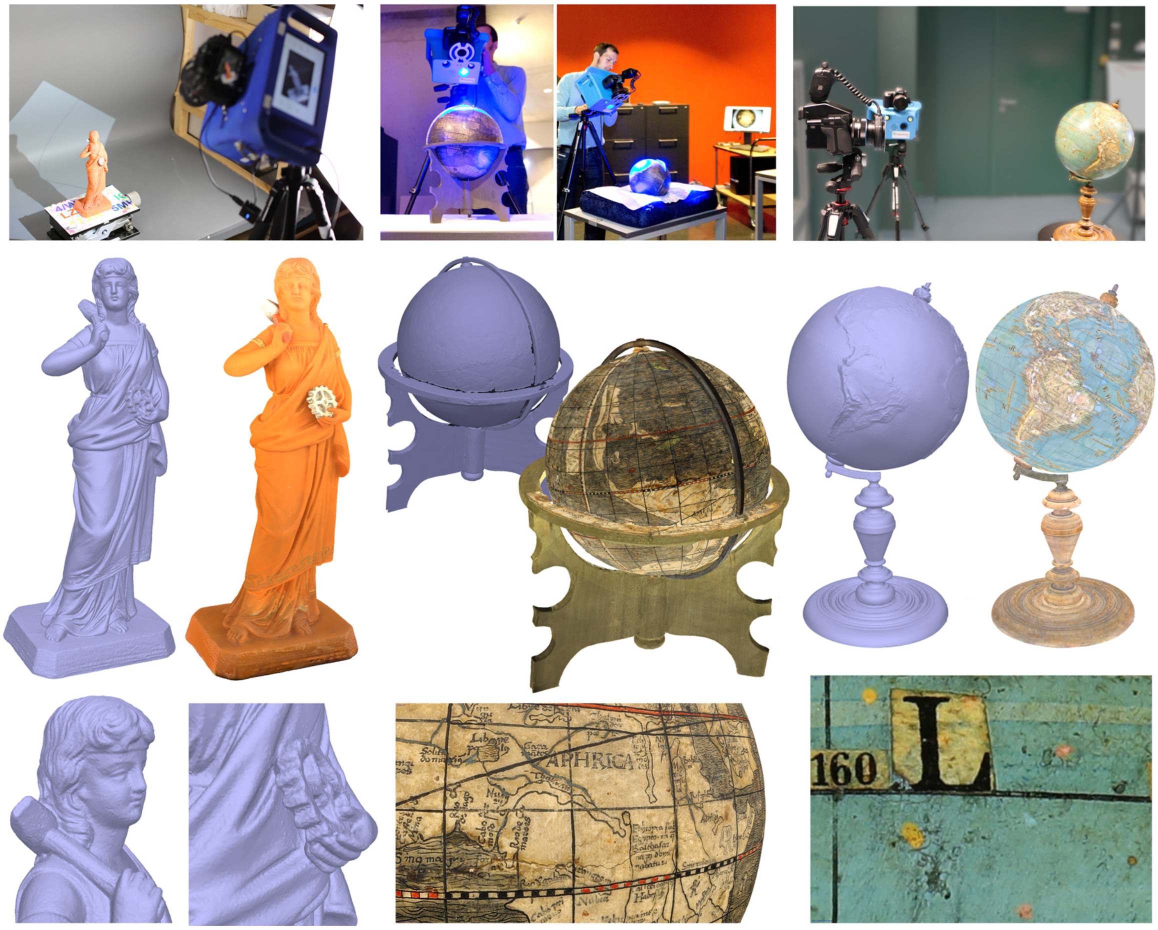

Fig. 5. Overview of exemplary museum objects Industria, Schöner globe and relief globe (from left to right) used to test the new 3D digitization procedure and the portable sensor equipment. Top row – photo of digitization arrangement, bottom rows – digital 3D models. For the relief globe, a high-resolution texture detail of 20 × 16 mm² size captured by a 150 megapixel DSLR camera is shown in the bottom right corner.

Results

3D digitization of museum objects

The 3D digitization procedure described above was tested with exemplary museum objects. In this article the following selection was used to investigate the new procedure and the portable system equipment:

(1) Terrokotta figure "Industria" (ca. year 1880, height ca. 26 cm) at GoetheStadtMuseum in Ilmenau
(2) Schöner globe (year 1515, diameter ca. 27 cm) at Herzogin Anna Amalia Bibliothek in Weimar:
  (2a) „Schöner globe" ball
  (2b) „Schöner globe within frame"
(3) Relief globe (year 1885, diameter ca. 25 cm) from geographic-artistic institution of Ludwig Julius Heymann in Berlin:
  (3a) "Relief globe with pedestal"
  (3b) "Relief globe" ball

The sensor setup described above was used for the digitization. The data acquisition on Industria and Schöner globe took place in-house at the particular museum so that the portable character of the system was checked. Fig. 5 shows the digitization arrangement and the 3D model results.

Table 2 provides an overview of the digitization parameters. At the digitization of Industria (1) and the relief globe (3b), the sensor unit was used together with an additional separate DSLR camera. These photographs were captured in the same object arrangement after the acquisition with the sensor unit. It is also noted that the sensor unit used the attached DSLR camera from [55] with external illumination by a daylight softbox lamp at the digitization of Industria (1). In all recording sessions, except for Industria (1), the objects remained fixed and the sensor unit / camera was moved around them. Due to the cramped space, Industria (1) stood on a small textured table which was turned manually to eight angular positions per 360° rotation while the sensor unit / camera was varied only in height.

The resulting 3D models from the exemplary objects demonstrate the performance of the new 3D digitization procedure and the portable capabilities of kolibri MOBILE. It was possible to reconstruct all-around textured 3D models with high resolution and quality in terms of shape and texture. The average distance of the 3D point clouds [72] and the RMS (root mean square) reprojection error [47,73] in Table 2 allow to assess the achieved accuracy. The distance of the 3D point clouds is on average in the range of 0.1 mm. The reprojection error is clearly below one camera pixel which indicates that residual misalignment between photographic and shape data is not visible to the eye. The quality of the digital 3D models was further analyzed through visual comparison with the original and by comparison with a pure SfM approach which is discussed in the next chapter.

At Industria (1), the occluded region behind the gear of the figure was not captured by the sensor. In case digital models should

Table 2
Overview of digitization parameters used for the objects in Fig. 5. The processing times were achieved on different workstations. The RMS (root mean square) reprojection error indicates the alignment accuracy of all stereo and photo camera orientations in terms of average pixel deviation. The average distance of the 3D point clouds indicates the accuracy of their registration neglecting the photographic data.

Object digitization	1) Industria	2a) Schöner globe	2b) Schöner globe within frame	3a) Relief globe with pedestal	3b) Relief globe
Sensor unit					
DSLR camera	Canon EOS 200D	Canon 5D Mark IV	Canon 5D Mark IV	Canon 5D Mark IV	Canon 5D Mark IV
Lens	28 mm	50 mm	50 mm	50 mm	50 mm
Acquisitions	21	70	79	83	17
Separate camera	Canon 5D Mark III	-	-	-	Phase One 150MP
Lens	50 mm	-	-	-	80 mm
Photographs	131	-	-	-	18
Acquisition time Sensor unit + Separate camera	20 min + 25 min	50 min	25 min	70 min	10 min + 10 min
Processing time in medium accuracy	ca. 2.5 h	ca. 2 h	ca. 2.5 h	ca. 3 h	ca. 35 min
RMS reprojection error	0.41 px	0.25 px	0.30 px	0.24 px	0.26 px
Average distance of 3D point clouds	0.03 mm	0.05 mm	0.11 mm	0.07 mm	0.13 mm
Comments	Object was put on a table with textured surface. Table and object were rotated manually to eight positions per 360° rotation. The point cloud registration was refined by an additional ICP.	Object was turned around after 34th acquisition.	One misaligned point cloud was removed manually.		The 150-megapixel photographs correspond to a GSD (ground sample distance) of ca. 0.03 mm on the object surface.

be reproduced by 3D printing such geometries are closed by interpolation methods.

At Schöner globe (2a), the ball surface shows a very realistic appearance. Difficulties occurred on the frame of the globe (2b). This element has neither distinctive texture nor geometric features so that the registration of some single 3D point clouds was inaccurate. Expert users could manually remove misaligned 3D point clouds from the process or correct them by using a mesh editing software tool, such as Meshlab (https://www.meshlab.net).

At the relief globe (3a) and (3b) the results are of very good quality.

The digitization of Industria (1) and relief globe (3b) demonstrate the capability to add multiple photo cameras into the workflow. A test with multiple 3D sensors was not performed in this research.

Influence of accuracy level

As mentioned above, kolibri MOBILE allows the user to select between five different accuracy levels and a preview mode. The selection enables the curators to find the best compromise in terms of quality and computing effort for specific applications. Using the dataset of the relief globe (3b), an evaluation of the processing time and a comparison of the resulting 3D models was carried out. The 3D models are shown in Fig. 6. The accuracy level clearly influences the level of detail of both shape and texture data. Less apparently, it also influences the alignment accuracy and color trueness. It is noted that the software enables the user to set varying accuracy levels at each step of the reconstruction pipeline, e.g. only a low resolved shape but a high resolved texture may be desired.

Fig. 7 indicates the achieved processing time divided up between the four procedural steps from Fig. 1 and the file size of the textured mesh model for each selectable accuracy level. This evaluation was performed on a desktop PC with a CPU Intel Core i7–7700 and a GPU AMD Radeon™ Pro-WX 5100.

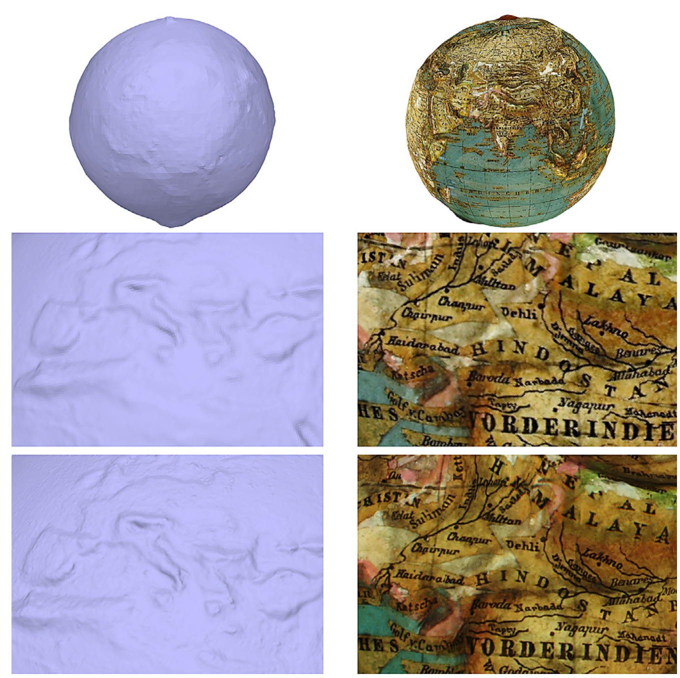

Fig. 6. Resulting bare (left) and textured (right) 3D models of the relief globe with different accuracy levels (from top to bottom): preview, medium, fine. The quick preview is suggested to check completeness of the scan data during acquisition. For medium and fine level, close-ups of size ca. 100 × 60 mm² and ca. 40 × 30 mm² are shown for the bare and textured surfaces respectively.

Comparison of kolibri MOBILE against SfM and ICP

Above, a list of potential advantages of the presented method against the standard SfM and structured-light were stated. Those were evaluated on the test objects from Fig. 5.

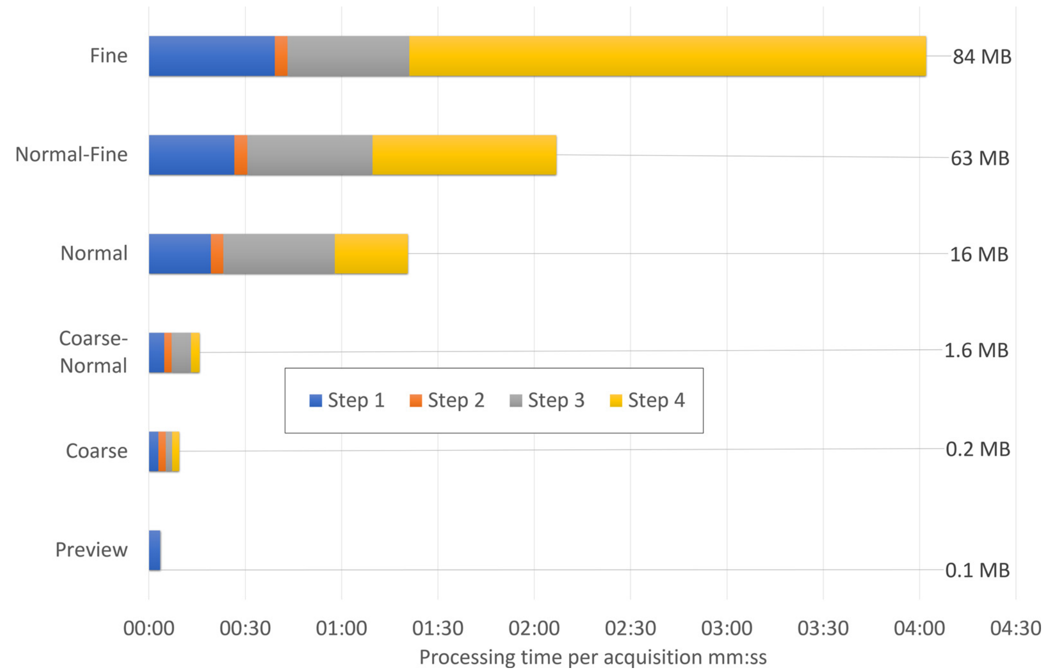

Fig. 7. Comparison of the accuracy levels regarding their computing effort. The horizontal axis shows the processing time as time per acquisition divided up between the four procedural steps in Fig. 1. The value beside the bars equals the file size in Megabyte (MB) of the textured mesh model as size per acquisition. The overall processing time as well as the overall file size can be estimated by multiplying the values in the diagram with the number of acquisitions. This evaluation does not consider additional photographs from a separate camera.

Fig. 8. Comparison of 3D results of SfM (left) and kolibri MOBILE (right) at object Industria. The SfM reconstruction was realized with Agisoft Metahape 1.5.3.

Industria (1) has a lot of geometric features, while the surface texture is not very detailed. In such a case of a low number of texture features, SfM is not capable to reconstruct 3D models with detailed shape features. For the 3D reconstruction by SfM, 131 photographs captured by a Canon EOS 5D Mark III camera with a 50 mm lens were used. The reconstruction was performed with Agisoft Metashape using the highest available accuracy parameters. The overall processing time was ca. 16 hours which is significantly more time-expensive than kolibri MOBILE with ca. 2.5 h. Fig. 8 shows a comparison between SfM and the result by kolibri MOBILE. The level of detail is clearly higher using the presented 3D digitization procedure.

The ball of the Schöner globe (2a) is an example where the ICP algorithm is limited to register a set of point clouds due to the absence of distinctive geometrical features. Even at the relief globe ball (3b) ICP is not robust, at least in the oceanic regions of the surface. A comparison between the registration by ICP and kolibri MOBILE is shown in Fig. 9. The accuracy in terms of the average distance of the 3D point clouds within the cutoff section is 0.22 mm for ICP and 0.11 mm for kolibri MOBILE registration.

Discussion

The new 3D digitization procedure described above was demonstrated with exemplary museum objects. The portable design of the developed sensor unit kolibri MOBILE allowed the 3D digitization of cultural heritage objects in-house in museums. The acquisition time depends on the number of acquisitions determined through the complexity of the object. It is typically in the range of tens of minutes. The system includes a preview mode which allows an assessment of the captured data during acquisition. Final processing of the 3D models takes between several minutes to some hours but can be realized in an automatic batch process offline after the acquisition process.

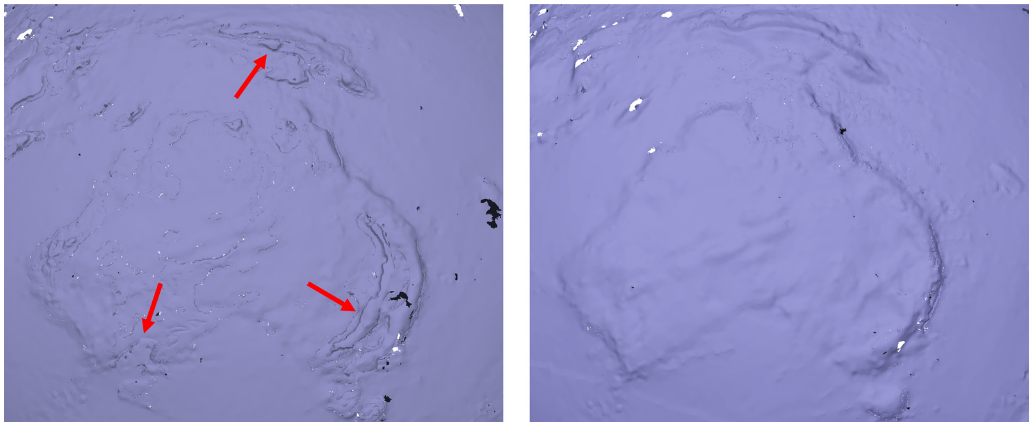

Fig. 9. Comparison of fusioned mesh models after ICP registration (left) and after registration by kolibri MOBILE (right) on the relief globe, detail view of Oceania. ICP was performed with the software Geomagic Qualify 12 (https://www.rsi-3dsystems.com) after manual prealignment of the 3D point clouds. Arrows mark distinctive artefacts.

At a rough estimate, an acquisition of two to three objects per hour is realizable, meaning a few thousand objects per year. Much time and risk can be saved because the objects can be digitized on-site without any transport. The intention to use the system for mass digitization is feasible.

A higher degree of automation in the acquisition can be achieved through the usage of a motorized turntable. Of course, this should be considered only if the object itself does not change its shape under movement (e.g. the globe ball can change its position within the frame). The kolibri MOBILE software includes an interface for an automatic turntable AT360 from 3D-Viz (https://www.3d-viz-technology.com) and an option to automatically capture a defined number of acquisitions per rotation. In this case the sensor unit is placed in a fixed position beside the turntable. The maximum allowed weight is 200 kg. Neither a calibration of the rotation axis nor the exact angular positions are part of the 3D digitization procedure in contrast to state of the art methods which use the turntable itself as the basis for 3D data registration.

Although the 3D model reconstruction is not strongly dependent on textural features on the object surface as with SfM, they are still required to register the 3D point clouds and the photographic data. This can lead to less robustness in the digital reconstruction of specific objects, e.g. the frame of the Schöner globe (2b). This limitation can be counteracted by using a textured base below the object. Munkelt et al. [74] describes a method which flashes a fixed pattern onto the object. This approach could be included into the workflow, e.g. by having an additional set of photograph and stereo camera bright-field pictures for each acquisition position including the pattern.

An even higher degree of automation could be achieved by mounting the sensor unit onto a robotic arm. This can be coupled with automatic view planning (e.g. [31,75]) to realize the acquisition completely without user interaction. Of course, this would reduce the portability of the system and may be inacceptable for sensitive cultural heritage objects.

It was mentioned that the presented 3D digitization procedure can be extended to include multiple structured-light 3D sensors and / or photo cameras. In this sense, spectral resolving cameras could be added to the workflow as well. Multi- or hyperspectral cameras are able to capture the spectral signature of surface points which increases the content of the digital copy of the object and can uncover hidden properties [76,77].

Conclusions

In this research a new 3D digitization procedure combining SfM and structured-light 3D scanning was studied. The procedure was investigated with a portable structured-light 3D sensor unit coupled to a DSLR camera. It was possible to acquire digital 3D models of sensitive cultural heritage objects in-house in museums. The system achieves a 3D data resolution and quality which can outperform pure SfM or structured-light methods. An accuracy in the range of 0.1 mm was achieved on two globes and one Terrakotta figure. Further investigations will extend the performance tests on more object classes, e.g. vases, frescoes, etc.

The acquisition of objects is possible within tens of minutes which makes the system potentially useful to digitize several thousands of museum objects per year. The 3D model processing is performed after the data acquisition and is fully automated.

This research did not cover methods regarding how the digital models are treated after the reconstruction. Guidelines for archiving the digital data are suggested e.g. in [78–80]. Specifically the digitization of historical globes allows the creation of cartographic 2D maps as shown e.g. in [22–25].

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  - https://3d-forensics.de

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- The software tool kolibri MOBILE uses:
  - Agisoft Metashape Professional (Version 1.5.3)
  - BINGO (Version 7.1)
  - Picture Window Pro (Version 7.0)
  - Meshlab (Version v2016.12)
  - ExifTool (Version 10.67)
  - Poisson Surface Reconstruction [67]
  - 3D-VIZ CTRL

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