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Review of Remote Sensing Technologies for the Acquisition of Very High Vertical Accuracy Elevation Data (DEM) in the Framework of the Precise Remediation of Industrial Disasters – Part 2

Based on the information gathered within the technologies review performed in the previous article, the authors analyse if the deferent technologies could efficiently (or not) support the excavation work to be performed for the remediation of industrial disasters. At first sight, some technologies reach the requested accuracy. But after considering the error propagation when the technologies are applied in the condition of the fieldwork, it turned out that none of the remote sensing techniques we have reviewed finally offers sufficient accuracy to reach the 2.5 cm relative vertical accuracy target that was set. The final conclusion is a direct real-time measurement in the field, and the development of an appropriate apparatus for the real-time control of the blade may be the appropriate solution to reach the targeted accuracy in the field. This approach should be examined and developed in a next research work.

Keywords: remote sensing, DEM, industrial disaster, remediation, LiDAR, photogrammetry, UAV, accuracy

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1. Introduction

Precisely eleven years ago, on 6 October 2010, Hungary was facing one of the most terrible industrial disasters of its history with the Kolontár red sludge event.[5] Since then, technology has evolved and researches were done on how to handle the remediation work more efficiently. Advantage could have been taken from the existence of geographic information prepared with remote sensing techniques;[6] the preparation of a detailed digital remediation plan and its implementation in the field with navigation technologies and machine control technologies.[7]

This study aims at identifying the most appropriate method(s) (and the associated technologies) in order to generate a very high vertical accuracy TIN to be potentially used in a 3D grading control system for the precise remediation of industrial disasters. Very high vertical accuracy means a priori that the value is smaller than 2.5 cm. This targeted order of magnitude was determined after investigating the horizontal accuracy achievable with classical positioning systems in civil engineering and precision farming.[8]

First of all, we believe it is of help to provide the reader both with a brief description of the background of the research work and with a recapitulative overview of the work achieved so far. This insight will help with: 1. introducing the different parts constituting the overall research work; 2. including this part in the overall research work; and 3. providing all the elements necessary to clearly and completely understand the research questions, challenges and issues related to the question of TIN generation in the specific scope of precise remediation.

Overall, our research work aims at developing an approach for precise soil excavation after an industrial disaster happens. The precise excavation consists in removing a targeted thickness of dirt from the top layer of the ground. It was demonstrated that with the help of remote sensing technologies (or more generally an association of techniques including remote sensing) it is possible to precisely map the extent and the thickness of pollution.[9] Using the resulting digital map as input, Lucas et al. developed a set of geo-processing tools that automatically prepare a detailed geospatial remediation plan figuring: 1. any single parcel associated with the footprints of the planned blade passage on the ground (polygon feature class); and 2. any navigation

5 László Kátai-Urbán – Zoltán Cséplő: Disaster in the Ajka Red Sludge Reservoir on 04 October 2010. In *Sixth Meeting of the Conference of the Parties to the Convention on the Transboundary Effects of Industrial Accidents.* The Hague, 8–10 November 2010. 1–19.

6 Csaba Lénárt – Andrea Ambrus – Péter Burai: GPS technológiák alkalmazási lehetőségei és vállalatirányítási rendszerben való szerepe a Havas '92 Növénytermesztő Gazdaszövetkezetnél. In *XII. Nemzetközi Agrárökonómai Tudományos Napok.* Gyöngyös, Károly Róbert Főiskola, 2010. március 25–26.

7 Gyula Vass – Attila Zsitnyányi: Multifunkcionális járművek alkalmazása a katasztrófavédelemben. *Hadmérnök,* 14, no. 2 (2019). 44–55.

8 Explanations are provided in Table 1.

9 Péter Burai – Amer Smailbegovic – Csaba Lénárt – József Berke – Gábor Milics – Tamás Tomor – Tibor Bíró: Preliminary Analysis of Red Mud Spill Based on Aerial Imagery. *Landscape and Environment,* 5, no. 1 (2011). 47–57; Csaba Lénárt – Péter Burai – Amer Smailbegovic – Tibor Bíro – Zsolt Katona – Roko Andricevic: Multi-sensor Integration and Mapping Strategies for the Detection and Remediation of Red Mud Spill in Kolontár, Hungary: Estimating the Thickness of the Spill Layer Using Hyperspectral Imaging and Lidar. In *2011 3rd IEEE GRSS Workshop on Hyperspectral Image and Signal Processing (WHISPERS).* Lisbon, Portugal.

lines (polylines feature class) planning the single move of grading equipment.[10] In order to complete the approach, a technical setup still has to be proposed for the precise positioning of the grading equipment in the field according to the geospatial remediation plan. The guidance of the heavy equipment in the x and y dimensions can quite easily be solved with classical navigation equipment.[11] The precise positioning and control of the blade of the grader in the z dimension is a more challenging issue. 3D grading machine control systems and software used in civil engineering potentially offer efficient solutions.[12] 3D grading systems require for their implementation a surface elevation model which figures the vertical reference surface. Underneath this surface, the soil should be excavated with the appropriate thickness. This digital surface model is provided to the 3D grading control software within the shape of a Triangular Irregular Network (TIN). The degree of vertical accuracy reached with elevation data acquisition/extraction method and the TIN model generation is the general scope of this study.

In the first section some conventions and postulates are introduced. In the framework of precision work, examining the accuracy question is essential. Then in the following section, we examine the accuracy achievement in the field by applying an error propagation analysis. Finally, we conclude about the advantages and disadvantages it offers in the specific scopes of our study. Then the discussion and conclusion follows.

2. Postulates and conventions with field practices – Analysis with field practices

2.1. Postulates

This work relies on three postulates. First, we assume that the blade is not performing levelling as it is commonly done in civil engineering work (making plane surfaces) but it should follow the terrain surface irregularities in order to excavate a targeted thickness measured from the surface. The postulate is that polluted soil can be modelled like a regular layer on top of the clean soil.

Secondly, we assume the thickness does not vary on a single work parcel. This is because in the remediation workflow, the terrain is categorised by class of pollution thickness, and each zone is cut into single parcels where the thickness has a known and constant value.

10 Grégory Lucas – Csaba Lénárt – József Solymosi: Development and Testing of Geo-processing Models for the Automatic Generation of Remediation Plan and Navigation Data to Use in Industrial Disaster Remediation. *Open Geospatial Data, Software and Standards,* 1, no. 5 (2016).

11 Grégory Lucas: *Advanced and Combined Utilization of Geographic Information Technologies in Industrial Disaster Remediation – Simulation with the Red Mud Disaster of Kolontár.* PhD dissertation (draft). Budapest, University of Public Service, 2021. 110.

12 Ibid. 115.

Third, concerning the field practices, a dozer or a wheel loader is carrying a blade or a bucket to perform earthwork and pushing the pollution located on soil surface at the end of a push line. The thickness of soil that is processed comprises the polluted part of the soil as well as (eventually) a not polluted part called the "security layer" in order that all the pollution could be excavated for sure (a complete remediation is set as the objective).

2.2. Gauging point density and appreciating vertical accuracies

Empirical and analytical rules can help to select a suitable grid resolution for output maps.[13] Among the criteria to consider there are the inherent properties of the input data;[14] also for DTM the cell resolution selection that should be based on point density and distribution, horizontal accuracy, terrain complexity;[15] and finally, the relevant scale and scale combination for the process or attribute being modelled.[16]

2.2.1. Scale comparison issues

In our case we consider the scale elements first. Regarding terrain irregularities, three situations can be observed.

1. The irregularities are too small to be considered compared to the blade positioning capacity when: irregularities are smaller than the blade positioning accuracy; irregularities are falling across the blade width; and the grading control system does not allow enough velocity to follow the terrain irregularities in time while the equipment is moving. In such cases it is pointless to try to properly position the blade to handle the terrain irregularities.
2. The blade fit in between the terrain irregularities and positioning capacities is sufficient. In this case, it is technically possible to achieve the positioning and control of the blade if the terrain model provides sufficient details.
3. Several blade lengths or width can fit into the terrain irregularities as the terrain is more regular. In that optimal case efficient grading control can be achieved. This is the favoured scenario.

The blade presents two dimensions and two different scales must be considered: 1. the blade length (oriented in x); and 2. blade width (orientated in y). It is possible to imagine some situations where the width of the blade does not fit within terrain irregularities whereas the blade length does.

[13] Tomislav Hengl: Finding the Right Pixel Size. *Computers and Geosciences,* 32, no. 9 (2006). 1283–1298.
[14] Ibid.
[15] Ibid.
[16] Stefano Cavazzi et al.: Are Fine Resolution Digital Elevation Models always the Best Choice in Digital Soil Mapping? *Geoderma,* 195–196 (2013). 111–121.

Figure 1: Terms definition and dimensions
Source: Compiled by the author.

2.2.2. Gauging the appropriate cloud point density

The cloud point density refers to the raw source data density: cloud point before filtering in the case of ALS data, cloud point extracted with dense matching in the case of SfM, etc. The repartition of the point on surface does not privilege any orientation, only an average point density can be foreseen (and an average sampling distance defined). This sampling distance should be adapted to the "finest" terrain irregularities the equipment can handle, for instance the irregularities fitting in the x direction. In such condition, the sampling distance in y will be small compared to the scale. Consequently several points will fall along the blade profile and some regression methods should be decided.

As a general rule, it can be set that the cloud point density is appropriate if it can figure out properly the variation of terrain elevation.[17] As a consequence, if the terrain elevation is not varying that much, the point cloud density can be lowered; if the terrain elevation is varying a lot, the point density has to be higher for its correct representation. This rule and remarks are fundamental but still they are not usable as they remain relative and are not connected to the field practices. We have to find a way to figure out a reference point density. This is connected with the scaling issues mentioned before. To do so we propose to consider the blade width and terrain roughness to: 1. consider which profile sampling distance would be useful to reach a fine blade positioning (along y) (Figure 2); 2. consider the frequency that would ensure an appropriate correction of the blade position (along x) (see Figure 3).

[17] Hengl (2006): op. cit.

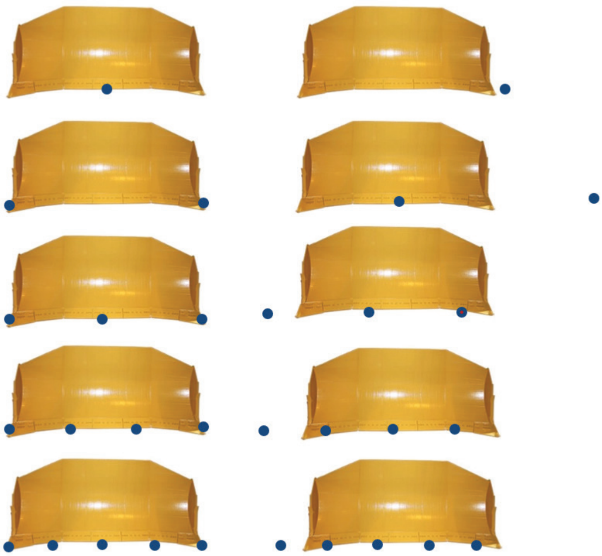

Figure 2: Sampling distance compared to blade profile positioning
Source: Compiled by the author.

Figure 3 shows the configuration blade/point density based on a point sampling pattern ranging from 1 to 5. In our opinion, the configuration starts to be secure with 5 point per blade length. Then the appropriate regression method would have to be thought over (statistical point of view) to properly weight and use the points.

As point sampling is the same in the x and y direction, the point sampling along the working equipment direction will be the same as for the profile sampling. Figure 2 shows how point repartition would look like in the case of a 5 points sampling per blade length in a terrain with a small gully. If sampling distance is increased, one can figure out that the blade will follow less accurately the exact gully profile and the excavation work will become more approximated. We can logically argue that the terrain model should figure out terrain irregularities which are same scale as the blade. And we can also propose that the sampling distance should be at minimum blade length divided by four; generating 5 points per blade length in x and y directions. This value has to be compared and be in coherence with the distance run between two blade position updates (refreshment distance, see below).

As we mentioned in the introduction of this section, more flexibility is available to follow terrain profile along x than along y. The reason is that the blade tilting can be tuned, but the shape of the blade cannot. A smaller blade can be mounted if remediation achievement objectives require more performance to follow the irregular terrain along y for the clean-up.

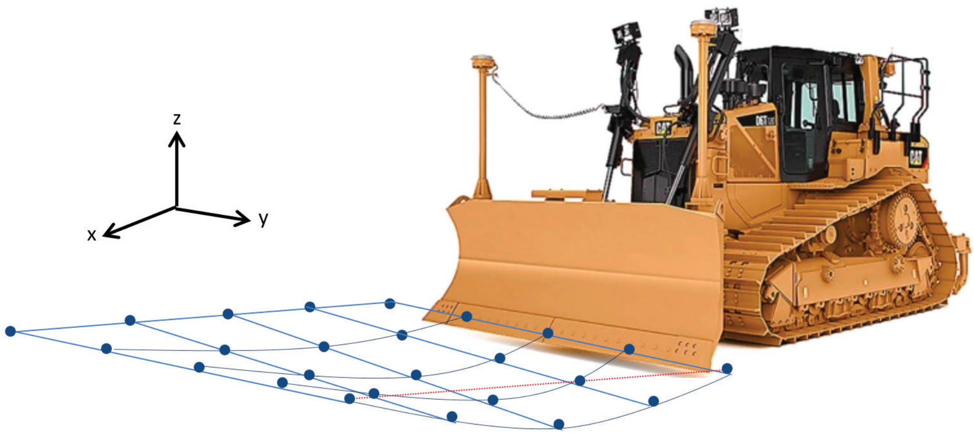

Figure 3: Scale model of correction along the push line with 5 points sampling/blade length
Source: Compiled by the author.

Finally, a pragmatic way of solving the problem is to examine how frequently can the blade height be updated by the control system. Based on the frequency and the speed of the equipment during the clean-up work, a corresponding distance (refreshment distance) could be calculated and used as a reference metric for the calculation of the sampling distance.

Finally and to conclude, the value to be selected is the smallest between the refreshment distances, the sampling distance based on irregularities and the blade smallest dimension (assuming remote sensing is not the bottleneck and it offers the possibility to collect a sufficient point density).

2.3. Target for the vertical accuracy of the TIN model

As stated in the introduction, it would look a priori appropriate if the vertical and horizontal accuracy could be close to each other (which means few centimetres in practice as the horizontal accuracy is few centimetres). Examined more in details, the reference metric in this situation is the volume of soil associated to the accuracy; the volume of dirt is the physical parameter which cost in earth work operations.[18] Any bulked volume of soil has to be excavated and hauled. In our research,[19] we demonstrated that with a classical 4 m blade, a 5 cm deviation along y moves the same volume of dirt as a vertical deviation of 2 mm (along z) when 15 cm thickness is excavated. The table below recapitulates the matches for several thickness values, all standing for a 4 m blade. So having the same accuracy objective in x, y and z is

[18] Manuel Parente et al.: Metaheuristics, Data Mining and Geographic Information Systems for Earthworks Equipment Allocation. *Procedia Engineering,* 143 (2016). 506–513.
[19] Lucas (2021): op. cit. 109.

not coherent in regards of the costs (calculated on the volume generated by the excavation). And a consequence, if we want to have coherence, is that the vertical accuracy should be much higher in z than in x and y.

Table 1: Calculation of the vertical deviation producing a volume matching with the one of horizontal deviation of 5 cm for several thicknesses
Source: Compiled by the author.

Thickness (cm)	**Volume for 1 m push length (m^3)**	**Horizontal deviation (cm)**	**Vertical deviation (mm)**
5	0.05 × 0.05 × 1 = 0.0025	5	0.6
15	0.0075	5	1.9
30	0.0150	5	3.7
45	0.0225	5	5.6

In practice because of the "construction" of our approach, we end up with results of relative vertical deviation which is much more than the relative horizontal deviation. This difference can be explained as follows. Part of the vertical deviation is related to the uncertainties of the source DEM. The second deviation we can mention is related to the blade positioning deviation, resulting of GPS positioning errors, grading system control error. Finally, a deviation exists on the thickness of the pollution layer as it is an estimation. Because of those uncertainties, the blade should be positioned deeper than the pollution thickness if we want to be sure to remove the pollution completely. The thickness of this "security layer" should correspond to the square root of the sum of the square of the three deviations therefore mentioned [Equation (1)]:

Security layer thickness = $\sqrt{}$ (bucket positioning deviation)^2 + (DEM deviation)^2 + (pollution thickness deviation)^2) (1)

The resulting proper positioning of the blade corresponds with the sum of the pollution thickness and the security margin. As the security margin layer is the result of a sum and as it positions the blade part of the line in a clean soil (because of precaution), it represents a waste (volumetric with excavation, energetically and a destruction of soil). Consequently, the influence of the diverse deviations should be particularly considered;[20] and because of the scope of this paper in particular the one of the DEM.

[20] At this point it can already be assumed that the sum of the several sources of error will not result in an appropriate magnitude value for the relative vertical accuracy. It is discussed in details in the discussion.

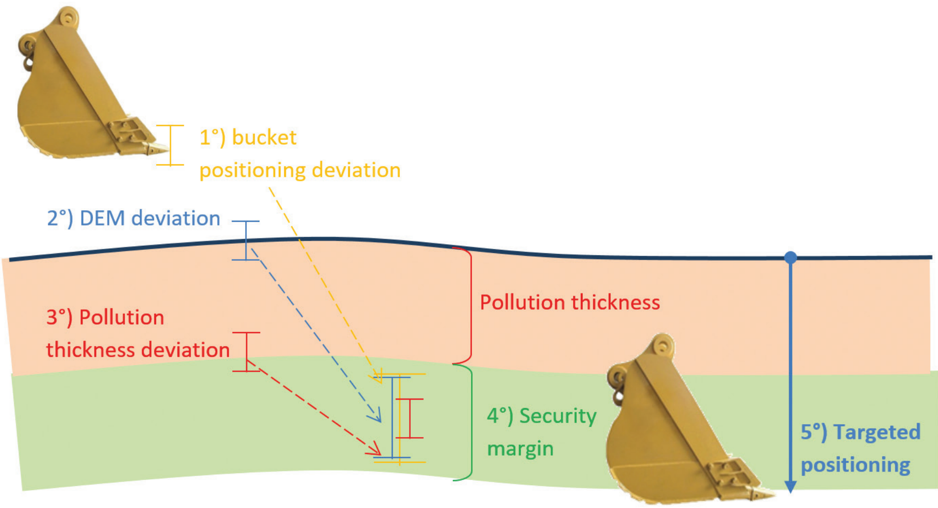

Figure 4: Deviation sources and effect on the optimal position
Source: Compiled by the author.

Having the field situation and requirements clearly examined and stated, we will now review what technologies can be used in the fieldwork.

3. Discussion about the real accuracy achievement of the technologies in excavation approach compared to accuracy requirements

With the development of our accurate approach, it is critical to assess the efficiency and the accuracy achievements. As mentioned in the vertical accuracy target part, there is a quite important difference between the absolute accuracy of the positioning of the blade (few cm to few mm, based on the DGPS setup) and the relative accuracy of the positioning of the blade compared to the targeted pollution layer. Even if technology allows achieving a relatively good absolute accuracy with the blade positioning (few cm to few mm), the error measured relatively to the pollution layer become quite high because it results from the combination of the errors from three different measurement sources (elevation on surface, blade positioning, estimation of the pollution thickness). Reasonably, with a 5 cm accuracy with the elevation model and few centimetres for the blade positioning as well as at least 5 cm with the pollution thickness estimation, the approach ends up with a possible 7.7 cm error on the relative positioning of the grading tool compared to the positioning target.

The 7.7 cm result value can be compared to other achievements/values. First, a comparison can be done relatively to the targeted thickness. 7.7 centimetres of positioning error when targeting a 30 centimetres excavation depth (resulting in 25% volumetric error) sounds more reasonable than 7.7 centimetres error when excavating 1 cm of soil (resulting in 770% volumetric error) but it should be mentioned that

25% could be a too important error when talking about precision work. Another comparative value is the relative horizontal accuracy error. If the positioning in x, y has a 2–3 cm accuracy, the relative positioning accuracy of one strip to another is 2.8–4.2 cm. It is twice less (and twice better) than the achievement with the relative vertical accuracy. Finally, it should be noted that the vertical accuracy and the horizontal accuracy does not have the same consequence with their effects. The horizontal accuracy will affect the efficiency of the process in time and in energy consumption but the same quantity of material will be collected. The vertical accuracy will affect the volume of soil to be collected and hauled, which at the end drastically increases the project costs. This volume should be moved, excavated, hauled, processed and brought back for restauration. So, it then counts several times and not only one time as it could appear at first glance; and has financial costs associated with the increase of each the operations workload.

Considering those elements of reflection, we should ask ourselves of the possibility to achieve better vertical accuracy with another approach. A direct measurement of the height in the field would avoid the combination of errors for diverse sources (DEM and part of positioning) and could lead to better achievements. The possibility to use sonic sensors or a combination of sensors in combination with a 2D control system should be examined. With the appropriate equipment setup, the vertical accuracy with the estimation of soil surface could then be lowered to few millimetres in optimal conditions, leading to a relative accuracy close to the thickness estimation deviation. However, it should be noted that such an approach does pass through neither support the creation of a DEM.

As part of the vertical inaccuracy of the DEM is inherited from the vertical inaccuracy of the GPCs used for DEM preparation, we have considered making a zeroing with the DTM datum in the field so as to nullify the inaccuracy mentioned here above. But this approach should be very regularly made. The use of a sensor could be the solution for its automatisation. In practice, this solution would quasi cumulate the "sonic sensor solution", need a survey flight, a DEM preparation and investment in 3D machine control system. It is clearly neither efficient nor worth the money.

4. Conclusions

In our specific situation (with the precise remediation requirements), considering only the vertical absolute accuracy offered by the technology is an incomplete and flawed approach. The study demonstrated that the most critical issue to consider in our situation is the relative vertical accuracy between the positioning of the blade of the grading equipment and the bottom of the polluted soil layer. In the workflow developed for the precise remediation approach, the errors related to 1. the estimation of the pollution thickness (external factor we cannot improve); 2. the positioning of the TIN surface model; and 3. the positioning of the blade got combined and result in a final value which is questionable as regards the objectives of precise remediation. The relative vertical accuracy results with 7.7 cm whether DEM preparation is done with ALS or UAV photogrammetry. When compared to several other metrics in the context of the "precise remediation approach" – in particular the volumetric excavation error compared to the targeted volume to excavate – these values end up being much consequent. In conclusion, the remote sensing approaches we have considered do not satisfy the accuracy requirement (2.5 cm relative accuracy compared to the targeted height).

As further research work, we have to consider whether a direct remote sensing measurement (advantageous because it is robust in field condition) made in the field during the remediation work with one or a combination of sonic sensor(s) sensing the soil surface could overcome the aforementioned issues. Machine control system could be guided very accurately and remediation objectives fulfilled the best. This approach – which is using remote sensing – dispenses with the preparation of a DEM and the use of 3D machine control system. Development based on this new idea will be tested in our coming research work.

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