SURFACE RECONSTRUCTION ALGORITHMS FOR DETAILED CLOSE-RANGE OBJECT MODELING

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ABSTRACT

Nowadays 3D modeling is generally performed using image or range data. Range sensors are getting a quite common source of data for modeling purposes due to their speed and ability to capture millions of points. In this paper we report about two surface measurement algorithms for precise and detailed object reconstruction from terrestrial images. Photogrammetry has all the potentialities to retrieve the same details of an object that range sensors can achieve. Using advanced measurement techniques, which combine area-based and feature-based matching algorithms we are able to generate dense point clouds of complex and free-form objects, imaged in closely or widely separated images. Different examples are reported to show the potentiality of the methods and their applicability to different close-range data sets.

1. INTRODUCTION

Three-dimensional modeling from images is a great topic of investigation in the research community, even if range sensors are becoming more and more a common source and a good alternative for generating 3D information quickly and precisely. 3D modeling of a scene should be meant as the complete process that starts with the data acquisition and ends with a virtual model in three dimensions visible interactively on a computer. The interest in 3D modeling is motivated by a wide spectrum of applications, such as animation, navigation of autonomous vehicles, object recognition, surveillance, visualization and documentation.

In the last years different solutions for image-based 3D modeling have been developed. Most of the current reliable and precise approaches are based on semi-automated procedures, therefore the introduction of automated algorithms is a key goal in the photogrammetric and vision communities. 3D modeling methods can be classified according to the level of automation or the required input data while their strength is reflected by the variety of scene that can be processed and the level of detail that can be reconstructed.

The common fully automated 'shape from video' framework [e.g. Fitzibbon & Zisserman, 1998; Nister, 2001; Pollefeys et al., 2004] requires good features in the images, very short baseline and large overlap between consecutive frames, requirements which are not always satisfied in practical situations, due to occlusions, illumination changes and lack of texture. So far, automated surface reconstruction methods, even if able to recover complete 3D geometry of an object, reported errors between 3% and 5% [Pollefeys et al., 1999], limiting their use for applications requiring only nice-looking 3D models. Furthermore, post-processing operations are generally required, which means that user interaction is still needed. Indeed the most impressive results are achieved with interactive methods and taking advantage of the environment constraints, in particular for architectural objects. For different applications, such as cultural heritage documentation, semi-automated methods are still preferred as smoothed results, missing details or lack of accuracy are not accepted.

In this article we report about two surface matching algorithms developed for the precise and detailed measurement and 3D modeling of complex and free-form terrestrial objects, like pots, reliefs, statues, façades, etc. Commercial photogrammetric stations generally fail with tilted close-range images, therefore the topic still need some developments. We will concentrate only on the measurement of the object surface, assuming the calibration and orientation of the images already performed. As the network configurations that allow full and precise camera calibration are usually very different from those used for scene reconstruction, we generally first calibrate the camera using the most appropriate set of images and afterwards recover the orientation parameters of the scene's images using the calibration results. The orientation is generally performed by means of a photogrammetric bundle adjustment, extracting the required tie points with automated approaches [Remondino & Ressl, 2006] or manual measurements.

The first surface measurement algorithm presented afterwards matches the points in image-pairs, the second one works simultaneously with many images. Both methods require some seed points between the images at the beginning of the process, to initialize it and improve the performances near surface discontinuities. The seed points can be provided manually (stereo or monocular measurements) or extracted automatically, leading to a fully automated surface reconstruction method. The number of seed points depends on the set of images, their disparity and texture content. Starting from these seeds points, a dense and robust set of correspondences covering the area of interest is generated.

Our research aims to combine area-based and feature-based matching techniques to recover complete and detailed 3D surfaces. The methods can cope with depth discontinuity, wide baselines, repeated pattern, occlusions and illumination changes.

In the next sections, after an overview of image-based modeling works and matching strategies, the two matching strategies are described in details. Then some examples demonstrating the potentialities of the algorithms and their applicability to different close-range data sets are reported and discussed. Results in form of 3D point clouds, shaded and textured 3D models are shown.

2. 3D MODELING FROM IMAGES

Recovering a complete, detailed, accurate and realistic 3D model from images is still a difficult task, in particular if uncalibrated or widely separated images are used. Firstly because the wrong camera parameters lead to inaccurate or deformed results. Secondly because a wide baseline between the images generally requires the user interaction in the measurement phase.

The research activities in terrestrial image-based modeling can be generally divided in area-based [e.g. Pollefeys et al., 2004] and feature-based [e.g. Schmid & Zisserman, 2000] methods. A more detailed classification of point-based methods is:

1. *Approaches that try to get automatically a 3D model of the scene from uncalibrated images* (also called 'shape from video' or 'VHS to VRML' or 'Video-to-3D'). The fully automated procedure widely reported in the vision community [Fitzibbon & Zisserman, 1998; Pollefeys et al., 1999; Nister 2001; Mayer, 2003] starts with a sequence of images taken with an uncalibrated camera. The system then extract interest points, sequentially match them across the view-pairs and compute the camera parameters as well as the 3D coordinates of the matched points using robust techniques. This is done in a projective geometry framework and is usually followed by a bundle adjustment. A self-calibration, to compute the interior camera parameters, is afterwards performed in order to obtain a metric reconstruction, up to a scale, from the projective one. The 3D surface model is then automatically generated by means of dense depth maps on image pairs. See [Scharstein & Szeliski, 2002] for a recent overview of dense stereo correspondence algorithms. The key to the success of these automated approaches is the very short interval between consecutive images. Some approaches have been also presented for the registration of widely separated views [Pritchett & Zisserman, 1998; Matas et al., 2002; Xiao & Shah, 2003; Lowe 2004] but their reliability and applicability for automated image-based modeling of complex objects is still not satisfactory, as they yield mainly a sparse set of matched feature points. Dense matching results under wide baseline conditions were instead reported in [Megyesi & Chetverikov, 2004; Strecha et al., 2004].
2. *Approaches that perform an automated 3D reconstruction of the scene from oriented images*. The automated 3D reconstruction is generally based on object constraints, like verticality and perpendicularity [Werner & Zisserman, 2002; Van den Heuvel, 2003; Wilczkowiak et al., 2003] or using the geometric epipolar constraint [Gruen et al., 2001].
3. *Approaches that perform a semi-automated 3D reconstruction of the scene from oriented images*. The semi-automated modeling rely on the human operator and produced so far the most impressive results, in particular for architectural objects [Debevec et al., 1996; El-Hakim, 2000, 2002; Gibson et al., 2002]. The interactive work consists of the topology definition, segmentation, editing and 3D data post-processing. The degree of automation increases when certain assumptions about the object, such as perpendicularity or parallel surfaces, can be introduced.

Manual measurements are also performed in some projects, generally for complex architectural objects or in cultural heritage documentations where highly precise and detailed results are required [Gruen et al., 2004]. Manual measurements are time consuming and provide for less dense 3D point clouds, but have higher reliability compared to automated procedures.

3. MATCHING FOR SURFACE MEASUREMENTS

Image matching represents the establishment of correspondences between primitives extracted from two or more images. In its oldest form, image matching involved 4 transformation parameters (cross-correlation) and could already provide for successful results [Foerstner, 1982]. Further extensions considered a 6- and 8-parameters transformation, leading to the well known non-linear Least Squares Matching (LSM) estimation procedure [Gruen, 1985; Foerstner, 1986]. Gruen [1985] and Gruen & Baltsavias [1986] introduced the Multi-Photo Geometrical Constraints into the image matching procedure (MPGC) and integrated also the surface reconstruction into the process. Then from image space, the matching procedure was generalized to object space, introducing the concept of 'groundel' or 'surfel' [Wrobel, 1987; Helava, 1988].

Even if more than three decades have been devoted to the image matching problem, nowadays some important limiting factors still remain. A fully automated, precise and reliable image matching method, adaptable to different image sets and scene contents is not available, in particular for close-range images. The limits stay in the insufficient understanding and modeling of the undergoing processes (human stereo vision) and the lack of appropriate theoretical measures for self-tuning and quality control. The design of an image matcher should take into account the topology of the object, the primitives used in the process, the constraint used to restrict the search space, a strategy to control the matching results and finally optimization procedures to combine the image processing with the used constraints. The correspondences between images are matched starting from primitives (features and image intensity patterns) and using similarity measures. Ideally we would like to find the correspondences of every image pixel. But, in practice, coherent collection of pixels and features are generally matched.

A part from simple points, the extraction of feature lines (see [Dhond & Aggarwal, 1989; Ziou & Tabbone, 1998] for a review) is also a crucial step in the surface generation procedure. Lines (edgel) provide more geometric information than single points and are also useful in the surface reconstruction (e.g. as breaklines) to avoid smoothing effects on the object edges. Edge matching [Vosselman, 1992; Gruen & Li, 1996; Schmid & Zisserman, 2000] establishes edge correspondences over images acquired at different standpoints. Similarity measures from the edges attributes (like length, orientation and absolute gradient magnitude) are a key point for the matching procedure. Unfortunately in close-range photogrammetry, the viewpoints might change consistently; therefore similarity measures are not always useful for edge matching.

4. STEREO-PAIR SURFACE MEASUREMENT

The first developed algorithm is a stereo matcher with the additional epipolar geometric constraint. The method was firstly developed for the measurement of human body parts [D'Apuzzo, 2003] and afterwards also applied to full human body reconstruction [Remondino, 2004] and rock slopes retrieval [Roncella et al., 2005]. It has been now extended to include also edge matching. The main steps of the process are:

1. *Image pre-processing:* the images are processed with the Wallis filter [Wallis, 1976] for radiometric equalization and especially contrast enhancement. The filter enables a strong enhancement of the local contrast by retaining edge details

and removing low-frequency information in the image. The filter parameters are automatically selected analyzing the image histogram.

2. *Point matching:* the goal is to produce a dense and robust set of corresponding points between image-pairs. Starting from few seed points well distributed in the images, the automated process establishes correspondences by means of LSM. The images are divided in polygonal regions according to which of the seed point is closest. Starting from the seed points, the automated process produce a dense set of image correspondences in each polygonal region by sequential horizontal and vertical shifts. One image is used as template and the other as search image. The algorithm matches correspondences in the neighborhood of a seed point in the search image (approximation point) by minimizing the sum of the squares differences of the gray value between the two image patches. If the orientation parameters of the cameras are available, the epipolar geometric constraints between the images can also be used in the matching process. Generally two stereo-pairs (i.e. a triplet) are used: the matcher searches the corresponding points in the two search images independently and at the end of the process, the data sets are merged to become triplets of matched 2D points.
3. *Edge matching:* the approach extracts line features based on the edge detection and linking proposed in [Canny, 1986] and [Henricsson & Heitger, 1994]. For each image, only the edges longer than a certain threshold are kept. Afterwards an edge matching is performed for each image pair of the set. Firstly the middle points of the edges are matched, providing a preliminary list of edge correspondences. Afterwards, starting from the matched middle point, the other points lying on the edge are matched in a propagative way.
4. *3D Point cloud generation:* the 2D matched points and edges are transformed in 3D data by forward ray intersection, using the camera exterior orientation parameters.

The developed matching process works on image pairs and integrates the epipolar constraint in the least squares estimation, limiting the patch in the search image to move along the epipolar line. To evaluate the quality of the matching results, different indicators are used: a posteriori standard deviation of the least squares adjustment, standard deviation of the shift in x and y directions and displacement from the start position in x and y direction. Thresholds for these values are defined manually for different cases, according to the level of texture in image and to the type of template. The definition of the seed points is generally crucial, in particular if discontinuities are present on the surface. The matcher, working only with stereo-pairs, is less robust than a multi-image strategy which takes into account all the available and overlapping images at the same time, but it is still able to provide for accurate and detailed 3D surfaces.

5. MULTI-IMAGE SURFACE MEASUREMENT

The multi-image matching approach was originally developed for the processing of the very high-resolution TLS Linear Array images [Gruen & Zhang, 2003] and afterwards modified to accommodate any linear array sensor [Zhang & Gruen, 2004; Zhang, 2005]. Now it has been extended to process other image data such as the traditional aerial photos or close-range images. The multi-image approach uses a coarse-to-fine hierarchical solution with an effective combination of several image matching algorithms and automatic quality control. Starting from the known calibration and orientation parameters, the approach (Figure 1) essentially performs three mutually connected steps:

1. *Image pre-processing:* the set of available images is processed combining an adaptive smoothing filter and the Wallis filter [Wallis, 1976], in order to reduce the effects of the radiometric problems such as strong bright and dark regions and optimizes the images for subsequent feature extraction and image matching. Furthermore image pyramids are generated.
2. *Multiple Primitive Multi-Image (MPM) matching:* this part is the core of the all strategy for accurate and robust surface reconstruction, utilizing a coarse-to-fine hierarchical matching strategy. Starting from the low-density features in the lowest resolution level of the image pyramid, the MPM matching is performed with the aid of multiple images (two or more), incorporating multiple matching primitives (feature points, grid points and edges) and integrating local and global image information. The MPM approach consists of 3 integrated subsystems (Figure 1): the feature point extraction and matching, the edge extraction and matching (based on edge geometric and photometric attributes) and the relaxation based relational matching procedure. Within the pyramid levels, the matching is performed with an extension of the standard cross-correlation technique (Geometrically Constrained Cross-Correlation -GC^3-). The MPM matching part exploits the concept of multi-image matching guided from object space and allows reconstruction of 3D objects by matching all available images simultaneously, without having to match all individual stereo-pairs and merge the results. Moreover, at each pyramid level, a TIN is reconstructed from the matched features using the constrained Delauney triangulation method. The TIN is used in the subsequent pyramid level for derivation of approximations and adaptive computation of some matching parameters.
3. *Refined matching:* a modified Multi-Photo Geometrically Constrained Matching (*MPGC*) and the Least Squares B-Spline Snakes (*LSB-Snakes*) methods are used to achieve potentially sub-pixel accuracy matches and identify some inaccurate and possibly false matches. This is applied only at the original image resolution level. The surface derived from the previous MPM step provides well enough approximations for the two matching methods and increases the convergence rate.

The main characteristics of the multi-image-based matching procedure are:

- Truly multiple image matching: the approach does not aim at pure image-to-image matching but it directly seeks for image-to-object correspondences. A point is matched simultaneously in all the images where it is visible and exploiting the collinearity constraint, the 3D coordinates are directly computed, together with their accuracy values.
- Matching with multiple primitives: the method is a robust hybrid image matching algorithms which takes advantage of both area-based matching and feature-based matching techniques and uses both local and global image information. In particular, it combines an edge matching method with a point matching method through a probability relaxation based relational matching process.
- Self-tuning matching parameters: they are automatically determined by analyzing the results of the higher-level image pyramid matching and using them at the current pyramid level. These parameters include the size of the correlation

window, the search distance and the threshold values. The adaptive determination of the matching parameters results in higher success rate and less mismatches.

- High matching redundancy: exploiting the multi-image concept, highly redundant matching results are obtained. The high redundancy also allows automatic blunder detection. Mismatches can be detected and deleted through the analysis and consistency checking within a small neighbourhood.

More details of the matching approach are reported in Zhang [2005].

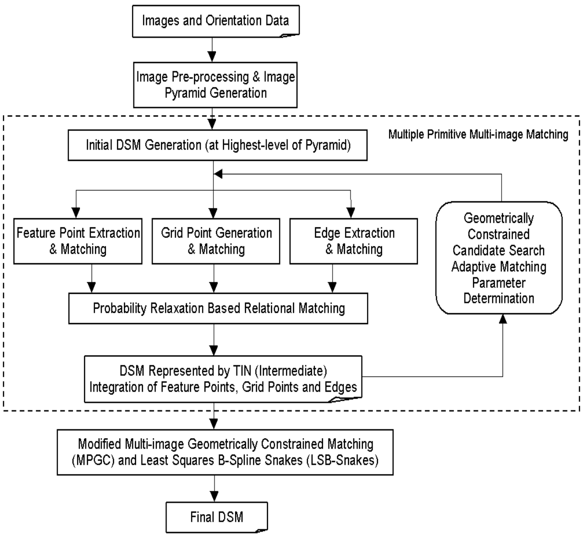

Figure 1: Workflow of the automated DSM generation approach. The approach consists of 3 mutually connected components: the image pre-processing, the multiple primitive multi-image (MPM) matching and the refined matching procedure.

6. EXPERIMENTS

We have performed many tests on different close-range data sets with the two surface reconstruction approaches. So far the results are checked just visually, as no reference is available. In the future an accuracy test should be performed. In the next sections we report results from widely separated images, untextured surfaces and detailed heritage objects. More examples are reported in our homepage.

Test1. Three images of the main door of the S. Marco church in Venice (Italy) are used. The image size is 2560x1920 pixels. The triplet is acquired under a wide baseline (base-to-distance ratio ~ 1:1.4) and very fine details are present on the object. Both methods could correctly retrieve the surface details, as shown in Figure 3. The stereo-pair strategy matched approximately 590 000 points between the two pairs while the multi-image matching recovered ca 700 000 points.

Figure 2: The three images of the church's façade acquired under a large baseline.

Test2. A very small pot (ca 3x4 cm) is modeled with the two presented matching strategies. Six images, with a size of 1856 x 1392 pixels are used. The detailed results are shown in Figure 4 as textured and shaded surface model.

Test 3. The data set consists of 6 images of a Maya relief in Edzna, Mexico. The object is approximately 4 meters long and 2 meters high. The images have different light conditions and scales. Due to the frontal acquisition, the upper horizontal part of the relief is not visible in the images, leading to some gaps in the matching point results and some stretching effects in the meshed model. Both methods could reconstruct all the details of the heritage. The stereo-pairs approach (performed on 4 pairs) generated ca 860 000 points and 7 900 edges while with the multi-image strategy a cloud of 1 940 000 points and 23 000 edges was produced. The results are shown in Figure 5.

Figure 3: Results of the stereo-pair matching method (above): recovered 3D point cloud, displayed with pixel intensity values and a particular of the generated shaded model. Views of the shaded and textured surface generated with the multi-image method (below).

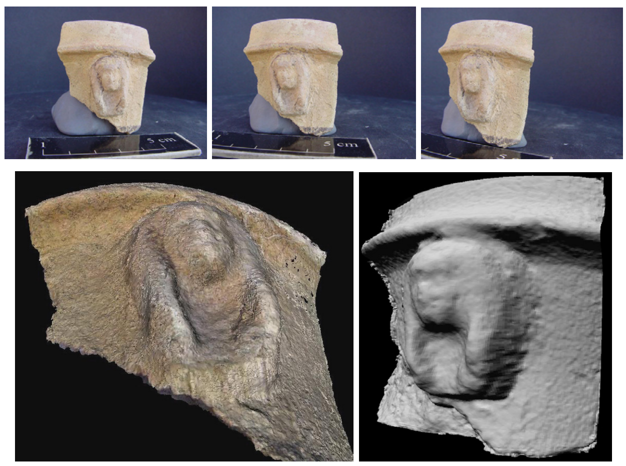

Figure 4: Three (out of 6) image of the small pot (above). The surface reconstructed with the stereo-pair matching and with the multi-photo approach.

7. CONCLUSIONS AND OUTLOOK

We have presented two matching strategies for the precise surface measurement and 3D reconstruction of complex and detailed terrestrial objects. The stereo-pair approach constraints the search of correspondences along the epipolar line while the 3D coordinates of points and matched edges are computed in a second phase, using rejection criteria for the forward ray intersection. The multi-image approach is more reliable and precise but requires very accurate image orientation parameters to exploit the collinearity constraint within the least squares matching estimation. The maximum orientation errors in image space should be less than 2-3 pixels.

The two approaches use points and edges to retrieve all the surface details and they have both advantages and disadvantages. They can be applied to short or wide baseline images and can cope with scale changes, different illumination conditions or repeated pattern. Employing the precise LSM algorithm, they can recover sub-pixel accuracy matches. They both need some seed points to initialize the matching procedure and the number of seed points is strictly related to the image texture and surface discontinuities.

The results so far achieved are promising but more tests have to be performed as well as an accuracy assessment of the two strategies. Photogrammetry has all the potentiality to retrieve the same results (details) than range sensors. But to asses the accuracy of the systems is not an easy task. Assessment on the whole measured surface would require the two models to be in the same reference systems or to set one model as reference and transform the second one into the first reference system.

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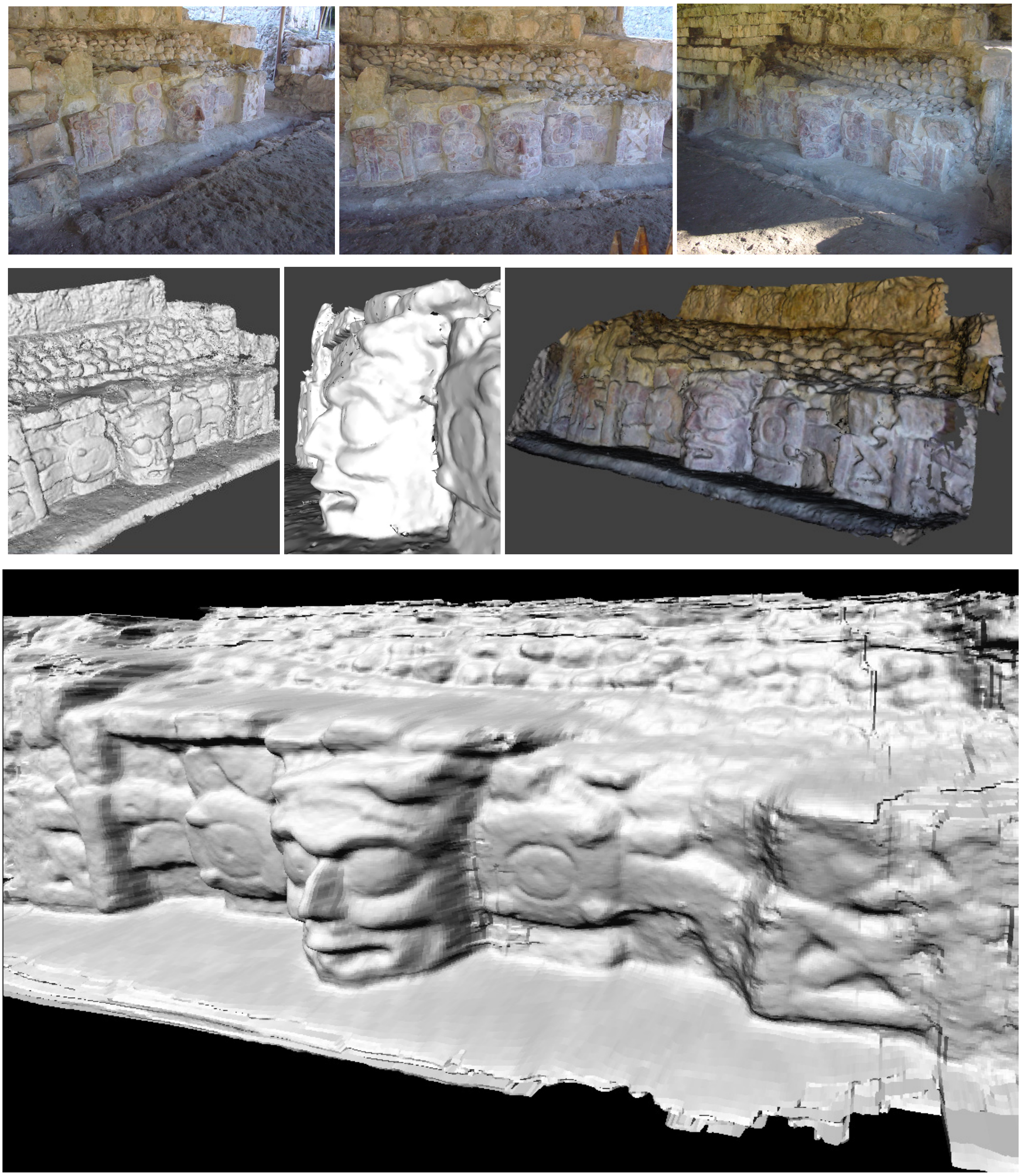

Figure 5: Three (out of six) images of a Maya relief (above). Results of the stereo-pair matching (4 pairs) displayed as shaded model (with a close view of the mesh) and as textured model (middle). Shaded model obtained with the multi-image matcher simultaneously run on 6 images (bottom).

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