Review

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Title: Full 4D Change Analysis of Topographic Point Cloud Time Series using Kalman Filtering
Author(s): Lukas Winiwarter et al.
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Reviewers: Roderik Lindenbergh and Mieke Kuschnerus

Summary

This article presents methodology to extract changes from extensive (hundreds of epochs) time series of 3D topographic data obtained by a permanently installed terrestrial laser scanner. It does so by running a Kalman filter on individual time series of spatially smoothed bitemporal point cloud distances at many different spatial 'core' locations. The Kalman filters are used to smooth the time series, to reduce uncertainty by averaging, but also to incorporate uncertainty in the change analysis. This procedure allows detecting changes that are smaller than just based on the raw time series. Smoothed time series are further clustered using k-means clustering. The new methodology is demonstrated both on a simulated data set and on a real data set of an active landslide.

Major Points:

- M3C2 distances are quantified perpendicular to the surface. What is the consequence of a changing surface orientation in (potentially) long time series?. Could the orientation be somehow incorporated in the Kalman filter?
- What is the consequence of using a reference epoch? Are the changes detected in, say, the 2nd half of time series independent of the choice of a reference epoch?
- F2b) suffices, no need to also show F2a;
- On the other hand, would be good to add one visualization of the synthetic data set to S2.2
- Ch. 3: the wording in the points 1-4, the section names 3.1 to 3.4 and the wording in F3 are all different, for clarity please use more similar wording and show more clearly in F3 where the steps 1 to 4 occur.
- Eq. (2) is generally known as the "error propagation law" and holds for any linear relation between observed and estimated parameters, compare, "Tiberius, C. C. J. M., van der Marel, H., Reudink, R. H. C., & van Leijen, F. J. (2021). Surveying and Mapping.", p69, https://textbooks.open.tudelft.nl/textbooks/%20catalog/book/46
- Therefore, error propagation can also be applied to the median filter, S3.2, when the smoothed value is obtained as a linear combination of existing values (with uncertainties) within the sliding window.
- The explanations on page 12 could be made more clear:
    - R278 introduces a measurement noise matrix 'R', but this matrix is not used in the consecutive explanation. Would be good to see 'R at work' in some equations.
    - R280 introduces Q, in the following, Q_{xva}, Q_{xv} and Q_x are used, but never properly introduced.
    - Similarly, \sigma_a^2, and \sigma_v^2 are never introduced (in general: explain all symbols)
    - R287: mentions \sigma^2 and refers to Eq. (6), but there is no \sigma^2 (without subscript) in Eq. (6).
    - What is the relation between 'discrete white noise" (R 286) and the following?
    - What do you mean by 'highest order"? Order in the sense of polynomials?

- In the presentation of the results, I would not present “linear interpolation” as (yet) another method, but as the raw time series
- F4: would be good to also include the original time series (“linear interpolation”). In addition, I cannot see any dotted lines in my A4 color print-out, the level of detection is not visible in the print out.
- Extend the explanation of ‘reduced level of detection’ due to Kalman filter approach (seems to be an important result)
- P368: intersection at “change of curvature” point: bug or feature? Is this good or bad to have?
- P376: please add a reference for the ringing artifacts.
- I feel for F5 and F6, three different locations should be enough: a) is similar to e) and somehow to d); that would also allow to merge F5 and F6, by showing the results now in F5 and F6 for say, a) c) d) together (directly below each other).
- 398: “gold standard”: for local validation the Total Station data could be used. Future work could also include the Kalman predicted displacement for next epoch with the measured displacement (as another way of validation)
- F9 and F10 are shown but hardly discussed, do they really contribute to the manuscript?
- Looks like there is no link from the text to Fig. 8. Either remove the figure or discuss it (I would suggest to discuss it)
- In general, further focus your results, e.g. by elimination: First, choose your best settings for the time series processing; Second, show the improvement in change detection between best settings and traditional pair-wise M3C3, Finally, show some different results for k, but only using the best settings; The results of the simulated data set could also be moved to the discussion -> are both Figure 11 and 12 needed? Could be combined into one, showing the most interesting results
- Would be interesting to see the average Kalman velocity (acceleration) per core point.
- I would move the percentages of change locations (4.26 % in r 441) to the results
- “The Kalman filter is ill-suited to represent sudden changes”: possible future work could be to test if a new measured value fits the Kalman trend given the confidence in both the trend and the measured value, this could result in a kind of trend change detection,
- Kalman filtering has been previously used to smooth bathymetric MBES data, e.g. Bourgeois, B. S., Elmore, P. A., Avera, W. E., & Zambo, S. J. (2016). Achieving comparable uncertainty estimates with Kalman filters or linear smoothers for bathymetry data. *Geochemistry, Geophysics, Geosystems*, *17*(7), 2576-2590.

Minor Points:

- Abstract: “almost double”, relative to what baseline method?
- Abstract: “this can be a critical’: can be positive or negative, maybe reformulate as ‘This is a solution for subsequent analysis methods that…”
- Intro, r28: “needs to” -> “is” (needs to would require a mathematical proof that there is no other way)
- Intro, r48: “detectable” -> “detecting”
- Caption, F2a): -> “Histogram of the number of points found”
- S3.3., r250: I would call it an “assimilation” method, rather than an “online” method.
- S3.3, r250: “post hoc” -> “a posteriori”
- R219: ‘right’ -> left
- R247: ‘empliyed’
- R259: -> “For a state vector x_t containing…”

- R263: -> The diagonal entries of Eq. (3) ensure”
- R280: skip “Finally”
- R305: -> The impact of the exact choice”
- R328: -> “time series similarity”
- R328: -> “How the differently smoothed time series” (right?)
- R331: -> “Euclidean”
- Ch 4: in the first lines, I would explicitly introduce S4.1 to s 4.4
- caption , F10: “larger” -> “starting from”