

Dear colleague,

Thank you very much for your effort and valuable comments. We have tried to consider every single one of your suggestions – hopefully to your satisfaction.

Best regards

The Authors

## Response to reviewer #1

1. Overall: can you characterize in which cases ICProx works better? E.g. when deformation is all scattered over the scene (rock fall?), or when it is more focused, e.g. when considering a glacier that flows between stable rock beds.

We have added some sentences to the conclusion: “In general, the algorithm performed well for the data presented in sections **Error! Reference source not found.** and **Error! Reference source not found.** where geometric changes occurred in a connected fashion. The most challenging task was represented by the data presented in section **Error! Reference source not found.** due to the fact that deformation was scattered all over the datasets and that the deformation rates were comparably low.

2. Related: could you characterize the different movement related/expected for the three geomorphological processes you consider?

It would be possible to compute deformation vectors similar to Teza et al. (2007) after the datasets would have been registered. However, the approach would only lead to one vector per octree cell and would hence be a “mixed signal” meaning that parts of the cell could move into different directions in reality. Hence, we’re currently working on entity-based approaches rather than generating numbers for individual voxels.

Teza, G., Galgaro, A., Zaltron, N., Genevois, R. (2007): Terrestrial laser scanner to detect landslide displacement fields: a new approach. *International Journal of Remote Sensing*, 28(16), pp. 3425-3446.

3. Overall: (maybe for discussion): what would be a strategy in case of more than two epochs?

We have added one sentence to the outlook section. However, a general strategy cannot be mentioned since every area of interest requires its own unique strategy, e.g. register all epochs into the reference epoch or register pairwise, epoch 1 into reference epoch, epoch 2 into the geodetic datum of epoch 1 and so on.

“Since geomorphometric monitoring is usually carried out frequently over long periods, strategies have to be developed in order to process time series that consist of several epochs.”

4. Overall: could the method be improved by making it iterative (smaller voxels) to better detect the boundaries of deforming areas?

The reviewer’s suggestion has been considered. The following sentences have been added:

“An alternative strategy could be to apply the ICProx-algorithm in an iterative fashion where the octree size gradually decreases. By this, the boundaries of deformed regions would be detected at a higher resolution.”

5. Overall: or alternatively: could it be extended by a testing step, that after application of optimal transformation parameters, detect which difference can be considered change, given the quality of the data?

This is in fact one of the key features of the algorithm and is hence already implemented. Please see Wujanz et al. (2016) from page 8 onwards for details.

Wujanz, D., Krueger, D. and Neitzel, F.: *Identification of Stable Areas in Unreferenced Laser Scans for Deformation Measurement*. The Photogrammetric Record, 31(155), pp. 261-280, 2016.

#### 6. Overall: how should the voxel size be chosen given the point density and the expected change?

These are two very different aspects. The voxel size controls the resolution of the result – the smaller it is, the finer will be the resolution of the classification process. The local point density on the other hand, which is an inherent characteristic of the input data, controls the detectability. So, if the local point sampling is low, the local detectability of deformation is also comparably low. Quite frank, the algorithm cannot do anything about the data quality. We have mentioned this aspect in the conclusion.

“However, the importance of carefully acquiring data is particularly apparent in section **Error! Reference source not found.** as it clearly demonstrates the inherent link between local sampling density and potential detectability of deformation. It is important to point out that the effects provoked by the sampling uncertainty of TLS notably surpass their capabilities in terms of achievable 3D-precision.”

We have also added two sentences to section 3.

“As already shown in Wujanz et al. (2016b) the choice of the octree cell size has notable effects onto the outcome. In general, a smaller octree size leads to a higher degree of detecting stable regions while the computational effort notably increases. Hence, setting the octree size is a balancing act between resolution and computation time.”

#### 6. Abstract: -> “E.g. terrestrial laser scanners capture a region of interest in a quasi-laminar ...”

The sentence has been rephrased to “...e.g. by capturing a region of interest with terrestrial laser scanners which results in a so-called 3D point cloud.”

#### 7. Abstract: you mention a central problem, but do not state it explicitly, please do so. “The central problem considered in this work is...” To me this seems to be target free registration in areas where it is not clear where stable subareas are.

We tried to argue in a sequential fashion: Problem #1: Computation of transformation parameters. Problem #2: How can one achieve this and what are possible disadvantages? Etc.. In order to clarify this issue the sentence has been altered to:

“The central problem in deformation monitoring is the transformation of 3D point clouds captured at different points in time (epochs) into a stable reference coordinate system.”

#### Abstract: -> “For every case, two epochs... is 70 % on average”. Also mention here the reference data

Sentence has been altered to:

“For every example two epochs were processed while the ICProx-algorithm’s classification accuracy is 70% on average in comparison to reference data.”

#### 9. Intro: -> “Monitoring surface changes...”

The authors have addressed the reviewer’s remark.

“Monitoring surface changes in hazardous areas has been an important task of the geodetic community in the last decades.”

#### 10. Intro, r24: “occurrences”, of what? Please specify.

This sentence now reads:

“Due to the predicted increase of natural disasters (Anderson and Bausch 2006) this problem domain will hence gain importance in the future.”

11. P2r5: “congruence model”? Either explain or omit it here.

Parts of the sentence have been deleted. “In order to process the acquired TLS data, an appropriate deformation model has to be chosen (Heunecke and Welsch 2000).”

12. P3r15: explain in 1-2 lines what radiometric features are and why these can be used for registration;

The according part has been extensively extended and now reads:

“Point clouds captured by terrestrial scanners also contain radiometric information (Höfle and Pfeifer 2007), which is referred to as intensity, in addition to the geometric content. Intensity values are assigned to individual points and are based on the strength of a reflected signal. If the topology of points within a dataset is known this information can be used to convert a point cloud into an image where intensity values represent the brightness of individual pixels. By doing this, well established techniques from the field of image matching can be applied to 3D-datasets. As a first step so called keypoints have to be extracted, which are distinct features within a local neighbourhood in terms of their grey scale values. After keypoint extraction descriptors are used to establish correspondences between keypoints from different datasets (Lowe 1999). Based on this information transformation parameters can be computed. Since the long-term stability of radiometric information captured by TLS has not yet been studied, this strategy is not considered in the following. The successful application over short periods of time has been demonstrated by Böhm and Becker (2007).”

Same, explain what is meant by direct georeferencing.

The according sentence has been extended to “Instead of computing transformation parameters based on established correspondences the relation between different local coordinate systems can also be achieved by observing their location and orientation within a superior coordinate frame. For this, additional sensors are required while the general concept is well known, for instance in aerial photogrammetry (Cramer et al. 2000). Methods for direct georeferencing of TLS were initially just of scientific interest (e.g. Paffenholz et al. 2010) while lately several commercial systems emerged (Rieggl 2017), (Zoller + Fröhlich 2017). A significant drawback of direct georeferencing is the extension of a scanner’s error budget (Soudarissanane 2016), due to the use of additional positioning- and orientation sensors such as GNSS-equipment or electronic compasses. With increasing scanning range the impact onto the relative rotation between two point clouds also increases, which is a result of the limited accuracy of compasses.”

P3r31: -> “A substantial advantage of the last strategy is the actual use of the information present in the point cloud”.

The reviewer’s suggestion has been considered.

14. P4r2: -> “In order to obtain a satisfactory..or pre-a lignment algorithms” (skip point clouds)

The reviewer’s suggestion has been considered.

“In order to obtain a satisfactory pre-alignment, several strategies appear to be suitable such as direct georeferencing, manual pre-alignment or pre-alignment algorithms.”

15. P4r16-r20 and r 22-24: double information: avoid repetitions

The reviewer’s suggestion has been considered.

“In order to avoid falsification of the deformation measurement process and consequently the analysis of deformation, it is unavoidable to identify deformed areas within point clouds and to reject them from the

computation of transformation parameters. For this task the iterative closest proximity-algorithm (ICProx) was used that consists of three essential phases:”

16. P4r17-> “and identification of deformation..”

The reviewer’s suggestion has been considered.

17. P14r18: again congruent is mentioned but not explained.

The reviewer’s suggestion has been considered.

“Congruent respectively stable areas in terms of geometry are detected by a combinatorial approach termed the maximum subsample method (Neitzel 2004) which is, in terms of robustness against outliers/deformation, more reliable and hence superior to robust estimators or RANSAC.”

18. Ch 2 + Ch 2.1 (p3) could be called “Existing approaches” as this reviews literature. Your methodology basically starts at Ch 2.2, please make this clear.

The structure of chapter 2 has been altered. The caption of Ch. 2.1 has been removed while the content of 2.2 was moved to chapter 3.

P4r29: “The first one automatically....data. For this purpose the 4PCS-algorithm is...

Removal of the first part of the sentence as suggested by the reviewer may confuse the reader since the third sentence in this paragraphs refers to “a step” and not a “phase”. Hence, the sentence has not been modified.

20. P4, last paragraph: what is the third step of Phase 1?

The reviewer’s suggestion has been considered.

“Subsequently the ICP-algorithm is locally applied within each octree cell that represents the last step of Phase 1.”

21. P5r4: -> “that occurred between scan acquisitions”

The reviewer’s suggestion has been considered.

“The general idea behind this approach is to locally increase or decrease the portion of deformation in order to identify geometric changes that occurred between scan acquisitions by means of suitable criteria in Phase 2.”

22. P5r13-r14: “to clarify...object’s surface”: this I don’t get, please clarify.

The reviewer’s suggestion has been considered.

“This information is required in order to determine if an octree cell can be associated to a congruent set of cells or not.”

“The general concept of this feature considers the fact that every scan of a stable object yields in a different point sampling (Wujanz et al. 2016b).”

23. P5r15: how are these “stable regions” obtained?

The reviewer’s suggestion has been considered.

“This time however only stable regions, that were detected in Phase 2, serve as input which are processed as a whole and not in segments.”

24. P5r17: -> “deformation estimation” (not measurement)

The reviewer's suggestion has been considered.

The result of Phase 3 is a set of transformation parameters that forms the basis for the deformation estimation.

25. P5r20: -> "is to identify"

The reviewer's suggestion has been considered.

26.P5r21: I would not call this "segmentation" but "decomposition" or "voxelization"

The reviewer's suggestion has been considered.

27. Table 1: make separate columns for GSD and scanning increment

The reviewer's suggestion has been considered.

28. P7r5: "...at an elevation...and is ~ 900 m long and ~350 m wide"

The reviewer's suggestion has been considered.

29. P7r11: "and has reported to have a slower upper part..."

The reviewer's suggestion has been considered. The according sentence was quite lengthy and thus has been split into two sentences.

"The rock glacier itself shows distinct patterns of surface elevation changes and surface displacements. In addition, the rock glacier has reported to have a slower upper part and a rapidly moving lower part with maximum horizontal displacements of up to 2.5 m per year (Avian et al. 2009)."

30. P7: last paragraph: this is discussing existing work and fits better in a Ch 2 "Existing approaches"

The authors tried to move the very first sentence of the last paragraph into chapter 1 or 2 yet it did not really match the given content. Hence, the sentence remains as it was. The remaining references refer to research that is directly connected to the observed site and thus also remained in its original form.

31. Fig.3, caption I see a white circle, not a red circle?

The reviewer's suggestion has been considered.

"Figure 3: Scanner configuration at Hinteres Langtalkar rock glacier. The scanning position HLK is indicated by a red ellipse with a white edge, the rock glacier outline by a white dashed line. White circles with green edges highlight registration points (image, 28.08.2012)."

32. P8r9: -> "in the Central part of the Austrian Alps"

The suggestion by the reviewer has been considered.

"The Pasterze glacier (N 47°04', E 12°44') is located in the Central part of the Austrian Alps."

33.P8r15: -> "The current retreat of.. glacier has been observed using TLS since 2001..."

"The current retreat of the terminus area of Pasterze glacier has been observed using TLS since 2001 covering an area of appr. 0.9 km<sup>2</sup>."

while 6.3m vertical loss was detected..."

The reviewer's suggestion has been considered.

“On average the annual elevation change within the debris covered part sums up to approximately 3.7 m while 6.3 m vertical loss was detected in the clean ice section between 2011 and 2012.”

34. P9r11: “computed transformation parameters” computed by who?

The reviewer’s suggestion has been considered.

“As a consequence the computed transformation parameters based on the reference points can only be seen as an approximate solution as they are very likely to be subject of extrapolative effects and hence have been refined by surface based registration.”

35. P10: “nunatak mountains”??? Please explain

The reviewer’s suggestion has been considered. An additional reference has been added that covers this geological term.

“The rock fall area Burgstall comprises the two former nunatak mountains (Kellerer-Pirklbauer et al. 2012) of Mittlerer and Hoher Burgstall which were encompassed from Pasterze glacier until the beginning of the 20<sup>th</sup> century.”

36. Ch 4: p11: this page contains more general info, (like classification problem). This kind of info should be presented earlier, chapter 1, or chapter 3. Here just present and analyze the results.

We have carefully considered your suggestion and moved the according paragraph into different chapters. However, we decided to move back to the original logical sequence since the described assessment scheme is quite important for the reader since the results are presented in the very same section.

37. Also here you could mention once how the reference data is obtained; Later in the discussion: what is the effect of the location of the selected stable areas? If this location is rather small or badly covering the full extent of the ROI, this could affect the validation.

We have mentioned how reference data was generated in every subsection of chapter 4, for instance (from section 4.3): “Yet again, the sampling of reference points has to be rated as unfavourable. Hence, initial transformation parameters have been computed based on the reference points. Afterwards, deformed regions were manually rejected while the remaining points were used to refine the relative alignment between points clouds based on the ICP.”

38. Ch4: what do you mean by “inspection map”? Is there not a more descriptive name for these images? Is this not just a “change map”?

The reviewer’s suggestion has been considered. The problem is that there are numerous names for the very same outcome such as inspection map, difference map, change map, deformation map,... We decided to replace “inspection” with “change”

39. P14 r14: -> “in orange corresponding to large and detected geometric changes”

The reviewer’s suggestion has been considered.

“...glacier tongue is highlighted in orange corresponding to large detected geometric changes.”

40. P14r24: can you quantify these “margin of detectability”?

Not exactly, since we cannot visualise the uncertainty of distances between octree cells (the illustration would be chaotic while many coloured lines are overlapping). Instead we have added additional figures where the uncertainty values of individual octree cells are depicted. This shows the reader the heterogeneous distribution and magnitude of uncertainties.

41. P18: could you do and add some experiments with different resamplings (thinning of the data set)?

After long discussions we have decided not to reprocess the data even though we have done similar experiments at the very beginning of this project. We believe that the effect of sampling uncertainty is now a lot clearer to the reader since we have added some more figures according to comment #40.