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Interactive comment on "Dense point cloud acquisition with a low-cost Velodyne VLP-16" *by* Jason Bula et al.

Anonymous Referee #2

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Dear authors,

I was asked to provide a review of the paper: "Dense point cloud acquisition with a low-cost Velodyne VLP-16" authored by Jason Bulla, Marc-Henri Derron and Gregoire Mariethoz.

General comments:

This paper shows how a lidar hardware, mass-produced for the autonomous car industry, hence cheap, but not designed for topographic measurements, can be assembled with common equipment to build a tool for dense point clouds generation. This subject is really appealing for many geoscience researchers. You make a point at staying as pratical and low-tech, as well as low-cost, as possible. The core of your contribution

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resides in determining two unknown values which bias the data: the angle between the local vertical and the scanner's scanning angle origin (alpha-1) and the scanning plane angle (alpha-2) with respect to the supporting platform rotation axis. In essence, the exercise solved expresses a scanner's rotating (time variant) XYZ coordinates into a static (time invariant) cartesian reference frame.

This goal is very valuable. It would further benefit the geoscience community to a higher degree if the resolution code was provided as supplementary material.

The paper is concise. It is appreciable in many respects. This conciseness is however detrimental at times. In particular, the presentation of the equipment and its specific setup is too elusive, and the wording not sufficiently defined. The reader needs to grasp what output data is provided by the Velodyne scanner and by the rotary motor. In what form ? XYZ, time, intensity, polar coordinates? How the synchronization between the platform and the scanner perfomed? These are the prior information for solving the unkonwn variables, but they are not explicit in the text.

A second point is the need to specify the domain of application targetted by this equipment. What would be the required point density and precision to deem the equipment fit for its intended purpose?

This being said, I would really like to start testing this Equipment for my own applications and see plenty of usage for underground permanent scanning in Dangerous areas. This is good job to have tested and published the results.

Specific comments: On the paper structure: The abstract should absolutely state the term Terrestrial Laser Scanner (TLS) so as to understand what range of problems are addressed with this hardware solution. It should also state the point precision and the range within which is achieved (line 6: "good result" must be qualified). And also qualify explictly what you mean by expensive and cheap device. Price is set forward as the core issue? But then there is no extension of what low cost would mean in terms of applications. It opens the door to measuring risky sectors where instrument loss is high but information valuable. It also enables using multiple scanning devices. This is what your contribution opens.

The introduction does not do justice to your work. The introduction contents does not frame your work properly. An introduction should specify the scientific and technical landscape in which your study is set, establish gaps in previous works, sketch the question that you will solve and evoke the technicalities to solve them. In essence your introductory section contains 3 paragraphs: what is a laser? what properties does a Terrestrial Laser Scanner have? And then, what you have done. The reader does not have a good overview of laser scanning applied to geosciences nor of pending issues that you set out to solve. You evoke issues linked to hardware cost, 3D point cloud density, scanning duration and point cloud accuracy. The logic articulating these 4 ideas however remains elusive.

Here is an attempt at repackaging this introduction. My understanding of your paper is that you try to create an accurate depiction of your 3D environment with a lidar profiler designed for the autonomous car industry. The chosen model is mass-manufactured, hence cheap, but designed to address obstacle avoidance issues, not 3D environment reconstruction. The Velodyne VLP-16 scans 16 parallel profiles in a field of view of +/-15° above and below the scanning plane, 360° around the scanner's axis. Each lidar profiler is set 2° apart in a plane normal to the profile rotation axis. Your aim is to densify points in the 2° interval using an external rotating plate.

Note that rotating the scanning plane of a profiler is the solution adopted by all TLS manufacturers since the early 2000. The mathematical solution therefore exists somewhere, refering to it may be useful if explicit documentation exists on the matter. But since it may not be clearly exposed by manufacturers, or you may have an original approach, there is value in (re-)exposing the methodology in a free and open access article. To prove your point, you show an implementation with much cheaper hardware than that currently for sale. This option goes with its own issues which you then discuss.

Your list of applications papers is rather short and perhaps not exhaustive enough for pioneering works with laser scanning (references in the end of this review). For TLS applications on landslides and rockfalls, perhaps add citations for Lim et al. (2005), Dewez et al (2007), Abellan et al. (2009). For permanent laser scanning applications, you cannot miss Williams et al (2018). It is another application where the use your low-cost solution has a future. For mobile laser scanning, there are the studies using boatborne systems e.g. Michoud et al (2015), Feldmann et al (2018). Mobile handheld devices such as Geoslam's Zebedee in different versions was discussed among others by James & Quinton (2014), Chang et al (2016), Dewez et al (2017).

When it comes to the essence of the paper, the reader is left in the dark on many issues.

A figure decomposing the different reference systems and key variables of the lidar and assemblage would be extremely useful. This will help the reader grasp the essence of the problem. Figure 4 is not sufficient to understand the geometry of the acquisition system. Make it in relation with the terms given in table 1 and 2.

In table 1, What does the vertical angle increment and horizontal angle increment mean? Can you sketch these on a figure ? The issue tackled is that of a moving reference frame. The rotation motion is eccentric and in some non-vertical plane. A clear description of the different reference systems and how they relate to one another would clarify the problem. Please also state what the digital output of the lidar is. Does it output a series of XYZ point coordinates associated with a time stamp for each? Does one have access to the lidar beam index number? Does one have access to the "horizontal" angle? Is there an index point value to know which one of the 1810 angular increment a reflector is related to? In Riegl's vocabulary, the different reference frames are called SOCS (Scanner's Own coordinate system) and PRCS (Project's Reference Coordinate System). Using a similar terminology will perhaps help to clarify the concepts. And even within the SOCS reference frame, there is one associated with the scanner and one relative to the rotary motor rotation. Inside the

VLP16 each of the 16 beams scan a circle around a rotation axis clockwise. The direction of each beam diverges by 2 degrees. This divergence make that the lidar traces 16 cones of revolution about a centre. The origin of the circle of revolution (Y axis on figure 4) may be offset. It would be usefull to spell all this out both in text and drawing.

I also feel uneasy with undefined terminology which confuse me alot. What is the meaning of "10 frames per second" (line 28)? What is a "frame" in this context? Does it have a raster meaning ? If it is a 2D grid in some reference frame, which one? Could it be a grid in polar coordinates? In this time-variant system, should I understand a frame as something acquired during a short duration like a photograph? Defining this term will reduce speculations. Line 59: "Each frame is rotated by an angle" How so? Isn't it a continuous rotation? What is a "frame" in this context?

What is an image (line 39)? Does it mean a "representation" ? Is it a 2D raster grid with values? Can it just be a vector of polar distance with time? Again, not defining this term leaves the reader speculating

Why talk about time lapse (line 58)? Isn't it a continuous acquisition? I understand "lapse" as a series of static snapshots. Do you mean the Syrp Genie motor is stepping by increments? Or is it continuously rotating? Please mention this is in Section 2.3

Calibration (line 88): what do you mean? You are certainly trying to resolve (i) the eccentricity, (ii) the angle between the scanner's origin Y axis and the plumbline vertical, and (iii) the inclination of the scanning plane with respect to the plate rotation axis. Here by vertical I refer to the direction of a plumbline under the scanner, not the abusive "vertical" term used in table 1, which only marks the direction of the rotation axis. The plumbline direction may not coincide with the motor's rotation axis orientation if the tripod head is not level (not discussed but worth mentioning). Please make an explicit note about the abusive use of "vertical" and "horizontal" in table 1. You may very well keep on using vertical and horizontal abusively in the text, but warn the reader you do so.

Section 3.3 (line 115) You write that a plane is fitted in the distance range 3-7 m from the lidar. It is probably for this reason that the alpha-1 and alpha-2 determination yield the residual error pattern seen on figure 6b. The two-tailed error pattern gives the impression that the inversion solution was not trying to optimize the appropriate mathematical function. Dropping the negative error branch unilaterally seem not properly justified. You are hiding errors arbitrarily. With this double branching function, computing a moving average would cancel the error rather than bias things further by using just one branch.

For a different approach, you may want to look at Chang et al (2016). They based their tests on reconstructing geometrical shapes. In the corridor where the scan is tested, you could have used the planar walls and rectangular section properties to assess lidar "refocussing".

Section 4 Result line 150: Figure 5 is absolutely not visually explicit on a printed version. You try to exhibit cloud roughness in Figure 5a, and how your post-processing (rather than the word "post-treatment") improves results in figure 5b and 5c. Why did you not use Cloud Compare's Roughness estimator (radius > 20cm) ? Cloud Compare's EDL shading is very smooth, too smooth perhaps to show your point. Roughness with a single appropiate colour ramp for all 3 figures should demonstrate your need (along histogram of rpoughness values to objectivate your statement?). Alternatively, you may want to compute normals at 10-cm radius and display them. 10-cm is the half wavelength of the floor artefacts (figure 9). The surface roughness will appear as very variable values.

Section 4.2 Densification quality Cloud Compare's Cloud2Cloud distance estimate is used. This only provides a one-sided (absolute value) distance. Why not use M3C2 to provide a VLP16 to Zeb-Revo signed distance? What is the quality of the scan with Zeb-Revo?

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Table 5 and table 6: what are the units of alpha-1 and alpha-2 ?

Section 5.3 line 211 "... with the Geolsam superposition +/- 2cm is present": what does it mean? line 212 "...presence of people in the scan" Why didn't you remove these points before collating the statistics. They are irrelevant for describing scanning quality. line 2018 "The wave frequency...", do you mean wavelength?

Sectiton 5.4 Origin of the short range artefacts Have you tried to check the ground pattern from a single beam? Glennie et al 2016 show that there are ranging inconsistencies in some beams of the VLP16 they tested. Their most external beams were range-biased. Could these defects explain the pattern you guys observe? Or else, is the tripod sufficiently rigid? Is there a ranging error dependant on a non-steady time constant?

Section 6 conclusions line 227: "The results ... are satisfactory" How so? There is no mission statement to argue about the acceptable nature of the result. You should state what acceptable means for your applications and perhaps reflect on a few applications which would be satisfied with this level of precision and this tool.

line 229 "... verified the quality of registration". Registration of what? Wording ambiguous

Reference list Chang et al 2016 (http://www.ingentaconnect.com/content/10.1127/pfg/2016/0294) Dewez et al 2007 (https://www.researchgate.net/publication/340621519_Laser_survey_and_mechanical_modelling_of_cha Dewez et al. 2017 (https://onlinelibrary.wiley.com/doi/full/10.1111/phor.12223) Feldmann et al 2018 (https://www.researchgate.net/publication/329707149_Scanner_laser_mobile_sur_bateau_methode_de_ James & Quinton 2014 (http://doi.wiley.com/10.1002/esp.3489) Lim et al 2005 (https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1477-9730.2005.00315.x) Michoud et al 2015 (https://link.springer.com/article/10.1007/s10346-014-0542-5) Williams et al 2018 (https://www.earth-surf-dynam.net/6/101/2018/)

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