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***Interactive comment on* "Development of smart boulders to monitor mass movements via the Internet of Things: A pilot study in Nepal" *by* Benedetta Dini et al.**

Anonymous Referee #2

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The presented work focuses on the deployment of accelerometers and its real-time data transmission as possible low cost means of surveillance for large single blocks to identifiy mass movement associated with landslide type of rock slides. It presents a substantial an thoroughly carried out field measurement campaign and careful data analysis. The use of IMU technology for boulder tracking and its possible applications for early warning systems is a highly relevant topic. The comprehensive presentation of this pilot study definitevly merits publication after some minor revisions.

Generally, the presentation of the entire work is very nicely done. I also have to thank the authors to present a carefully edited and proofread manuscript, which made reading easy and enjoyable.

Dear reviewer #2, thank you for taking the time to read our manuscript and for judging our work worthy of publication. We also thank you for offering interesting cues to references and use of techniques that we had not previously included. We tried to address the points you have raised in the manuscript and we give our response to each comment in teal below.

In the following some content and technical suggestions for improvement and addi- tional context are provided. IMHO the manuscript would benefit of some remarks on remaining challenges and disadvantages of IMU tracking/signal processing.

Introduction l41: Large boulder movement rarely comes isolated. While the approach to use large boulders as particle marker for mass movements with modern technology is new, the general statement that the motion of large boulders and its damage potential is not discussed in literature may be a bit exaggerated.

We did not mean to imply that hazards that involve the movement of large fragments have not been studied. The presence of boulders of given sizes in given proportion has not been, to the best of our knowledge, directly accounted for in hazard assessments of landslides and floods. However, we deleted this sentence since it is more relevant for another part of our work that is not included in this publication.

L54: large boulders can be detected via RADAR/LiDAR technology, which is truly re- mote. The target boulders here predominantly are early warning signs

L64: State-of-the art RADAR (no interferometric RADAR of course) techniques are able to deliver real-time data for immediate mitigation actions such as road closures etc. See https://ui.adsabs.harvard.edu/abs/2020EGUGA..22.5138W/abstract for the lack of better reference sake.

Thank you for this, mentioned.

General remark: With all the advantages listed for the IMU technology applied, one crucial disadvantage needs to me mentioned: The installation of the sensors do require physical presence at the block. While this may not be a problem for large boulder instrumentation in slowly evolving mass movements, this is certainly a major drawback to deploy the presented technique in active sites.

It is certainly a drawback (mentioned in text at l. 750) and it is true that it might be impossible to tag particularly dangerous sites. However, we did tag active sites (not rockfall sites) and also this technology could be used to tag upper reaches of catchments (e.g. km upstream of sites affected by flash floods). Equally, to install a monitoring network that requires the use of ground based LiDAR or RADAR, a base station has to be placed with line of sight of an active site. This is also not feasible in many instances. The answer is probably that no technique is perfect for all cases, but each case would have to be evaluated carefully to decide what technique is more suitable (also in terms of economic efforts). The network type we propose has the enormous advantages of becoming cheaper in the future and to allow for activation on movement.

Methodology 3.1 Network setup and components Really nicely presented methodol- ogy!

Thank you for this nice acknowledgment.

Notation remarks: âĂć Generally throughout the manuscript, change the notation of the local gravitational field of Earth to texit{g} or g as it denotes a physical constant usually denoted in italic font. This also removes the ambiguity of mg and mg. âĂć The same holds for x,y and z axis, variables denoted by italic characters. Any given coordinate system is given by its n-space.

We have changed the notation of g and x,y,z to italics, we hope we have correctly interpreted this comment.

3.2 Choice of tracked boulders l298 coherently collectively/mutually. Coherence would imply that the motion pattern is the same, as a laser has coherent wavelengths. Large boulders can move with the landslide but usually succumb to a slightly different kinematical regime. True coherence in nature is extremely rare.

We mean "as a whole". Clarified throughout.

3.3 Sensor Settings l323ff replace the " " with approx or the word roughly, about, etc.. Tilde means "similar to" and is usually used in plain mathematical context.

Done.

l352 maybe add "before the peak when sampled at 2 Hz." If sampled at higher fre- quency, such double or three peak hits are not that uncommon.

True. Peaks would not be uncommon if movement occurred in which case one could expect to observe a sequence of simultaneous peaks in all axes and with different values attained during or after the end of the movement sequence (see a comment above in response to reviewer #1). But surely the fact that we are sampling here at 2 Hz, as you say, makes the peaks we see even less likely to be associated to real movement. Suggestion added.

4 Result Thorough presentation of the results. Only notation of axis and g and " " characters would need some attention.

Done.

5 Discussion Validation of motion is partly done via camera imagery. While I would agree that only tilting motion of an embedded rock is not feasible to be detected via imagery, I would argue with the progress in resolution an image processing, a pixel tracking via cross correlation analysis of interval imagery might well track slow motion onsets. The spatial resolution is then given by the camera's resolution. Just one of a zoo of cross-correlation papers (https://nhess.copernicus.org/articles/17/2143/2017/)

The detectable grain size would highly depend on resolution/distance and the detectable movement also on the movement magnitude. Here we are talking of boulders imaged at a distance of approximately 600-700 m (depending on exact point within the network). This, according to the resolution of the camera, should give a pixel size for the scene acquired of about 15 cm. Indeed, we can see quite clearly large boulders in the channel. The landslide area however, as it can be seen both in figure 7A and in the video provided as supplement, is at a relatively low angle with the LOS of the camera. The camera looks towards ESE (approx. 119°) and the direction of the plane of the landslide is NW (approx. 327°). Finally, the tilting of the boulders in that region is shown in the accelerometer data to be of a few degrees only. Slow motion onset of the whole landslide mass is indeed well visible and this could surely be tracked with appropriate pixel offset techniques. Though this would be useful, it is beyond the scope of our paper.

L668 while in the introduction the https://nhess.copernicus.org/articles/17/2143/2017/ heritage of animal tracking is mentioned, a com- parison with state of the art logistic tracking devices such as MSR sensors or trusted global devices (just to name two), would be interesting. Modern logistic shock tracker do also work with acceleration and angular velocity IMUs and sometimes even come with satellite network coverage to send the reports.

L688 As stated by the authors, independce of GPS/GNSS signals is of paramount importance.

Yes, and we have now achieved this with the new development. Thanks for acknowledging this.

L731 Accurate position information from IMU sensor integration requires sophisticated post-processing procedures in order to minimize integration error accumulation. This is feasible in case of periodic motion or motion patterns, where at specific positions intime a zeroing of the errors is possible.

If this is not the case, accurate position tracking via IMU is extremely challenging, especially for fast motion. If GNSS (maybe refer to GNSS than GPS alone, as there are many other systems in the sky then GPS only) measurements will become obsolete in the future, one will see.

Rephrased.