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ABSTRACT

Three-dimensional (3D) model is a major form of cultural heritage documentation. In most cases, the properties of digital artefacts (e.g. readability, coverage) are affected by the acquisition procedure (e.g. device, workflow, conditions) and the characteristics of the physical artefact (e.g. shape, size and materials). In this paper, we study how to combine two acquisition techniques to acquire detailed 3D models of large physical objects. Specifically, we combine two laser scanning instruments: Terrestrial Laser Scanning (TLS) and Structured Light Scanner (SLS). TLS provides millimeter-scale resolution with large field of view, while SLS provides sub-millimeter resolution for limited field of view. This paper focuses on the registration of SLS and TLS point clouds, a critical step which aims at aligning the acquired point clouds in a common frame. Existing registration systems mostly rely on manual post-processing or marker-based alignment. Manual registration is however time consuming and tedious, while markers increase the complexity of scanning and are not always acceptable in cultural site documentation. Therefore, we propose an automated markerless registration and fusion pipeline for point clouds. Firstly, we replace the marker-based coarse alignment by an automated registration of SLS and TLS point clouds; secondly, we refine the alignment of SLS point clouds on TLS data using the Iterative Corresponding Point algorithm; finally, we seamless stitch the SLS and TLS point clouds by globally regularizing the registration error for the all the point clouds at once. Our experiments show the efficiency of the proposed approach on two real-world cases, involving detailed point clouds correctly aligned without requiring markers or manual tuning. This paper provides an operational process reference for automated markerless registration of multi-source point clouds.

Keywords: heritage documentation; terrestrial LiDAR; structured light scanner; point clouds registration

1 Introduction

The digitalization of Cultural Heritage material is nowadays a common process, enabling long term archiving, simple sharing and digital presentation for research and diffusion to the general public [1]. Due to the rich information usually found in Cultural Heritage materials, e.g. fine and vivid work art, complex and diverse surface, 3D digitalization is today becoming the standard in most application cases, yielding important research efforts for the 3D modeling of Cultural Heritage content. Especially, the choice of a specific acquisition technique is a determining factor for the quality and properties of the virtual description of the Cultural Heritage artefacts. In some cases, it might be necessary to combine multiple acquisition techniques at once [2], which imply a final registration step to merge the heterogeneous data in a unique and consistent

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model.

The simplest form of 3D models is a set of 3D coordinates sampling an object surface, called a point cloud. Most acquisition techniques acquire physical objects as point clouds, e.g., laser scanners, structure from motion and structured light [3]. Laser scanning is nowadays a very common acquisition technique, and we refer the interested reader to the survey by Vacca et al. [4] on laser-based acquisition for Cultural Heritage applications. We consider in this work Terrestrial Laser Scanning (TLS). A TLS instruments can provide high precision 3D point cloud with millimeter accuracy over varying field of views. In practice, devices with large field of view (e.g., 360 degrees in the horizontal direction) have low horizontal sampling rate which reduces the amount of details acquired by the scanner. Structure from motion (SFM) extracts corresponding points from overlapping images and generates detailed 3D models [5], but without guaranteed accuracy and correctness [6]. Meanwhile, in some specific cases with high surface erosion and other defects, the lack of texture information might limit the efficiency of SFM techniques. Instead of relying on the surfaces textures, Structured Light Scanners (SLS) project light patterns on the object and obtains a point cloud model from distortions of the pattern [7-8], reaching submillimeter accuracy [9]. Compared with TLS, SLS can get more detailed 3D point clouds. However, due to their limited field of view, SLS instrument might require multi-station scanning to acquire large-scale objects or scenes.

This motivates the need of 3D registration techniques, which align several point clouds acquired from different points of view and/or with different instruments. Marker-based registration requires positioning artificial markers in scene, and then using these markers to find correspondences between several scans and align the associated point clouds [10]. In practice, complex scenes might require to set a large number of markers so they are visible in multiple scans. In addition to be time consuming, fixing markers on ancient objects might cause secondary damage to the cultural heritage site, which is obviously undesirable. Instead of using physical markers, several techniques automatically extract geometric features, assuming they will be detected consistently in the input point clouds and used as marker substitutes by the registration algorithms [11-12]. In practice however, descriptor-based approaches might not be robust to variations of noise, details and missing data, i.e. the defects that are usually occurring when processing point clouds generated by multiple acquisition systems [13]. Alternatively, exploration-based registration approaches explore the space of rigid transformations to find the configuration maximizing a given metric (e.g., overlap). The state-of-the-art algorithm is 4-Points Congruent Sets (4PCS) [14-15], which matches almost-planar 4-point basis in two input clouds. Despite its efficiency, this approach might in some cases require a lot of computational time [16]. More recently, the variant Super4PCS [17] greatly increased the computational efficiency of 4PCS by reducing the computational complexity required for the exploration.

We also refer the interested reader to the survey by Gomes et al [18], where the authors review the principal steps and associated challenges related to the acquisition and processing of 3D content for Cultural Heritage documentation. After acquisition and coarse registration, the 3D point clouds transformations need to be refined to avoid error accumulation occurring when combining multiple pairwise registrations.

2 Research aim

In order to obtain robust, accurate and detailed 3D models of cultural heritage sites in a non-destructive way, this work combine the advantages of TLS (e.g., large-scale) and SLS (e.g., accuracy) for 3D modeling of Longmen Grottoes. A TLS point cloud represents the whole cultural heritage site, and each SLS point cloud is a detailed part of it. These point clouds are aligned automatically by Super4PCS, and then pairwise registration and global regularization are applied to the point clouds to generate the final 3D models. The main contributions of this work is a practical system for the automated registration of multiple point clouds with

varying accuracy and sampling, allowing large scale acquisition of Cultural Heritage sites with locally detailed areas.

The rest of this paper is structured as follows: Section 3 describes the experimental material and the registration method of point clouds. The experimental results are presented and discussed in Section 4. Finally, the conclusions are stated in Section 5.

3 Material and methods

3.1 Data description

Excavation of Longmen Grottoes (Fig. 1) has been ongoing since 493 AD. It is one of three notable stone carving treasures in China and is known as one of the world's greatest classical art treasures. The site was placed upon the UNESCO World Heritage List in 2000, and the World Heritage Committee evaluated that Longmen Grottoes and Buddha is the largest and the most outstanding plastic arts from the later period of Northern Wei Dynasty to the Tang dynasty. These art pieces, which describe religious subjects of Buddhism in detail, represent the peak of Chinese art [19]. The protection of Longmen Grottoes has great significance for Chinese civilization and human art, and motivates its documentation and archiving.

In the past, manual measurement was the main way of cultural heritage information acquisition. In recent years, with the development of computer technology, photogrammetry, LiDAR, computer graphics and so on, protection of cultural heritage has progressed speedily, and displayed in the form of 3D model. 3D model has been widely applied in cultural heritage sites of the world by rich spatial information and the development of 3D information acquisition sensors [20-21]. However, because of long-term sunlight exposure, rain erosion and weathering factors, Longmen Grottoes statues have become so fragile that collapses occurred at any time. Therefore, high accuracy and non-destructive acquisition of 3D models is urgent for protection of Longmen Grottoes at present. Due to the fine and detailed structure information of Longmen Grottoes, the resolution of TLS is not enough to meet the demand; SLS has a higher resolution, but its field of view is limited, and multiple SLS point clouds registration easily produces cumulative error. Therefore, this paper combined the advantages of SLS and TLS to obtain 3D surface information of Longmen Grottoes statue.

The device parameters of SLS and TLS are shown in Table 1. For our experiments, we focused on one statue as experimental sample, and the height of the statue is nearly 0.6 m, the average width of the statue is nearly 0.3 m. 1 TLS point cloud and some SLS point clouds are acquired as follows (Fig. 2).

3.2 Method

In order to perform automated markerless registration of point clouds from TLS and SLS for heritage documentation, this paper studies the registration from three aspects: pairwise coarse and fine registration, and global regularization. Coarse registration processes pairs of point clouds to align them roughly; fine registration refines the rough transformation estimate; global regularization removes the cumulative error introduced when combining multiple pairwise registrations. The workflow is as shown in Fig. 3.

3.2.1 Coarse Pairwise Registration

The goal of the coarse pairwise registration step is to find the relative position of each SLS point cloud on the TLS point cloud. As previously stated, marker-based alignment can provide such rough estimate, however it increases the acquisition time and may damage the cultural heritage artefacts. Alternatively, we propose in this work to use the state of the art registration technique Super4PCS, an algorithm which computes the rough alignment between one *source* point cloud to a *target* point cloud. In order to align all SLS point clouds on the same reference frame, we sequentially register each SLS point clouds on the TLS point cloud.

Super4PCS estimates a coarse alignment between two point clouds by exploring the set of rigid transformations (rotations and translations) using the input point clouds as priors. More formally, it selects 4 almost coplanar points in the *target* point cloud to form a so-called 4-point basis. Then it looks for all 4-points configurations with similar geometric properties in the *source* point cloud. For each configuration, a geometric transformation candidate T_i is computed by aligning the 4-points to the basis in the *target* cloud. Super4PCS selects the transformation that maximizes the overlap between the *source* and *target* clouds. The input point clouds are locally overlapping if their distance is locally less than a given threshold. Considering that the TLS point cloud has been acquired with 5 millimeters precision, we set the overlapping distance threshold at 1 centimeter for all our experiments. We used the implementation provided by the OpenGR library [22] for our experiments (Fig. 4 (a)).

Fig. 4 (a) shows two results of coarse alignment between a SLS point cloud (white) and the TLS point cloud (red). Super4PCS outputs correct rough estimate of the transformations, i.e. the SLS point clouds are overall well positioned on the TLS point cloud, but still need to be further refined in a second step.

3.2.2 Fine Pairwise Registration

The goal of the fine pairwise registration step is to slightly move the SLS point clouds so they fit as much as possible the TLS point cloud. This is a very standard process in point cloud processing, also known as local pairwise registration. The reference algorithm to solve this problem is the Iterative Closest Point (ICP) algorithm that was proposed by Besl and Mckay [23]. ICP is an iterative algorithm that minimizes the distance between pairs or corresponding points in the two point clouds. The algorithm repeats the selection of corresponding points to compute an optimal rigid-body transformation until converging on accurate matching results. Several variants have been proposed under the name Iterative Corresponding Point (see recent survey by Pomerleau et al. [24]), and ICP is nowadays considered as a very mature algorithm, implemented in most 3D software.

In a nutshell, given a *source* point cloud (in our case, any SLS cloud) and a *target* point cloud (in our case, the TLS cloud), the ICP algorithm first establishes a set of pair-correspondences between points in two clouds. Then, it computes a 3D rigid-body transformation minimizing a given error metric between the corresponding points, e.g. the point-to-plane distance.

To be consistent with the parameters used during the coarse registration step, we set the ICP error threshold at 1cm, the maximum number of iteration to 20, and the convergence threshold $\eta = 1.0^{-5}$. We show in Fig. 4 (b) how ICP refines the transformations (we used CloudCompare [25] for our experiments).

In this example, ICP produces good results even if it has to solve a relatively large motion between the rough estimate and the target configuration (Fig. 4 (b)). As registration is performed only between each SLS point cloud and the TLS point cloud, there is no guaranty that two overlapping SLS point cloud will be well aligned by this process (in blue boxes of Fig.4 (b)). This motivates the need of final global regularization to minimize the registration error globally between all point clouds.

3.2.3 Global regularization

In order to ensure gapless registration, we propose to globally adjust the sequence of SLS point clouds and TLS point cloud with a large overlap. As some point clouds may overlap, and other not, we propose to build a pose graph (Fig. 5) as follow: each point cloud is a vertex in the graph (denoted TLSv_0 or SLSv_i), and two vertices are connected by an edge e_i if the associated point clouds are overlapping. As for previous stages, we consider that two clouds are overlapping if their local distance is less than 1 centimeter, and we request at least 30% overlap to create an edge. As the SLS point clouds have been registered to the *source* TLS point cloud in previous steps, it is very likely that all SLS v_i vertices are connected to TLSv_0 in the graph.

Once the graph is created, we use multi-view ICP [26], an extension of the ICP algorithm that minimizes the registration error between multiple point clouds at once. It follows the overall ICP algorithm, except that the error is computed for all pairs of points between all connected clouds. It outputs the set of transformations for all the movable vertices in the pose graph. In our case, all SLS vertices v_i are marked as movable, but not the TLSv_0, which defined the common registration basis for the whole dataset. We used the implementation by Glira et al [27], and use same stopping criterions as for fine pairwise registration. The result of global regularization is shown as Fig. 6.

4 Results and discussion

We evaluated our approach on two datasets, acquired on two different Buddha in Longmen Grottoes (see statistics in Table 2). Each dataset is composed by one reference TLS point cloud spanning the whole scene, and multiple SLS point clouds detailing parts of the scene. The variations of sampling and amount of details between the SLS and TLS point clouds are shown in Fig. 7.

In this section, we evaluate each step of our approach on scene 2 that we believe challenging, considering:

1) The symmetry of the scene, which may introduce ambiguities at the coarse registration step,
2) The large feature-less regions that prevent to use descriptor-based alignment, and,
3) The variation of sampling and level of details between the SLS and TLS point clouds.

We also demonstrate in supplementary materials how our approach performs on scene 2. All our experiments have been performed on an Intel Xeon E5-2640 2.40GHz with 40 cores. We emphasis that both the coarse and fine registration steps can be ran in parallel, in order to align each SLS point cloud to the TLS reference point cloud simultaneously. We used single thread Matlab implementation [29] for our experiments, and better performances can be expected with optimized code. For our experiments we stop the ICP iterations when the registration error increases. As shown in Table 2, computing the coarse alignment between all clouds in parallel takes 2m15s with our setup, for 91m30s of total processing time. In addition, TLS point cloud and all SLS point clouds of all scenes were re-sampled according to the voxel size of 1 mm for the global regularization.

4.1 Coarse and fine pairwise registration

To evaluate the robustness of the coarse registration step, we used a fixed set of parameters for the whole dataset: target overlap 90%, registration tolerance 5mm, and 2500 samples per point cloud. Registration results are shown in Fig. 8. 39 SLS point clouds were correctly registered (in white, Fig. 8(a)), and 2 SLS point clouds were not correctly registered (in yellow, Fig. 8 (b-c)).

As shown in Fig. 8 (c), the two SLS point clouds describe mostly flat surfaces with low but regular curvature. The Super4PCS algorithm finds the transformation that maximizes the overlap between the two input clouds given the input tolerance value. In these two cases, it appears that this metric is not enough to distinguish between the correct pose and the found pose, where the SLS point cloud spans a part of the TLS point cloud. In practice, these two failure cases might be corrected by adjusting the Super4PCS parameters; we obtained good results by reducing the target overlap to 80%.

In summary, except for two features-less point clouds, all of the SLS point clouds can be registered with the TLS point cloud, which shows the high reliability of the Super4PCS algorithm for coarse registration. Also, in all cases we could refine the estimated transformation using ICP (see Section 3.2.2).

4.2 Global regularization

During the coarse alignment and fine registration steps, each SLS point cloud is registered to the reference TLS point cloud, without considering the registration error between adjacent SLS point clouds. In practice,

these gaps do not meet the standard of heritage documentation, and a global regularization is required.

In this section we evaluate the influence of the TLS point cloud in the global regularization step. In Fig. 9(a), we show results of scene 1, where only SLS point clouds are considered in the global regularization graph. The goal of this experiment is to simulate the registration of detailed point clouds without using a reference point cloud. Unsurprisingly, the SLS point clouds are correctly aligned, but the surface they describe deviates from the TLS point cloud: registration error is accumulated and the overall registration quality is reduced even if the registration error remains low.

On the other hand, we show in Fig. 9 (b) how using the TLS point cloud as reference greatly improves the registration result. By combining SLS-SLS and SLS-TLS registration at once, our approach provides point clouds with low local and global registration error.

5 Conclusions

The paper researched an automated markerless registration of SLS point clouds and TLS point cloud for the heritage documentation of Longmen Grottoes Buddha from three aspects: coarse alignment, pairwise registration, and global regularization. Our experiments showed that the SLS clouds can represent accurate surface information of Buddha, but may lead to high accumulative error due to the registration process. On the other hand, the TLS could get a whole 3D model of Buddha with one scanning, but the surface information is not detailed enough. The combination of SLS and TLS could not only represent details for the whole Buddha site, but also remove the accumulative error of a sequence of SLS point clouds registration. Besides, automated markerless registration approach reduced dependence on artificial markers and manual work, which improved the work efficiency. The proposed method provides an operational pipeline reference for automated markerless registration of multi-source point clouds. All our experiments were performed using available processing tools, and we will provide macros and scripts as reference for workers of digital documentation of heritage and point cloud processing.

The main aim of this research is to explore an automated markerless registration approach of point clouds for heritage documentation. The first step of our pipeline, i.e., coarse alignment, is a key factor in automated registration of point clouds. In case of feature less surfaces, it might however fail in some cases and becomes the main limitation for the high success rate of registration. In future work, we will focus on reducing the sensitivity of parameters which influence the success rate of coarse alignment and thus improving the success rate of the overall pipeline.

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Figure captions

Fig.1. Longmen Grottoes.
Longmen Grottoes is one of three notable stone carving treasures in China and is known as one of the world's greatest classical art treasures. The World Heritage Committee evaluated that Longmen Grottoes and Buddha is the largest and the most outstanding plastic arts from the later period of Northern Wei Dynasty to the Tang dynasty.

Fig. 2. Point cloud of Longmen Grottoes statue.
(a) shows two SLS point clouds of a statue; (b) shows one TLS point cloud of a statue.

Fig. 3. The registration pipeline and overview.
(a) shows the schematic view of the registration pipeline; (b) shows the overview of the registration pipeline from a data perspective, which includes four steps: (1) input, (2) coarse registration, (3) fine registration, and (4) global registration. The input consists of two types of point clouds: one sparse (TLS, in orange) and multiple dense (SLS). After fine registration between each SLS point clouds and the TLS reference point clouds, misalignments between SLS point clouds (black circle in the figure of fine registration) are solved by the process of global registration.

Fig. 4. Results of Super4PCS and fine pairwise registration.
(a) shows the result of Super4PCS, which estimates the transformation between each SLS point clouds (white) and the TLS point cloud (red); (b) shows the result after fine pairwise registration, where the transformations are refined with ICP. Note that the overlapping parts (blue box) may not be properly aligned as the error between the SLS point clouds is not considered for these two steps.

Fig. 5. Pose graph of global regularization.
SLS point clouds $\{v_1, v_2, v_3 \ldots v_n\}$ are overlapping with the TLS point cloud and thus connected to v_0. Also, all pairs of SLS point clouds with at least 30% overlap are connected in the graph.

Fig. 6. Global regularization results.
(a) shows the result of 16 SLS point clouds registration; (b) shows the TLS point cloud; (c) shows TLS and SLS point clouds in the same frame.

Fig. 7. The variations of details between SLS and TLS point cloud.
SLS point cloud (a) and TLS point cloud (b) from scene 1 rendered with Radiance Scaling [28].

Fig. 8. Results of coarse alignment.
(a) shows correct coarse alignment between each SLS point cloud and TLS point cloud; (b) shows incorrect coarse alignment; (c) shows the 2 incorrect SLS point clouds.

Fig. 9. Results of global regularization.
(a) shows the global regularization result of only SLS point clouds, (a-1) and (a-2) show the horizontal and vertical cross section of point cloud in yellow box, respectively; (b) shows the global regularization result combining TLS with SLS point clouds, (b-1) and (b-2) show the horizontal and vertical cross section of point cloud in yellow box, respectively. (TLS in red; SLS in white)

Tables

Table 1

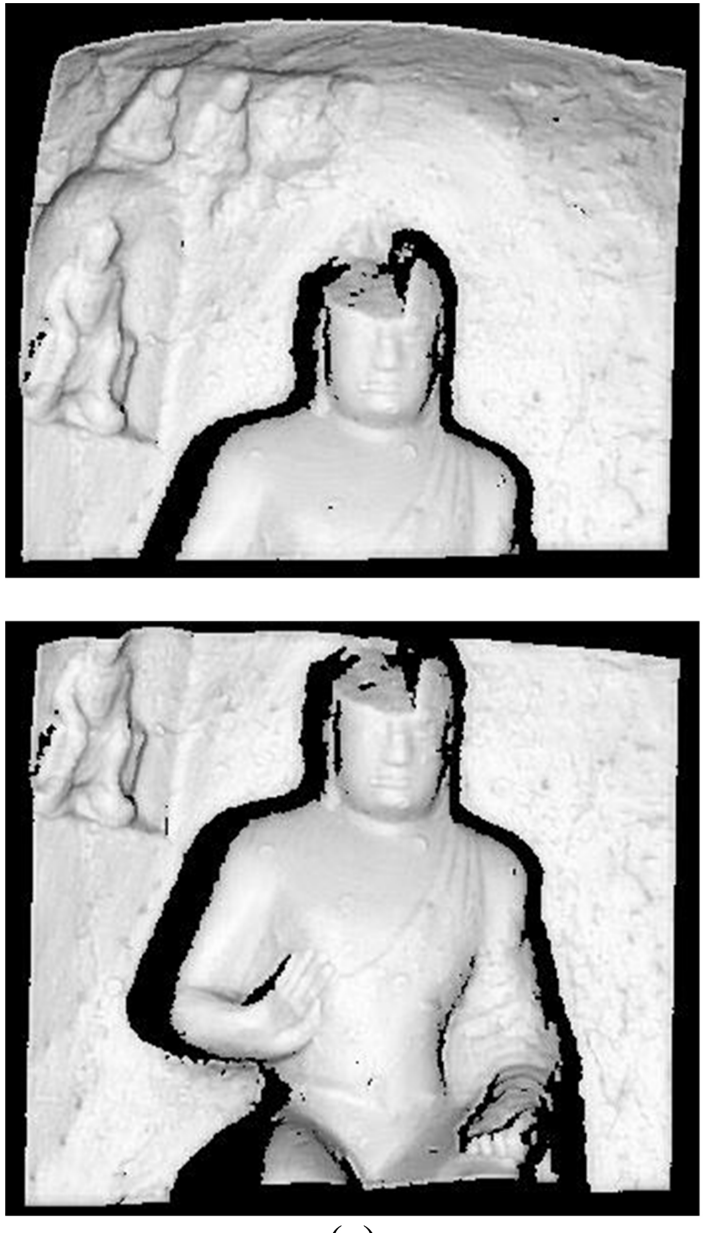
Device parameters

Parameters	SLS	TLS
Model	OKIO-5M-400	RIEGL VZ-1000
Max measure distance	1.5 m	1,200 m
Field of view	0.4m × 0.3m (at max distance)	100° × 360°
Measure precision	0.015 mm	5 mm

Table 2

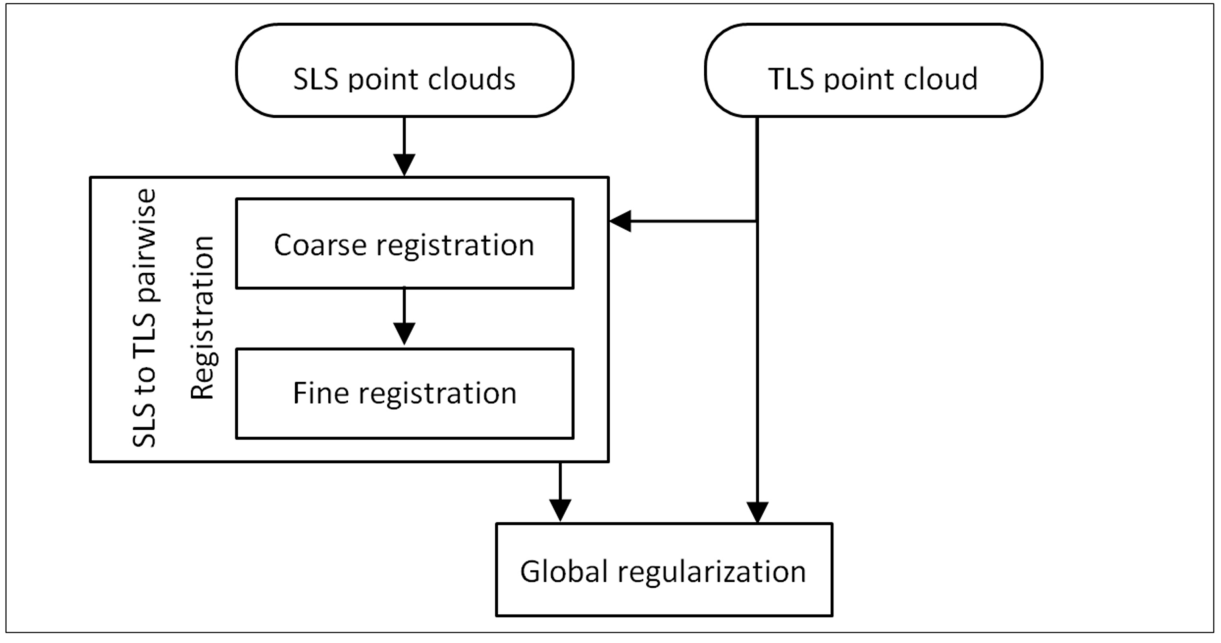
Datasets properties and processing time. For the coarse alignment and fine registration steps, we detail for each scene the processing time needed to register the SLS point cloud on the TLS point cloud in parallel, and the total time when registering the SLS point clouds sequentially on a single processing unit.

	SLS point clouds		TLS point cloud	Processing time – pairwise (total)		
	#clouds	#vertices/cloud	#vertices	Coarse registration	Fine registration	Global regularization
Scene 1	16	859,774	2,777,511	1m10s (18m40s)	3.1s (50s)	12.7m
Scene 2	41	926,830	2,732,000	2m15s (91m30s)	4.8s (3m20s)	27.5m

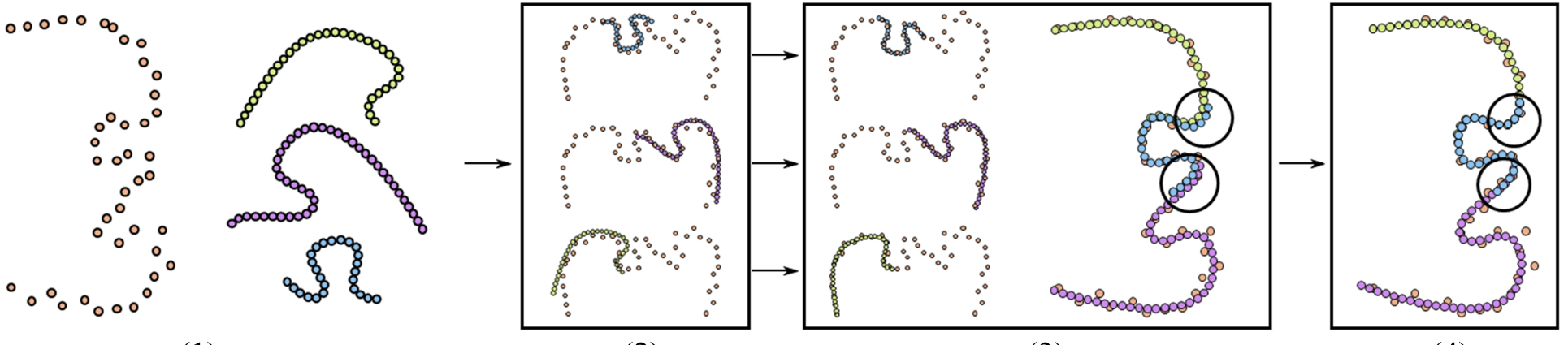


(a)

(b)

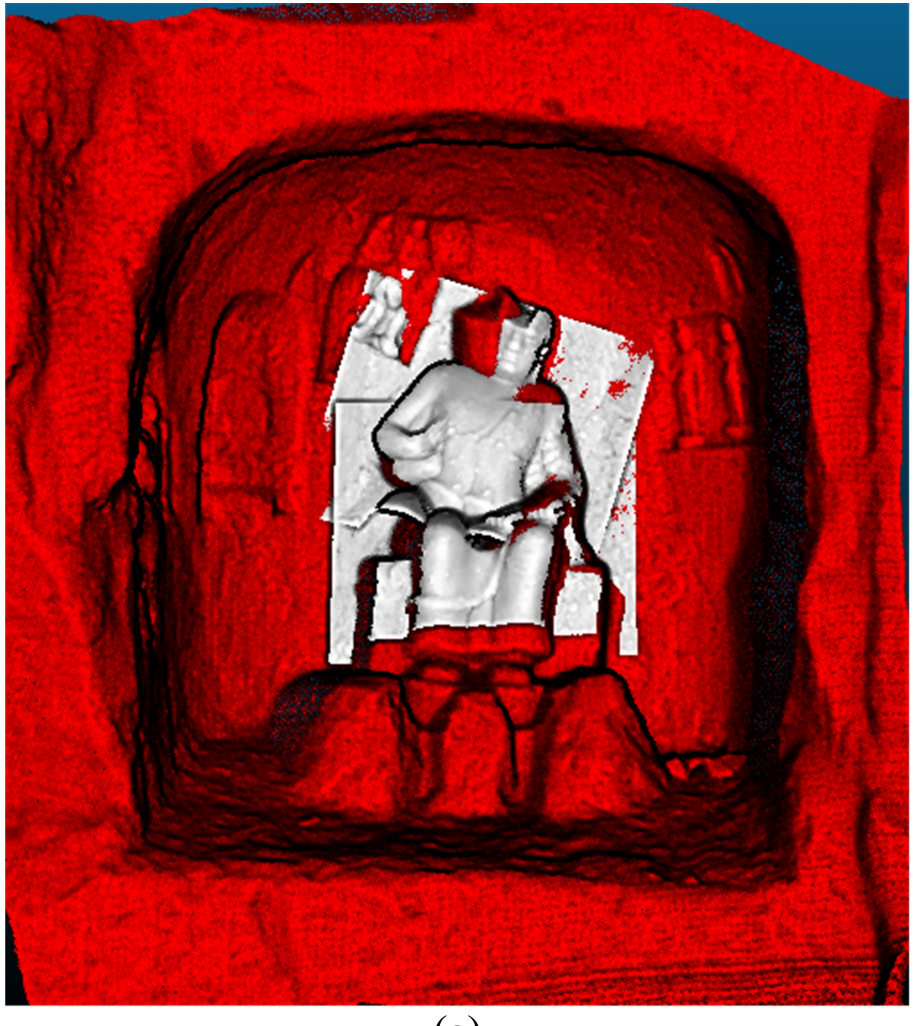

SLS point clouds
TLS point cloud
SLS to TLS pairwise Registration
Coarse registration
Fine registration
Global regularization

(a)

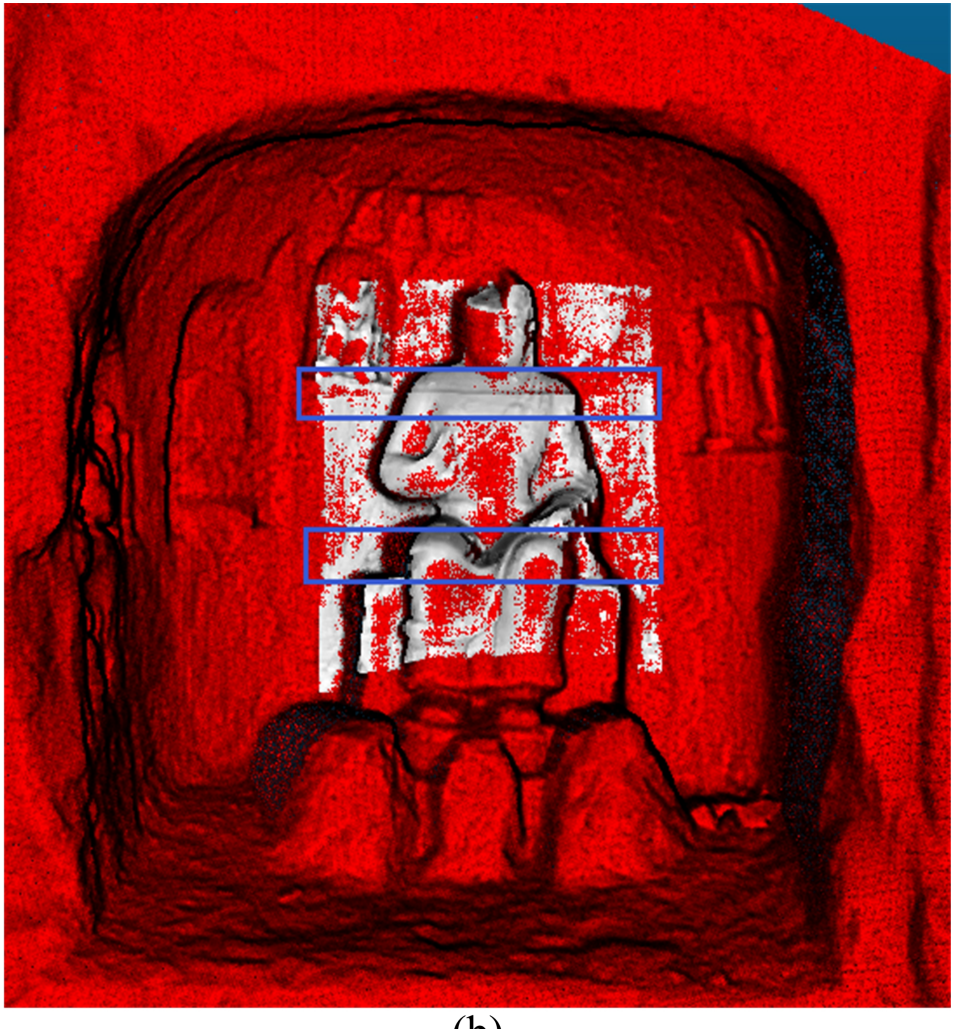


(1) (2) (3) (4)

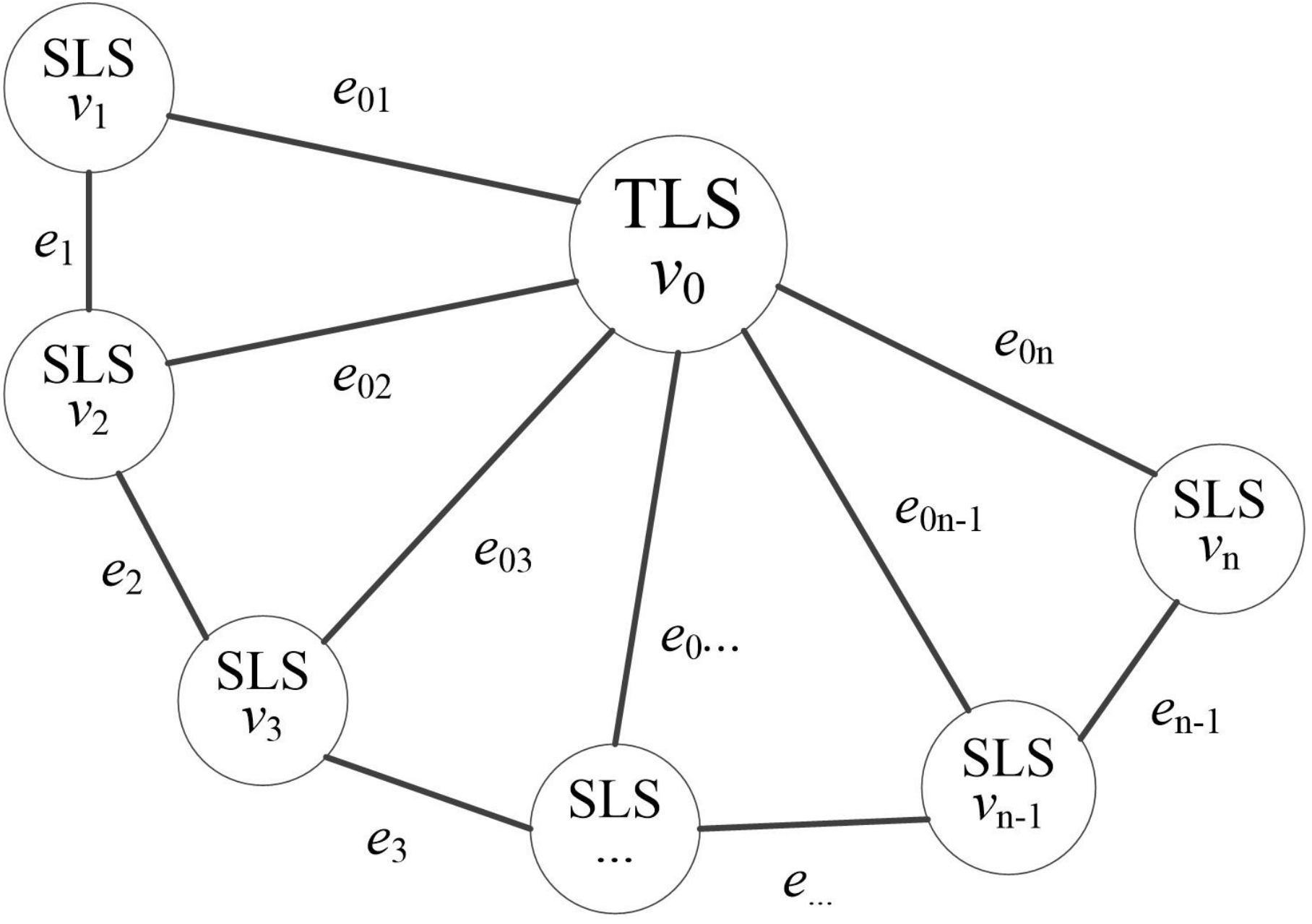
(b)

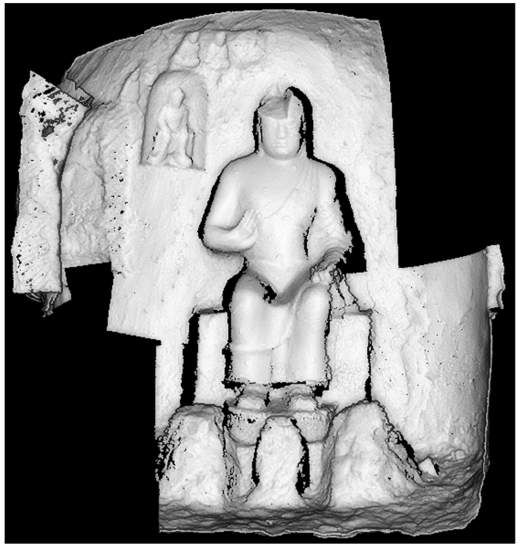


(a)

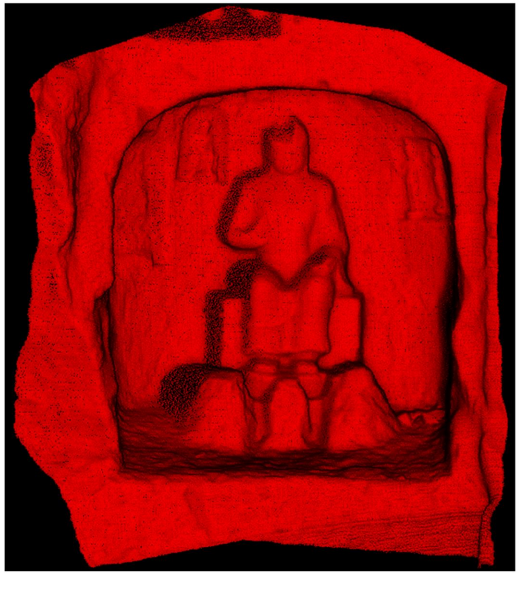


(b)


SLS
v_1
e_{01}
TLS
v_0
e_1
SLS
v_2
e_{02}
e_{0n}
e_2
e_{03}
e_{0n-1}
SLS
v_n
$e_{0\dots}$
SLS
v_3
e_{n-1}
SLS
v_{n-1}
SLS
...
e_3
$e_{\dots}$

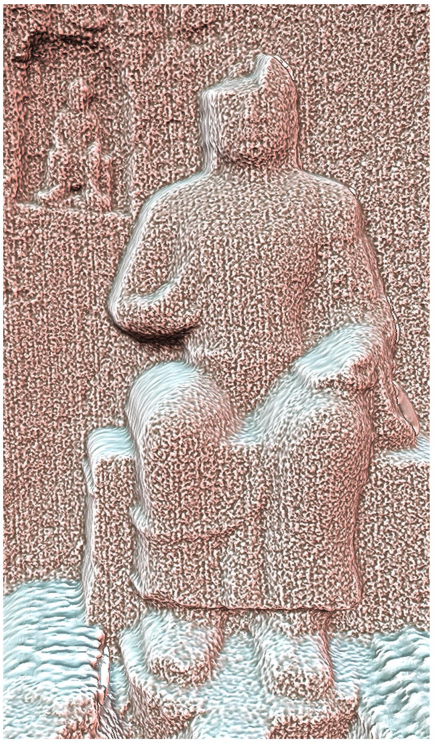


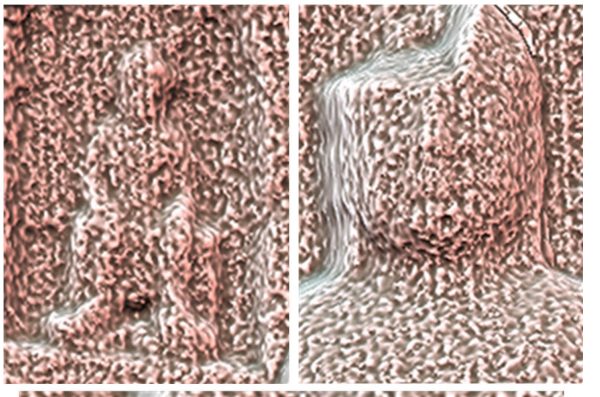
(a)

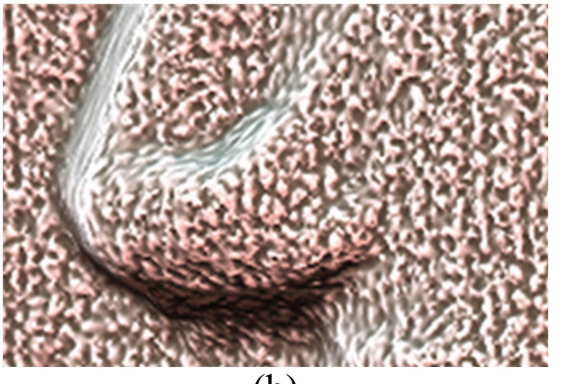


(b)

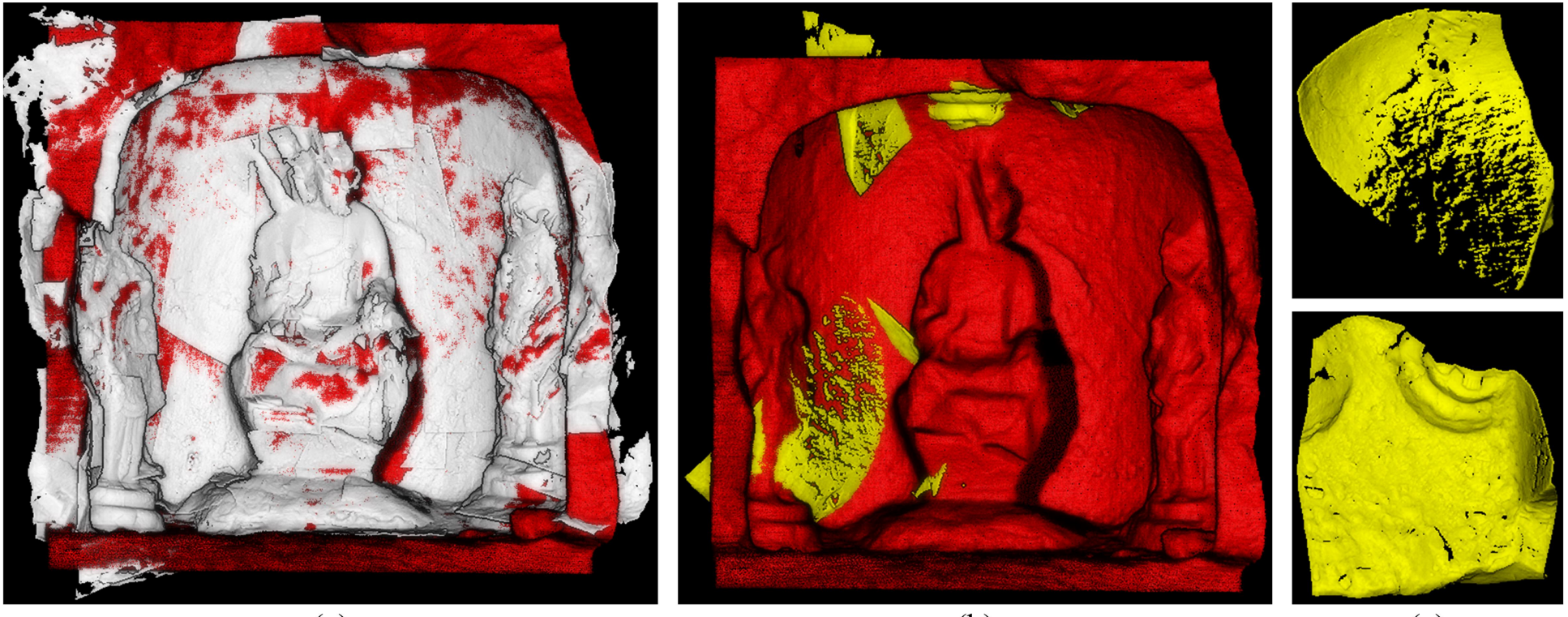
(c)



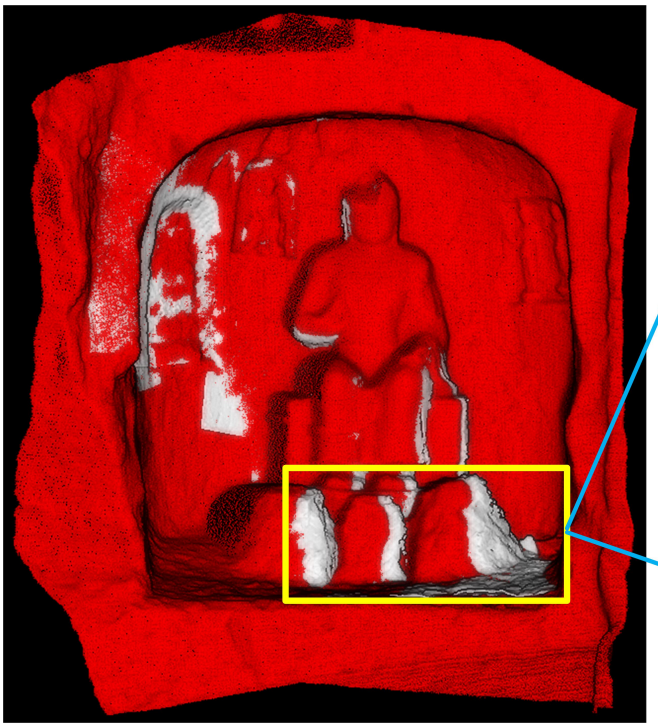


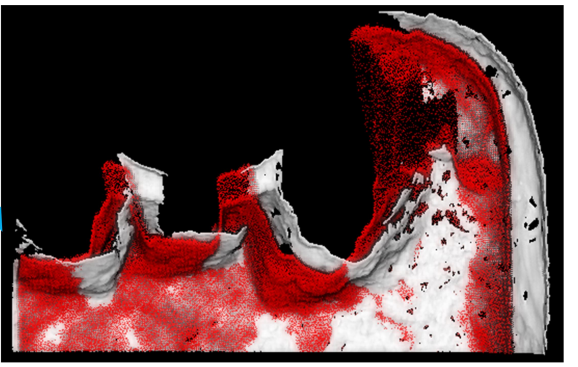


(a) (b)

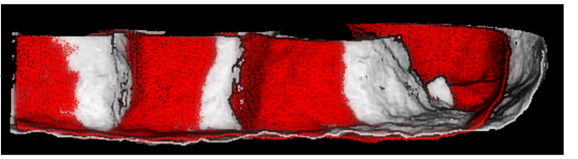


(a) (b) (c)



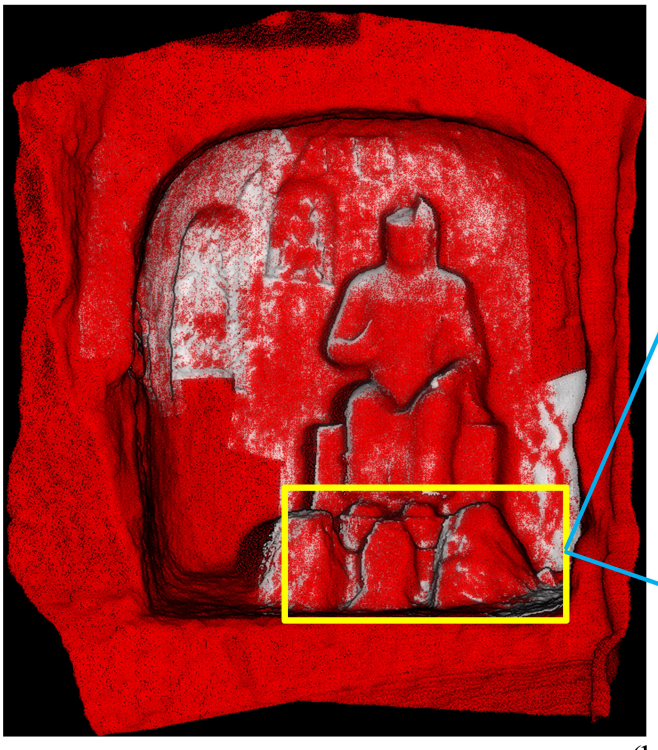


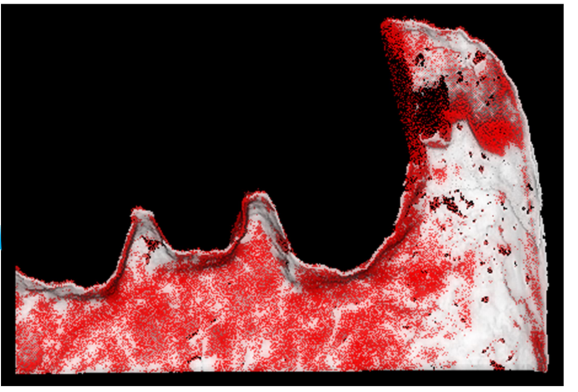
(a-1)



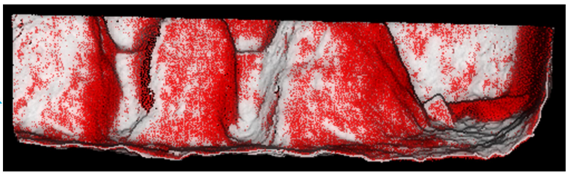
(a-2)

(a)





(b-1)



(b-2)

(b)