Author Response **"Automated Terrestrial Laser Scanning with Near Real-Time Change Detection – Monitoring of the Séchilienne Landslide"** ***by*** **Ryan A. Kromer et al.**

Earth Surf. Dynam. Discuss., doi:10.5194/esurf-2017-6-RC1, 2017

Anonymous Referee #2

Received and published: 20 March 2017

We would like to thank Anonymous Referee # 2 for the valuable and detailed comments. We have responded to each comment below in red and made the necessary changes in a marked changes version of the manuscript.

GENERAL COMMMENTS:

"This paper describes the setup of a terrestrial laser scanning based monitoring system, including the installation of the hardware, pre-processing of the acquired data (e.g. removal of outliers, atmospheric correction, etc.) and also some first analyses (i.e. deformation quantification) and visualization of changes. As test scenario a landslide in France is chosen. This contribution is dedicated to a very innovative and important topic and it is definitely a pioneer study in the field of automatic 4D monitoring of Earth surface dynamics.

The current manuscript reads like a scientific/technical report with clear focus on the documentation of what has been done in this study. The aim is to present the specific TLS-based monitoring solution. I wished to see more science-driven facts and arguments in the paper: It is not clear what parts of the workflow are general facts and are valid to any TLS-monitoring (also other phenomena or LiDAR systems) and which parts/settings/algorithms/etc. are specific for this study site or only for landslides? This is an important fact for all readers because we want to learn how to set up our own system in our research without re-inventing the wheel. This could be improved by making this separation between general findings and the use case more evident in the manuscript."

Throughout the manuscript, we have separated parts of the workflow that apply to TLS monitoring in general and those that are specific to our study case and that are specific to the instrument we used. We have made this distinction clearer in an opening paragraph in the methods (P.5, line 1-13). We have also made this distinction in throughout the discussion section of the manuscript.

"You are working on landslides. What are the specific "user requirements" for your landslide use case from a process monitoring perspective - regarding hardware, scan acquisition settings (e.g. temporal and spatial resolutions), data processing times, etc.? For example, what is "real-time" and "near real-time" in your case (note that you do not use it consistently in the manuscript)? It would help much if you could describe all requirements that determine how you set up the hardware, software and also analysis methods."

We have changed all occurrences of "real time" to "near real time" throughout the manuscript. We also added a description of what near-real time means in this case to P.6, lines 7-9.

"The processing workflow described in Sect. 3.2 was designed to monitor earth surface processes in near-real time, defined as immediate post processing after collection, taking less time than the time between scans"

We made the distinction between requirements for our study case and for general use of the system (see comment above) and include a more detailed description in Sect. 3.3, P.17, lines 4-20.

"Furthermore, from a scientific perspective I strongly suggest to publish also your tools and scripts along with this paper. You used many open source frameworks - thus it is straightforward to publish it also open source. This would help the readers to follow your workflow much easier and to follow your work in a transparent manner."

We will publish the source code as supplementary material. The parameters can also be found within the source code. We have added references in the text to the supplementary material on P.13, line 3 and on P.13, line 27.

“A critical aspect that needs to be revised and explained is the presented alignment of point clouds. If you assume deformations in your data, you should only use data parts (i.e. areas) that do not change (cf. Wujanz et al. 2016: http://onlinelibrary.wiley.com/doi/10.1111/phor.12152/abstract). You write on Page 13/ Line 4: "In the fine alignment stage, we use all of the points in the point cloud to optimize the alignment.". I could not find any solution to this fundamental issue of deformation analysis in your paper.”

What was meant here is that we feed the entire point cloud into the fine alignment routine rather than using a subsampled version (keypoints or voxels) as in the initial alignment. We use a rejection pipeline to filter out or trim down correspondences that are the result of outliers, deformation or surface change. This is described in Section 3.2.3. This rejection pipeline ensures that only stables areas of the slope are used to calculate the transformation. To add clarity, we have added a brief description of this process on P.13 following line 4.

We have also added the suggested reference to the discussion section (P.28, line 19) as an alternative to the registration method we applied here. Note that this paper was published in September 2016, after the system was developed and deployed at the landslide test site (testing of our system was in April – May 2016).

“Another critical aspect for improvement is the confidence interval calculation in Sect. 3.2.5. First, I need to mention that you somehow use "accuracy" synonymously to your LoD value (e.g., P15/L5, P19/L9-L14), which pretends that your system quantifies changes or distances with 2-10 mm at 1000 m range.”

Lague et al. (2013) uses the confidence level to estimate the distance measurement accuracy. This is what was also meant here. To increase clarity, we have removed the term accuracy and reserve the term for comparison with independent measurements. We also added more comparisons with independent measurements (extensometer, total station, radar) at the study site.

We have redefined our LoD estimation to include an empirical registration error term as is Lague et al. (2013) and Fey and Whichmann (2017). This is described on P.16, lines 10-21. The empirical registration term accounts for systematic errors in the total error budget. It now better matches independent measurements.

“Following the scanner datasheet specification, your scanner has a range precision of 7 mm at 100 m (1 sigma) and thus it might be worse at 1000 m distance.”

For a single scan point, yes, the reviewer is correct, the range precision is defined as such by the manufactured. The method described uses averaged distances based on spatial and temporal neighbor distances. This method increases measurement precision by a factor of $\frac{1}{\sqrt{NN*\text{Tstep}}}$.

“Second, there is no validation with independent reference data. On page 22/last paragraph you state one value comparison (with an extensometer), which is not sufficient to evaluate your results.”

We have included independent comparison points from total station and radar measurements. These independent measurements were added to Figure 11 for comparison and are described on P. 22, lines 1-14.

Note that this system was designed for deformation monitoring purposes for rock slope or landslide sites where independent measurements may or may not be available. For these monitoring purposes, it is more important to confidently show that something has moved or that movement is accelerating than the absolute accuracy of the displacement value itself.

“Without further (mathematical) proof and explanation of your spatio-temporal confidence interval, I cannot approve what you present in this section.”

With our redefined level of detection estimation, we closely match what was done in other studies, for example, Lague et al. (2013) and Fey and Whichmann (2017). By including an empirical registration term, we obtain a better estimate of the LoD, which closely matches independent measurements at the study site.

“Some issue to consider regarding your main assumptions: You do not repeat a single LiDAR measurement if you average over time because you measure something (slightly) different with each scan (i.e. epoch).”

Yes, the reviewer is correct, a single point in the comparison point cloud (data point cloud) is slightly different with each scan, as mentioned. However, with the 4D averaging technique, we account for this variability. By taking the average over space and time we get closer to the centroid point along the local normal vector. We limit the search radius for points close to the local normal vector (see new Figure 6) to a factor times the mean point spacing. By repeating scans, we will get a central tendency towards this centroid. This method is described in detail in Kromer et al. 2015b.

“Your measurements are not independent because you use spatial averaging with neighbors for your cloud-to-cloud distance calculation (Sect. 3.2.4).”

The independent measurements described here are the averaged reference to calibration cloud distances vs the averaged reference to data cloud distances. Not distances between neighboring points. Figure 6 adds clarity to the distance calculation step.

“At the current stage this section is not plausible for me, but I am looking forward for indepth clarification.”

The LoD value is calculated based on a statistical analysis of measurement uncertainty. It is extended from Lague et al. (2013) and Fey and Whichmann (2017) to include the effect of temporal averaging. The LoD calculation includes random instrumental errors, errors due to surface roughness and misalignment errors caused by changing point patterns. We have added a new empirical term to the LoD calculation (Equation 3). This term accounts for remaining errors in the total error budget. These errors are due to misalignment of the point clouds and due to changing systematic errors in the point clouds. Misalignment errors increase with a decrease in point spacing and changing systematic errors could be due to a loss of calibration, due to temperature of the instrument or differences in atmospheric layers, for example. This term is empirically derived by calculating the standard deviation of the distances at known or assumed stables areas of the slopes and for this landslide, at stable total station targets. This is described on P.16, lines 10-21.

“In Sect. 3.3 you finally list some of the settings that you used in your case study. However, many settings are not mentioned, mainly of the processing steps (e.g. threshold for outlier removal, etc.). To be able to reproduce your results, it is necessary to know all the major settings that you applied, which could be put into an appendix section.”

We have included the source code as a supplementary file. All settings used can be found in the source code. We also mention settings that are specific to our study site (P.13, lines 2-3 and 25-26)

SPECIFIC COMMENTS:

“- P1/L14: Keywords: "Near real-time" instead of "real-time". “

Near real time is what was meant. We have changed all real-time to near real-time throughout the manuscript.

“P4/L8: ..."of the valley"?”

Corrected to “of the valley”

“P5/L4: -85% compared to which value?”

Added “of peak velocity”

“P6/L6: -> "ILRIS" in capital letters (applies also for other occurrences in manuscript).”

Changed all occurrences to “ILRIS”

“P6/L20: -> "RAM"”

Changed to “RAM”

“P7/L6: "Software design": The word "software design" is misleading because you do not actually design a software (as computer scientists would see it); you "use" existing software in a processing chain/workflow.”

Changed to processing workflow design

“P7/Fig.3: I cannot see a pan tilt. Either mark it or add picture.”

Marked pan tilt in Figure 3C

“P10/Sect. 3.2.3: I do not really see the point of your initial alignment processing for each dataset because you use a static scanning setting. Of course, you need to deter- mine an initial alignment when you change the scanner position completely - but why processing it every time and not only if something changes? Please explain better. See also my general comment above.”

This is because there is a home position bias. This means that repeated scanning from the same position results in misaligned clouds. The initial alignment stage insures a good initial fit for the ICP algorithm. The initial alignment stage is also very quick compared to the ICP algorithm. By providing a good initial fit, we reduce overall processing time of the registration pipeline. We have added text to Sect 3.2.3 (P.10, line 30) explaining this reasoning.

“P10/L27: positon -> position”

Changed to position

“P10/L28-29: These are speculations. I would remove such speculations from the paper and replace it with some hard facts.”

Removed these speculations.

“P11/first paragraph: This might be only necessary for "slow" scanners. Newer generation scanners are quite fast and such full scans could also be splitted and treated separately because we know the timestamps for each laser point.”

We have added that this may be only necessary for slow scanners and that this applies to our scanner/survey design.

“P13/Sect. 3.2.4: A sketch figure explaining the 4D distance calculation would increase comprehensibility of the method in this paper.”

This part of the algorithm is explained in Kromer et al. 2015b. However, to improve comprehension we have drawn a new figure highlighting the distance calculation method (Figure 6).

“P14/24: pi is known and must not be explained.”

Removed pi as requested.

“P16/Sect. 4.1.: is a valuable section!”

“P17/9: You use "surface saturation" or "slope saturation level" to describe the changing reflectance of the surface when it gets wet. From a physical perspective the changing reflectance of the surface is the main issue. I think "saturation" does not really fit to explain this issue because it has nothing to do with saturation of soil/material etc. -> reflectance of surface/target in the laser’s wavelength.”

This has been reworded as requested in this section and in the discussion/conclusions sections.

“P21/Fig. 8: Difficult to see anything. Too small. Rework figure to be larger and you could mark the processes that you identified in this figure.”

We have reworked Figures 7-9 to be larger and easier to read.

“P23/Fig. 9.: Add infos/description about points also in figure caption.”

Added description of the points to now Fig 10.

“P27/10: You did not evaluate the accuracy of the system.”

Changed to uncertainty and included independent total station and radar measurements.

“P27/19: This statement is not generally valid because other LiDAR systems can penetrate water/rain/etc. much better due to their different wavelength (e.g. green wavelength TLS). For your specific system it is valid, but you should not draw general conclusions from it.”

Removed general statement and specified that the discussion applies to the TLS system used in the study.

“P27/22: affect -> effect.”

Changed to effect.

“P28/6: must be Eitel et al. (2016)”

Changed to Eitel et al. (2016)

“P28/12: "We were also...". Is there something missing in this sentence? Difficult to understand.”

Rewrote second part of this sentence to increase readability.