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Three-Dimensional Modelling and Visualization of Stone Inscriptions Using Close-Range Photogrammetry—A Case Study of Hero Stone †

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Abstract: Stone inscriptions and archaeological structures are an asset to humankind which contain the history of the past. Estampage is the traditional method used to obtain the replica of the inscriptions which is primarily used to decrypt texts and for documentation purposes. Presently, close-range photogrammetry is a useful remote sensing technique to digitize these inscriptions for study as well as preservation. The current study focuses on the creation of a 3D model of a hero stone using digital camera technology. These photographs were acquired using a Sony Alpha7 III camera with a 35 mm full-frame CMOS sensor. Two hundred and sixty-one images/frames were acquired from different heights above ground and with various positions and angles around the stone inscription to cover it all around. The data acquired were processed in a series of steps which included image matching, dense point cloud generation, mesh reconstruction, and texturing of the model. As the sensor is non-metric, two markers acquired from the field were added to the scene to scale it accurately. The dimensions of the hero stone are computed as 2.3 × 1.3 ft and the resulting model had a reprojection error of less than 0.011 pixels. The processed model has 10,915,514 facets (TIN) and 8000 × 8000 × 4 textures providing a realistic appearance. The recent developments in computer vision using the structure from motion (SfM) approach enables the reconstruction of the hero stone accurately with realistic textures and details useful for preservation work.

Keywords: close-range photogrammetry; inscriptions; digital documentation; structure from motion; heritage preservation

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1. Introduction

Letters inscribed or engraved commonly on stone, marble, metal, terracotta, or wood are called inscriptions. As a crucial historical source, inscriptions are texts found on stone (Pillars, Walls), metal (Copper plates), or other materials (Bronze coins) in temples, monuments, and historic places. They provide proof of the existence and operations of ancient rulers and empires including detailed specific religious practices. Epigraphy is the study of inscriptions or the science of identifying a grapheme of a particular script. A hero stone is a memorial that is dedicated to eternalizing the honorable deaths of heroes specifically illustrating the scenes of battle. The current hero stone which is documented was originally found in Halebidu, Karnataka. It is preserved in the Bengaluru Govt Museum, Bengaluru, Karnataka [1].

Estampage or stamping is the traditional method of creating a replica of an inscription used to decipher the script. However, preserving estampages is a challenging task as they fade away with time. Digital heritage [2] will help us in proper conservation as well as in detail preservation which can also be used for deciphering texts and studying them [3]. Hence, digitally preserving them would act as a suitable alternative to save them for future generations [4]. In this study, we used close-range photogrammetry as the primary tool for digitally documenting the hero stone. We can carry out this activity precisely by having a basic setup of gears such as a camera, lights, and measuring tools. Once the data are processed, we can visualize them as a three-dimensional model

2. Study Site and Dataset

The hero stone (Figure 1) documented in this study was originally found in an archaeological site of Halebidu, Karnataka, which was later shifted to the Bangalore Government Museum, Bengaluru. This hero stone dates to the time of Hoysala king Vishnuvardhana in the 12th century AD [5]. It is situated in an open area on the grounds of the museum where it is preserved carefully. A mirrorless digital camera was chosen to scan the hero stone and acquire the datasets.

Figure 1. Depiction of the perspective view of the hero stone.

3. Methodology

The first task of this study was to conduct a preliminary field survey/reconnaissance survey to understand the hero stone's location, lighting, and a few other basic data variables for the planning of image acquisition. A mirrorless camera with a 35 mm full-frame CMOS sensor of the Sony Alpha III model was used to scan hero stone. To capture the entire area, 261 photos were taken from various heights and angles, above ground and in various positions relative to the stone inscription. As the hero stone is situated outside the museum, natural lighting was sufficient to carry out photography. Furthermore, the dimensions of the hero stone were recorded on the field. These measurements are very important for scaling the model in the processing stage. Figure 2 shows the methodology used for the processing of the datasets.

All the data were transferred into the workstation and were well organized before processing in Agisoft Metashape in the 30-day free trial mode to process the dataset as a chunk. Before processing the images, there are several steps to be analyzed such as image alignment, dense point cloud generation, model texture generation, scaling of the model, and simplification [6].

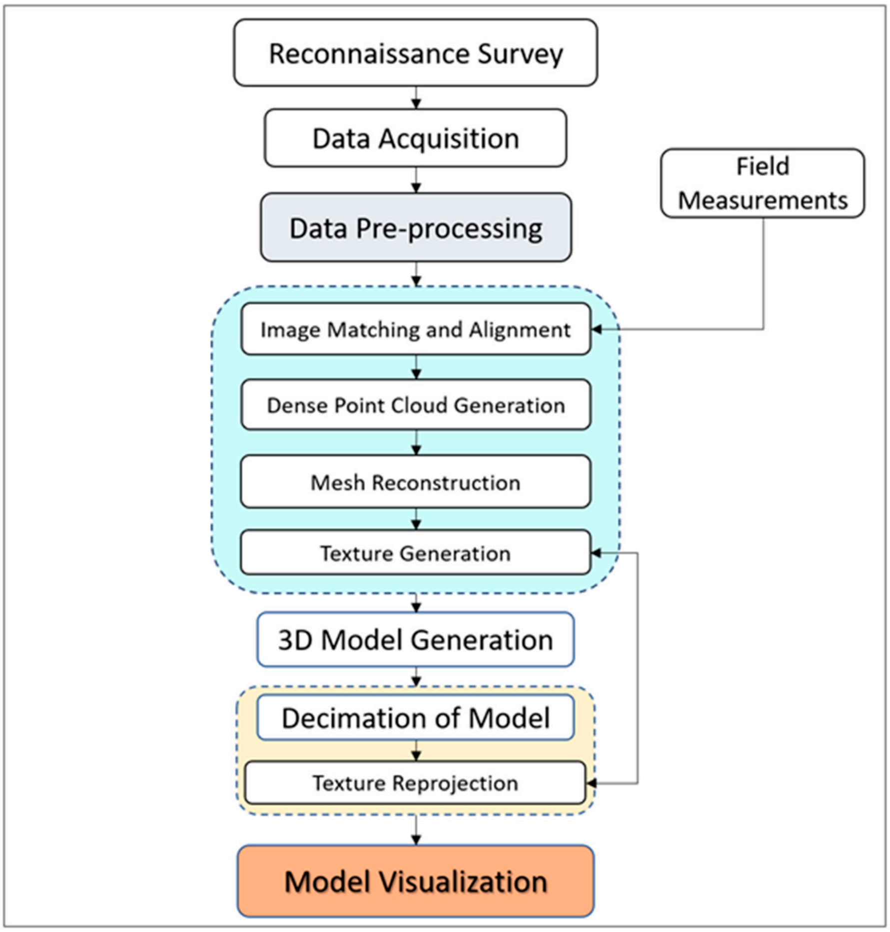


Figure 2. Methodology flowchart.

Ref. [7] Processing of the dataset was completed on a computer with 16 GB of RAM and 4 GB of graphics memory with an i-core 7 processor. The images should not be geometrically transformed in any way such as being cropped, rotated, resized, etc., because the software can process only unmodified photos as they were taken by a digital photo camera. The processing of manually cropped or geometrically distorted photographs is likely to fail or generate very erroneous results.

3.1. Image Matching and Alignment of the Dataset

The images were imported into Metashape as chunks, and separate chunks can be constructed for different datasets. The software examines the camera position at the instant an image is acquired, which is determined by the interior and exterior orientation parameters, at this stage. Interior orientation factors include camera focal length, image principal point coordinates, and distortion factors for lenses. Aerotriangulation is used to calculate the exterior and interior image orientation parameters with bundle block adjustment based on collinearity equations. Aerotriangulation enables onboard measurements and photogrammetric measurements of tie points to be collaboratively adjusted. As a result, exterior orientation characteristics for images are more precisely and consistently determined [8]. A sparse point cloud containing triangulated coordinates for matching image points and estimated exterior (translation and rotation) and interior camera orientation parameters make up the output of this processing stage. There were 134,364 tie points produced as a result of setting the parameters for this alignment stage to medium precision and generic preselection, along with a sparse point cloud of the scene. However, it is possible for blurring or insufficient overlap between the photos to occur when taking pictures, which could have a negative impact on the outcome.

3.2. Building of Dense Point Clouds Using Input Camera Data

This step comprises the matching and detection of feature points. The tie-points data will then be represented in 3D as a sparse point cloud as a result. To generate dense point clouds, dense stereo matching is used to construct depth maps [9]. For the overlapping picture pairs, depth maps are produced taking into account the relative exterior and interior orientation parameters obtained with bundle adjustment. To create a combined depth map, multiple pairwise depth maps created for each camera are put together. In this work, 261 ultra-high depth maps were produced using a mild filtering method, employing the color values of neighboring images and their pixels.

3.3. Mesh Reconstruction Based on Depth Maps

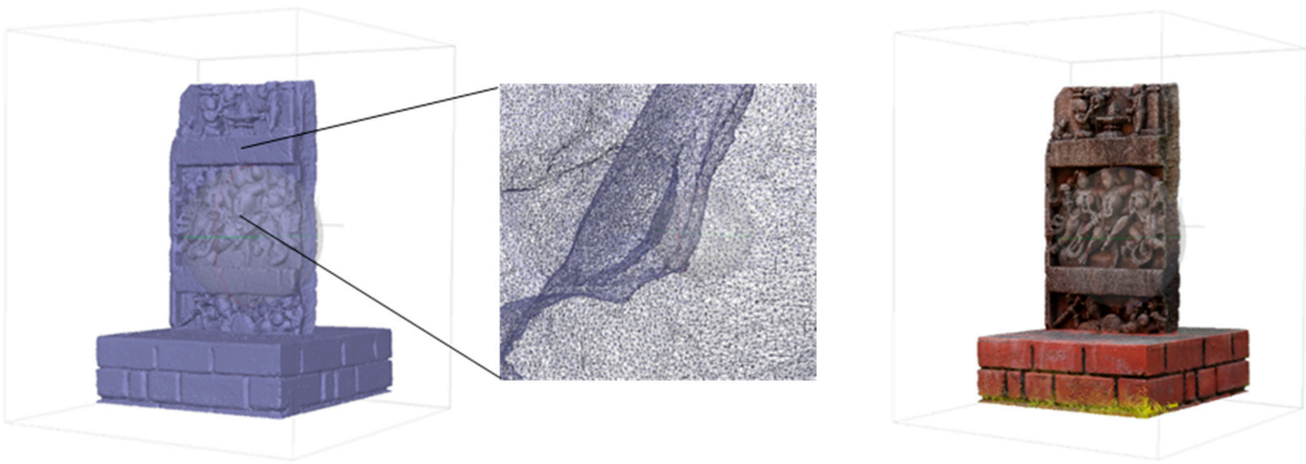
The software can reconstruct polygonal mesh models using depth map data or point cloud data (including dense, sparse, and point cloud data imported from external sources). In this study, depth maps were used as the input for generating mesh [10]. These inputs generate a depth map, where each pixel indicates how far it is from the camera. The technique also generates high-quality maps that show us how many views each pixel was correctly matched to. The depth maps are used as an input to the mesh generation which will be discussed in this step. A 3D range grid is back-projected onto each depth map. By joining nearby vertices on the grid, a rough mesh is created. All depth maps' vertices are combined and fed into the reconstruction method. This technique creates a triangulated surface that is impervious. The reconstruction algorithm assumes a whole, closed surface and fills in low point density regions with several triangles. Compared to dense cloud-based reconstruction, the depth maps setting makes better use of all the information from the input photos and uses fewer resources. Usually, this setting is used for arbitrary surface type reconstruction. Any form of an object can be modelled using any arbitrary surface type. It is typically chosen for enclosed items such as sculptures, structures, etc. It produces a high-quality mesh since it does not make any assumptions about the kind of object being modelled. The quality of the model will increase as the number of photographs increases, but it still will not be enough because the final mesh will always contain topology defects.

3.4. Texture Generation and Decimation of the Model

Using images as the source data and generic mapping mode, 8000 $\times$ 8000 $\times$ 4 textures were generated which gave a realistic view of the model. The final model generated was too high to visualize and hence it was decimated to 50,000 polygons including vertex color [11]. The original textures were reprojected onto this decimated model to regain its realistic view. A precise scale bar was made by placing two markers in the scene to reduce the model to its actual size.

4. Results and Discussion

Figure 3 shows a reconstructed mesh with TIN (a), and a 3D model with textures (b) of the hero stone. The processed model has 10,915,514 facets (TIN) and 8000 $\times$ 8000 $\times$ 4 textures providing a realistic appearance which was further reduced to 50,000 polygons and re-projected the same textures onto the model [12]. Two markers were placed in the scene and a scale bar was generated for which field measurements were used to scale it down to its actual size [13]. Table 1 shows the accuracy, projections, and errors in pixels of the two markers. Due to the high geometry of the model obtained, the errors were less than 0.1 pixels [14]. Figure 4 shows the results of the filter applied to the inscriptions. These models are ready to export for further analyses to any software desired.



(**a**) (**b**)

Figure 3. Reconstructed mesh with TIN (**a**); 3D model with textures (**b**).

Table 1. Accuracy of control points.

Markers	X Err (m)	Y Error (m)	Z Error (m)	Accuracy	Error	Projections	Error (pix)
Point 1	−0.328100	0.141343	0.028392	0.005000	0.358377	110	0.011
Point 2	−0.327890	0.121376	0.049821	0.005000	0.353166	98	0.011
Total Error of Control Points	0.327995	0.131738	0.04058		0.355781		0.011

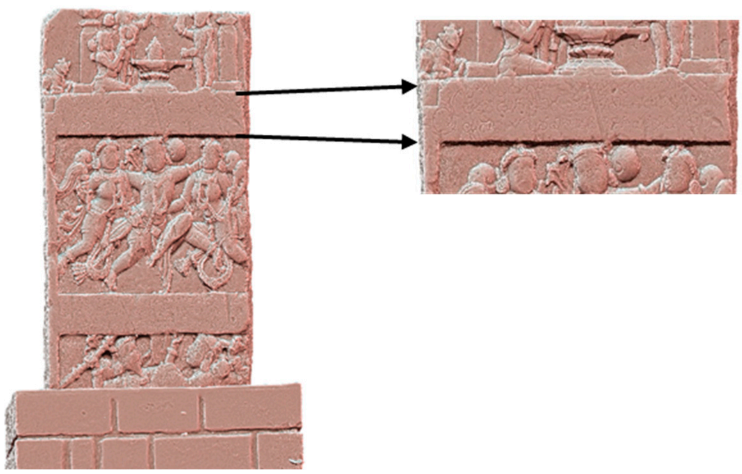


Figure 4. 3D model enhanced for readability.

5. Conclusions

This study reveals that the SfM-based 3D models are a low-cost alternative to the 3D modelling of a hero stone and in general for any structure with a good texture [15]. This method can be used in a variety of disciplines, each with its own applicability and ease of implementation. Heritage is explained in UNESCO documents as "our legacy from the past, what we live with today, and what we pass on to future generations" [16]. Heritage is anything that is respected and passed down from one generation to the next. Intangible or tangible, any form of heritage in an analogue state can be converted to a digital form using computer processing and other techniques for future preservation [17]. The results which are obtained here are accurate to a few cm level and these models can be used to study and decipher texts as well as preserve them digitally [18]. The output of the model has a variety of options to export such as .obj, .fbx, .stl, etc. Options such as STL (stereolithography) can be used to 3D print the same model with textures. Hence, close-range photogrammetry can be one of the best methods to record, handle, and process data for the preservation of heritage [19].

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