

## ***Interactive comment on “Image-based surface reconstruction in geomorphometry – merits, limits and developments of a promising tool for geoscientists” by A. Eltner et al.***

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-We would like to thank the referee for his/her helpful comments, which are very supporting and eventually lead to a significantly improved manuscript. Thank you for your effort and detailed considerations. -In the supplement we include the revised manuscript and marked changes that were made in regard to the original manuscript. Thus, in the answers to the reviewers we refer to the manuscript in the supplement.

The manuscript by Eltner and co-authors reports a complete review of the Structure from motion applications in geosciences. The manuscript is generally well written and organized. The authors give a general overview of the method describing the main

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algorithms implemented in the photogrammetric approach. 61 published papers are examined according to their application, divided into seven main topics. Where is provided by the authors, an overview of the obtained accuracies in the examined works is evaluated according to the main source error of the technique and to the error introduced for the accuracy estimation. Further frontiers for the SfM approach are discussed in this paper, highlighting the need of additional investigations on the technique and on the methods to estimate the accuracy, and the need to share a growing amount of data produced by this low cost technique. The Sections describing the accuracy estimation and the source errors could be improved by defining in the text the terms used for the accuracy analysis making it easier to understand and specifying the case studies that are examined for each analysis in order to help the reader for further investigations. The corresponding references could be also included in the description of the SfM applications for each investigated topic.

-Regarding section 4 (accuracy estimation), we describe used terms more specifically and include author/case study information to each analysis for clarification. This also applies to section 3 (SfM applications).

Specific comments

1. I suggest to report in the Section 3 all investigated papers (i.e. authors) for each topic. This could be done adding in the Table A1 a first column with a progressive ID number for each work. Then, for each topic, specify the corresponding ID. For example.1455, line 21: ": : in 7 publications", here, the ID of the relevant papers can be reported, or specify on the Table 2. This is a suggestion. Several published papers provide both a description of the SfM application and an accuracy analysis of the reconstructed object and therefore, it is appropriate to split the considerations about the applications and the accuracies, as done in this review manuscript. However, the Sections 3 (3.1,..., 3.7) should focus mainly on the description of the applications of the method including the authors (see comment before), the object of survey, and the platform used for each corresponding topic. Some applications are missing in the text, and

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should be provided in order to give a complete view of the main objects surveyed with this technique. To name a few, Woodget et al. (2015) quantified the fluvial topography using hyperspatial resolution UAV imagery and structure from motion photogrammetry; Piermattei et al. (2015) used the SfM for monitoring the mass balance of a debris covered glacier. These applications should be reported in the text.

-Thank you for the suggestion. We add an ID for each publication in Table A1 (appendix) and subsequently provide an additional column in Table 2 (SfM applications) to assign corresponding articles to the relevant topics. We also include the references provided by the reviewer in the manuscript.

2. The results of the statistical investigation on the achieved accuracies are reported in the main table (Table A1). Please define the parameter used to evaluate the accuracy also in the text and not only in the caption of the figures. The accuracy parameter named in the paper "measured error" is the standard deviation /RMSE measured in comparison to a reference data (e.g. LiDAR, GPS measurements or with Total station). Please clarify better in the text. Please define how the "superior reference ration" is calculated in the text. As reported in Figure 9 'superior reference ratio' is calculated as ratio between measured error and accuracy of the reference. Please define how the accuracy of the reference data was evaluated. Looking at the Figures about the error analysis (5, 6, 7, 8, 9, 10), a different number of data were plotted, but in the text is reported that 39 case studies provided a value of accuracy estimation. Please specify for each analysis how many case studies were considered and, if possible, report the corresponding references (see comment 1).

-Our apologies; we clearly define each of the accuracy parameters in the revised manuscript. Also, we specify the number of articles and their IDs included in each of the analysis performed.

Technical corrections

p.1448, line 2: 'Early works: : ...mapping (Laussedat, 1899)' Please remove this sen-

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tence or move to Section 2.

-Thank you for your comment. However, we would like to keep this very brief historical summary to highlight where photogrammetry and thus also SfM originally evolved from.

p. 1448, line 17: 'to data processing and data acquisition makes it...' It is also the easy data acquisition that increased the number of non-experts users.

-We include both statements in the revised manuscript - the ease of data acquisition and data processing.

p. 1448, line 21: I prefer report the automatism rather than "algorithmic advance". 'that utilizes the high automatism of the SfM algorithm are considered'.

-Thank you for your thought. We change the sentence respectively.

p. 1448, line 23: 'fully automatic' is not true for all applications and software used as for example the GCPs identification in the images or in the point cloud is still a manual operation in many case. Therefore, I suggest 'semi-automatic' and maybe specifying why: 'The data processing is highly automated and in many software the user-control is limited to some pre-processing step like the manual masking of moving object, the camera calibration parameters setting that can be applied to optimize both accuracy and precision, and the GCPs identification.

-Thank you for the suggestion. We adopt the manuscript according to your comment. However, we still would like to emphasize the potential of full automation, yet except for scaling/referencing. But even there significant progress has been made, e.g. minimising GCP identification solely to three points due to template matching (as implemented in the SfM-georef tool from James & Robson, 2012) or automatic marker identification due to thresholding (as partly implemented in Agisoft PhotoScan).

p. 1449, line 1-3: Please clarify this sentence. What do you mean with 'a novel point of view'? I suggest to simplify the sentence writing that the SfM characteristics (low-cost and high portability of the instrumentation) allow to increase the temporal analysis

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of the events but also the spatial analysis thank to the high versatility of the images acquisition. These characteristics and the possibility to acquire images also from aerial platform using UAV increase the applications of the survey method in remote area with limited accessibility and the detection of fast changing environment.

-Thank you for the suggestion. We modify the sentence following the reviewer's advice.

p. 1449, line 23: I suggest to specify the corresponding Section for each point as following: '1. The method... are clarified (Sect. 2); 2. Different field... (Sect.3); 3.... (Section 5); 4. ... (Section6)'. I suggest to move the Section 4 "non commercial software" in the Section 2, especially because at the end of Section 2, p.1453, line10-22, an introduction about the SfM software is provided. Maybe dividing the Section2 in two paragraph, '2.1 : : : state of art' and '2.2 : : : tool and data post processing. A brief description also about commercial tool should be described. See comment p.1457-1458.

-Thank you for the suggestion. We add the chapter number to the corresponding objectives in the manuscript. Also, we move section 4 into section 2. However, we mention commercial tools only briefly due to their usual lack of information about specific algorithmic realisations (black boxes).

p. 1450, line 14. '...usually at least nine homologous points per image' this statement requires a reference.

-Our apologies; we rephrase the entire chapter to shorten the review, whereby this specific information has been decided to be less relevant and thus is completely deleted from the manuscript.

p. 1450, line 22: the acronym SfM is already described.

-Our apologies; we remove this description.

p. 1451, line 6: I would mentioned also the need to scale the model, as reported also by Snavely et al., 2008, because the SfM estimated the relative position of each camera.

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To have metric information of the reconstructed surface, in local or global-coordinate system, the ground control points or a scale definition by using a known distance are required to scale and georeference the SfM 3-D model.

-Thank you for the suggestion. We add the further step to scale/geo-reference the model to SfM in a nutshell.

p.1451, line 25: 'These extrinsic parameters ...' the authors refer to camera position or also intrinsic parameter. Please clarify the sentence.

-Thank you for your comment. However, the entire paragraph is removed to shorten the script. In the revised manuscript we refer to Smith et al. (2015) for further reading.

p. 1452, line 27. Please change 'DSM' with 'DEM'.

-Thank you for the comment. We change it.

p. 1453, line 10: I suggest mentioning also the commercial software because they are used in the investigated papers.

-Thank you again. However, we prefer to not just yet refer to any software in particular because later on in the manuscript we give more detail about SfM tools. We change the sentence, accordingly.

p. 1453, line 23: I suggest to move the section 4 here, in connection with the paragraph above about the SfM software.

-Thank you for the comment. We follow the reviewer's suggestion.

p. 1454, line 25: Please define the acronym 'LiDAR'.

-Our apologies; we define it.

p. 1455, line 21: The authors may also want to refer to Ryan et al. (2014).

-Thank for the suggestion. We add this reference from Ryan et al. (2014) on 'Repeat UAV photogrammetry to assess calving front dynamics at a large outlet glacier draining

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the Greenland Ice Sheet’.

p. 1456, line 19: Ružić et al. (2014) is not mentioned in the bibliography.

-Our apologies; we correct this: Ruzic, I., Marovic, I., Benac, C. and Ilic, S.: Coastal cliff geometry derived from structure-from-motion photogrammetry at Stara Baka, Krk Island, Croatia. *Geo-Mar. Lett.*, 34, 555–565. doi:10.1007/s00367-014-0380-4, 2014.

p. 1456, line 20: ‘... have been retreating up to 5 m since the 1960s: : :’ it is not relevant there.

-Thank you for noticing, we remove it.

p. 1456, line 23: An emerging application of SfM is related to snow depth estimation, snow map and rock glacier monitoring. This topic should be reported here, or in the Section 3.3 extended the topic. For example, Fugazza et al. (2015), Dall’Asta et al.(2015).

-Thank you for the suggestions. We add these applications and references.

p. 1457, line 12: ‘Also : : intervals.’ please move this sentence in Section 6.6.

-Thank you for the comment. We follow the reviewer’s suggestion.

p. 1457, line 19: Please reorganize Table B1 regarding the software of photogrammetry and cloud processing (if you want to include the latter in this table). Additionally please report both in the text and in the table the free-web service SfM tool, like Photosynth and 123D Catch, especially because they are used in the investigated paper as reported in Table A1 and in Figure 3. In table B 1, I suggest to include also the commercial software adopted in the published papers.

-Thank you for the comment. We include the packages suggested. However, regarding the tool order, we do not completely understand how the table is supposed to be reorganized because we already ordered it according to SfM tools first and post-processing tools afterwards. Sf3M is listed at the end because it implements both, SfM

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and post-processing algorithms. Furthermore, in table B1 we would not like to mention commercial software packages due to their black box nature.

p. 1459, line 10: I have my doubts about this statement ‘: : the systematic error : : can be displayed by the mean error values’, please support by a reference. As reported by Smith and Quincey (2015), the Mean error values should be treated with caution to estimate the accuracy of SfM reconstruction that often include both positive and negative errors which approximately compensate for each other. Also Dietrich (2015), James and Robson (2014) demonstrated that the systematic error is visible as a pattern of positive and negative differences compared to a reference ground truth data. The effect of this error is principally caused by the parallel geometry of the photographs along the flight lines in case of UAV acquisition and by the radial distortion propagation(Dietrich, 2015) as it is reported in Sect. 5. However this error is not apparent in the mean values, but can be explained by an error distribution map. Perhaps worth a comment in the text.

-Thank you for the comment. We clarify this aspect in the text. We extend the explanation to the fact that of course deviation maps are important, as well. Mean error is not the solely measure for SfM performance evaluation but it is a significant supplement, which is calculated easily.

p. 1459, line 4: I suggest to include this Section in the previous one.

-Thank you for the comment. We move this section accordingly.

p. 1459, line 18: "measured error" please define better what represent this value (See specific comments). I suggest change line 17 to 'In this study, we reported with the term "measured error" the standard deviation or RMS calculated comparing the SfM reconstruction (point cloud, DEM or mesh) with a reference data (i.e. Lidar , total station or GPS measurements)’. Additionally, as reported in the lines 19-25, the GCPs residual error defines an approximate accuracy estimation, especially if the GCPs are including in the BBA. I suppose there is not a big differences by selecting the control

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point in the model (of course depend on the model resolution) or in the images as is highlighted in your plot (Fig.5). Instead, would be interesting the "measured error" depending on whether the GCPs have been performed in the BBA (one-stage) or after dense matching computation (two-stage).

-Thank you for the thoughts. We change the description regarding measured error to guarantee a better understanding. Regarding the type of GCP measurement, we do believe there is a quite significant difference between measuring in images, where sub-pixel assignment is possible, and measuring in point clouds, where features are approximated over several points (further depending on the point density). However, comparison with existing studies is difficult because many effects interact. Thus, another study just concentrating on this issue would be interesting. Considering two- and one-staged BA, we already performed this analysis by using the terms basic and simple SfM tools because their main difference (besides camera calibration) is the implementation of GCPs. However, we removed the corresponding figure (5) because after reconsidering the information, we think, possible trends are not as obvious.

p. 1460, line 27: '...an increase of distance the measured error decreases', looking at the Figure 5 probably you mean ' : : the measured error increase'. Figure 5 shows more than 39 values (number of case studies that performed the accuracy analysis) probably because it is included all available data from multi-temporal analysis. Please provide the total number of plotted values (See specific comments).

-Thank you for noticing our mistake. We correct this. Of course, we meant increase. Generally, the measured error tends to increase with distance, and also the error ratio. However, we have explored the reasons behind the departure of some studies from this tendency. We explain the figure in more detail in the revised manuscript, corresponding to the suggestion of the referee, to avoid confusion.

p. 1461, line 5: ' : : and at large distance'. Perhaps this sentence requires a reference or an example.

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-Thank you for your comment. However, we would like to keep it this way because this sentence refers to observations that can be made (in fig. 5a in the revised manuscript) reviewing the many papers using SfM.

p. 1464, line 3: 'Stumpf et al. (2014) show that higher overlap resolves in better results, even though ground sampling distance decreases due to a smaller focal length.' it is not clear in this sentence the connection with overlap and GSD. Please clarify this sentence.

-Our apologies; we remove the sub-clause regarding GSD due to missing relevance.

p. 1464, line 7: I consider Table 3 not necessary, I suggest to write in the text the number of published applications that use UAV or terrestrial acquisition. I suggest to rewrite this sentence.

-Thank you for the suggestion. We remove the table.

p. 1464, line 25-28. Please clarify the concept. The authors may also want to refer to Wenzel et al. (2013) that explain the relation between the intersection angle and the baseline, the depth accuracy and the image similarity.

-Our apologies; we clarify this by extending the explanation. However, we prefer not to refer to further literature because we believe this geometric principle accounts to basic (photogrammetric) knowledge.

p. 1465, line 11: ' : : 3-D reconstruction: : :' is defined in Table 1 as the three dimensional shape of an object reconstructed from overlapping images, but I suppose here the authors mean the camera geometry reconstruction.

-Thank you for noticing. We actually mean both object reconstruction as well as camera geometry. We correct this in Table 1.

p. 1465, line 12: I suggest to remove the sentence '...because MVS...point cloud'. The MVS algorithm is not the only algorithm used for the dense matching in the investigated

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papers, and furthermore the image matching computation to generate dense point cloud is mentioned in the next line (line 15: : :).

-Thank you for the comment. However, we do not agree completely. Indeed, we mean MVS because for the dense matching MVS algorithms work/start in the object space with the sparse points (e.g. PMVS), whereas other approaches of dense matching (e.g. stereo matching SGM) work in the image space and do not rely on the sparse point cloud. However, to avoid confusion (and due to lesser relevance) we consent and remove the sentence.

p. 1465, line 24: To estimate the accuracy of the sparse point cloud (tie points) before the dense image-matching computation, a possible solution is to compare the sparse points with an area-based truth data, if this is available. Many software allowed to export the computed tie-points that are used to estimate or refine the camera orientation, and therefore a preliminary accuracy estimation of the SfM reconstruction is performed. This could be explained in the text.

-Thank you for your comment. However, by internal quality control we explicitly do not mean comparison to external references rather than evaluating the image matching e.g. in regard to reprojection error of all tie-points (in pixels). Hence, error assessment would be independent from the reference accuracy and solely the performance of the BA evaluated in regard to image matches. SfM-georef and Sf3M give some information regarding the reprojection error, but are limited to GCPs only. We would like to keep the respective part as it is and solely do a short mention, which can be considered in more detail by consulting the reference, because we believe further explanation would rather cause additional confusion.

p. 1466, line 9: What do the authors mean with'..., if possible, : : :'. I suggest to remove it. Moreover, please provide the number of investigated case studies for the error assessment.

-Our apologies; we rephrase the sentence.

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p. 1466, line 20. I suggest to include the statement of Bemis et al. (2014) about the influence of the duration of the photogrammetric survey on the SfM 3D model quality. He reported that "model quality degrades significantly for durations >30 min".

-Thank you very much for this additional information. We include this information in the manuscript.

p. 1467, line 2: Here, may also provide the statement that by including the control measurements (i.e. GCPs) in the bundle adjustment the error is reduced. Javernick et al. (2014) provided a reduction of z-error to the decimetre level by including control points in the bundle adjustment.

-Thank you for the suggestion. We include this information regarding Javernick et al. (2014) in the text and make some further statements regarding the importance of GCPs for correct model estimation in the chapter dealing with the camera calibration because at this point we already made some statements accordingly but missed to state more clearly the importance of GCPs.

p. 1467, line 16: The authors may also want to refer to Piermattei et al. (2015) in this sentence: ': : : be possible (e.g. glacier surface reconstruction, Piermattei et al.,2015)...'.  
'

-Thank you for the suggestion. We include this reference.

p. 1467, line 25: Please include in the text these statements: Bemis et al., (2015) and Smith and Quincey (2015) reported that the control points should be distributed widely across the target area and at the margins, covering a good range of values in each spatial dimension. This is especially true in case of the GCPs are including in the bundle adjustment and the presence of parallel axis camera configuration. Additionally, linear configuration of GCPs should be avoid as reported by Smith and Quincey (2015).

-Thank you for the suggestion. We change the manuscript accordingly. However, regarding the usage of one-staged BA with parallel-axis configuration many literature

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(e.g. Kraus, 2007) and recommendation exist (due to already long lasting investigations in classical photogrammetry: especially close setup of GCPs around the area of interest as well as height control points in specific distances as a function of image number are relevant). We made some adjustment to the manuscript.

p. 1468, line 1-3: 'Figure 5 illustrates...'. I suggest to report that there is not difference in the measured error of the investigated studies if the GCPs were selected in the pointcloud or in the images. Contrary, white points (i.e. GCPs measured in the images) show higher "measured error" than gray points. However, a limited number of case studies selected the control data in the point cloud. Perhaps report the number.

-Thank you for the suggestion. We include number of studies where GCPs are depicted in point clouds and corresponding IDs. However, we would not like to make further statements because there are just too few studies using GCPs in point clouds to detect any trends. Further investigation of GCP measurement for studies under similar conditions would be advisable.

p. 1468, line 19: Please define what the authors mean with 'superior accuracy assessment' and the number of case studies that were considered for this accuracy evaluation (see specific comments).

-Our apologies; we rephrase the sentence for clarification.

p. 1468, line 22: Please change 'scale dependent' with 'to depend from the camera object distance.'

-Our apologies; we change it.

p. 1469, line 7: Please change '3-D reconstructed DEM' with '3D-reconstructed surface' as you explain after, the comparison can be done using the point cloud of the reconstructed surface and not only after the interpolation (DEM). I suggest to report here the necessity of a spatial error distribution for a proper evaluation of systematic error (see comment p. 1459, line 10).

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-Thank you for the suggestion. We change it. Regarding the error distribution, we already made a more detailed description in chapter 4 (as you suggested earlier).

p. 1470, line 11. If the authors want to report these results, please be more quantitative.

-Thank you for the suggestion. We include specific values.

p. 1470, line 12: Please provide the reference of this equation, Fraser (1996), and describe better the component. For example, the standard error is for the x, y, z object coordinates; q is a design factor expressing the strength of the camera network, basically dependent on the angles between intersecting homologous rays; k corresponds to the average number of images at each station; 'D mean distance object-target' probably the authors mean 'camera-object distance'; ': : : (0.29, : : :)' please provide the reference.

-Thank you for the suggestion. However, we already state a reference with the basic principle book by Luhmann et al. (2014). Thank you for noticing the mistake we made regarding object – camera distance. We also add some more information regarding the equations.

p. 1472, line 1-6: Perhaps this statement needs more clarification.

-Thank you for the suggestion. We clarify this.

p. 1474, line 23: The authors may also want to refer to Mulsow et al. (2013) about the time lapse application for monitoring the margin lake, and Whitehead et al. (2014) to use the time-lapse cameras to measuring the daily surface elevation change across antarctic glacier.

-Thank you for the suggestion. However, we do not include Mulsow et al. (2013) because they are using a single camera to track changes of lake levels with time-lapse (as there are many applications in this regard). Also Whitehead et al. (2014) use only a single camera and thus no time-lapse SfM as in James & Robson (2014).

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p. 1492, Table 2: I suggest to put the references for each topic. It could be done adding a consecutive ID in the table A1 and reporting here the relative ID in order to help further investigation (see specific comments). This is especially suggested because in each section about the SfM application for each topic not all corresponding papers are described. I think it could be useful write the work/authors for each topic, in the table2 or at the beginning of each paragraph. Some observations about the Table: The last column represents the total number of reviewed papers, please provide a title to this column; the last row is the sum of each column. But if it is like so, probably there is an error in the number: 11(7) rather than 10(7).

-Our apologies; we correct this.

p. 1493, Table 3: Wrong number of investigated studies '62'. In the text is reported 61 publications. Additionally I consider this table not significant.

-Thank you for your comment. We remove this table.

p. 1495, Table A1: Different symbols (comma or dash) are used to separate the values. Please try to be more consistent or specify the differences.

-Thank you for noticing. However, dashes and commas are used differently on purpose if more than one value is reported and should be auto-plausible. We would prefer to leave the table as it is regarding this matter to keep it as short as possible.

p. 1499 Figure 2 is not reported in the text.

-Thank you for the comment, but at chapter 3 figure 2 is mentioned at the end of the first paragraph.

p. 1500, Figure 3: Wrong number of investigated studies '62'. In the text is reported 61 publications.

-Thank you for your comment. We correct the number of reviewed studies.

p. 1505, Figure 8: Please specify what represent the different scales in the legend and

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in the caption. I am assuming that 'scale' refers to the 'camera-object distance'.

-We would like to keep it as it is because we clarify in chapter 5.2.1 the meaning of scale and sensor to surface distance and use both terms separately during the entire manuscript.

p. 1508 Figure 11 is not reported in the text.

-Figure 11 is reported in chapter 7 (conclusion). However, in the revised manuscript this figure is implemented at a more convenient position (fig.1 in the revised manuscript).

Please also note the supplement to this comment:

<http://www.earth-surf-dynam-discuss.net/3/C704/2016/esurfd-3-C704-2016-supplement.pdf>

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Interactive comment on Earth Surf. Dynam. Discuss., 3, 1445, 2015.