Using a 2D-profilometer to determine volume and thickness of stockpiles and ground layers of roads

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Abstract

Construction materials and related management, handling, and storage provisions account for a large part of road construction expenses. For that reason, improved material flow monitoring techniques can achieve significant cost and time savings, as well as better quality control. The study assessed the performance of a solid-state pulsed time-of-flight laser lidar profilometer in measuring the volume of soil stockpiles and road layer thicknesses. The 3D (X, Y, Z, and intensity) image calculation was based on the analysis of multiple combined point clouds measured with an excavator-integrated profilometer. Error analysis confirmed the accuracy of road layer thickness estimation within one centimetre and an error level of approximately 3% when measuring soil stockpile volumes. In combination with a theoretical model of the superstructure, this 3D measurement technique can help contractors and supervisors to ensure road quality.

Introduction

Road construction is an important element of the global infrastructure sector. Road networks are central to a country's development and social wellbeing and contribute to economic growth by helping to attract investment (Harmann and Ling 2016). About $10 trillion is spent on construction-related goods and services every year, making the construction sector one of the largest components of the world economy and that amount is projected to increase to $14 trillion by 2025 (McKinsey Global Institute 2017). Globally, labour-productivity growth in the construction sector has averaged 1% annually over the past two decades as compared to 3.6% percent for manufacturing and 2.8% for the world economy as a whole (McKinsey Global Institute 2017). This poorer productivity in the construction sector owes in part to the cost and time overruns that afflict many construction projects (McKinsey Global Institute 2017), as well as to workforce and management factors, changes during the execution phase, and issues related to equipment, tools, materials, technology, and the environment (Tam et al. 2021; Green 2016).

In some instances, new technologies can help to improve productivity and build quality; one important case in point is the measurement of layer thicknesses in roads under construction. Accurate measurement can achieve significant savings as well as better road durability and less subsequent maintenance. Other fundamental civil engineering processes that can also be improved using new measurement technologies include the management, handling, and storage of various bulk materials (Tucci et al. 2019). Following a review of the strengths and weaknesses of various 3D measurement technologies currently used at construction sites, we assess the suitability of a new type of 2D measurement system. The measurement accuracy is tested in two typical measurement cases, and the advantages and disadvantages of the measurement method are discussed in relation to other technologies.

Literature review

Studies of roadway layer thickness measurement have evaluated various technologies, including ground-penetrating radar (Tarefder and Ahmed 2018), enhanced resonance search (Wang and Shan 2019), lidar sensors and inclinometers (Liu et al. 2016), micro-electro-mechanical sensor (microphone) systems (Bjurström et al. 2016), scanning lasers (Walters et al. 2008), magnetic pulse induction (Grove et al. 2012), ultrasonic tomography and impact echo methods (Edwards and Bell 2016) and computer vision (Brayn et al. 2015). According to the literature, these technologies have only been used to determine the thickness of the asphalt layer. As asphalt is often the most expensive road layer, accurate measurement is crucial for project profitability. However, other layers also incur significant costs; for example, a gravel cost of 25 € per ton means that every one centimetre reduction in thickness for a ten-kilometre road with an average layer width of six metres can save about 20 000 €. Minimizing excessive or unnecessary materials can reduce material and transport costs (including less fuel consumption and lower emissions). Traditionally, contractors determined the thickness of gravel and soil by performing a site survey using a total station. Current state-of-the-art navigation systems for mobile construction machinery incorporate inertial measurement unit (IMU) and global navigation satellite system (GNSS) sensors for precise tool trajectory measurement (Lee et al. 2012).

Trajectories use absolute bucket location to measure the road course and other topologies, but this method provides only the coordinates of individual surface points. In the past, soil stockpile volume measurement was based on a few significant points selected and measured by the operator using traditional earthwork calculation methods. More recently, these methods have been replaced by total stations and global navigation satellite systems using real-time kinematic (GNSS-RTK) techniques (Tucci et al. 2019). A robotic total station can measure the distance to a target automatically based on the time required for a light wave to travel to and from that target. The main advantages of a robotic total station include a good measuring range (up to 200 m) and accuracy; its main disadvantages are that the device is quite expensive and requires a skilled operator (Zhou et al. 2021). In addition, this measurement process is time-consuming, costly, and sometimes dangerous if multiple points have to be measured from the surface. Modern measurement techniques include photogrammetry (Smirnow 1996; Zheng et al. 2013) and light detection and ranging (LIDAR) (Gao et al. 2017; Palacin et al. 2007). The laser scanner emits a beam to a rotating mirror and scans the laser across the target, which reflects the beam back to the scanner to provide 3D geometric data. The advantage of laser scanning is that it provides an angular breadth of approximately 270 degrees of solid angle. Another significant advantage is that each scan occurs automatically, and the process is reasonably quick (approximately 20 minutes). The main disadvantage of laser scanning is that the device is costly (c. €30,000); accuracy is 2–3 mm at a scanning distance of about 70 m, and a reliable unit weighs at least 7–8 kg (Galanakis et al. 2021). One common method employs a sensor attached to an unmanned aerial vehicle (UAV) (Di Leo et al. 2011), which enables monitoring of large areas (Zhu et al. 2020; Jensen et al. 2020; Han et al. 2022). The choice of an appropriate technique depends on site dimensions, morphology, and topography, as well as accessibility, visibility, safety, and careful cost-benefit analysis (Tucci et al. 2019). For UAV-based 3D scanning, the photographed area should be as open as possible, free of trees, tall objects, shadows or vegetation that might hinder accurate image recording. Flight conditions must also be good (low wind, clear sky); a flight can currently last about 35 minutes before the UAV's batteries need to be changed (Kim et al. 2018). Vegetation-induced elevation error has been studied using convolutional neural networks and drone-based high-resolution orthophotos (Jiang et al. 2022). A data file of 900 images takes 24 hours to process on a computer (PC), but a high-performance computer (HPC) can complete the analysis in 1.6 hours (Gillan et al. 2021).

In previous work, we measured a soil surface profile by acquiring a point cloud of an area of about 48 m^2 with a single sweep of an excavator arm equipped with a solid-state 2D line profiler (Niskanen et al. 2020). That preliminary study confirmed the potential of the proposed technology for construction settings. In the present study, we measured larger 3D areas and volumes by combining multiple point clouds acquired by sweeps of the excavator's arm at several locations around the target object. One notable novel feature of this approach is the use of a custom-designed miniaturized solid-state line profiler mounted on the excavator boom to generate the required 3D data within the excavator's coordinate system. The resulting 3D range image data are produced by successive measurement of horizontal line profiles, where the elevation and angle of a given line profile is determined by the corresponding position of the excavator boom. This profiler is potentially less costly, and miniaturization allows ease of mounting on the excavator boom. As a viable alternative to methods like UAV-based 3D scanning, this setup can provide almost real-time high-precision 3D measurements of the working area (data lines recorded every 40 ms) while operating the excavator without any need for external 3D measurement equipment. Table 1 summarizes the performance of this 2D pulsed time-of-flight profile measuring system as compared to other methods.

As shown in Table 1, the profilometer offers a quick, easy, and cost-effective solution for measuring soil stockpile volume, and the observed level of accuracy meets several application requirements. The proposed method also requires a 3D machine control system (MCS), which includes GNSS IMUs for the excavator. MCS is quite an expensive investment (28-35 000 €); its main function is to convert virtual terrain models into real terrain landscaping.

The primary focus of the present study was to measure the volume of a soil stockpile and the thickness of soil, sand, and gravel layers, using an excavator equipped with a solid-state 2D line profiler and other relevant sensors. Our goal was to reduce costs at a road construction site by developing an accurate method for preventing excessive use of materials. As well as documenting the quality of soil layers and the volume of soil stockpiles, the proposed method provides intensity information that can distinguish between sand and gravel and recognize stockpiles using reflective surface markings. Because this involves the rapid location of digital tool trajectories above and below the desired surface level, the excavator operator must use manually logged points; to do this accurately, the machine operator must have extensive training and know-how.

Materials and methods

2D pulsed time-of-flight (TOF) profilometer

The 2D profilometer developed for this application field is based on the pulsed laser time-of-flight (TOF) technique. The TOF profilometer illuminates a stripe-like horizontal surface area in front of the excavator with a laser pulse beam spread with an opening angle of +/−20° and 0.3° in the horizontal and vertical directions, respectively. The transmitter is based on a custom-designed double-heterostructure diode laser that emits short (~200 ps) but relatively high-energy (~2 nJ) laser pulses at a rate of ~150 kHz (Ryvkin et al. 2009). The profilometer can measure the distance to 256 directions with a measurement rate of 25 frames/s to a maximum measurement range of approximately 5 to 10 m in sunny outdoor conditions and up to about 30 meters in darker indoor or outdoor night lighting conditions. The heart of the device is a full custom CMOS integrated circuit that includes an 8 x 256 array of single photon detectors (SPADs) and 257 time-to-digital converters (TDCs) on a single die. Each SPAD has a different field of view of the illuminated stripe, i.e. each SPAD “sees” a small section of the reflected laser pulses, and therefore the profiler can measure laser pulse flight times to and from the target region simultaneously in 256 separate directions. Because the SPADs operate in single photon detection mode (probability for per-pixel photon detection for a single laser pulse < 1), the total number of detections per specified measurement interval (e.g., for 5,000 emitted laser pulses) correlates with the target’s per-pixel reflection coefficient. In other words, dark targets such as soil and light colored targets such as sand can be distinguished from the measurement results in addition to the distance to the targets.

Using this setup, the accuracy and precision of distance measurements are better than about 1 cm, with a horizontal angular resolution of about 0.15 degrees. For example, as the profilometer measures the distance of 256 measurement points within a measurement angle of

+/−20°, the distance between measurement points at a distance of 10 metres is less than 3 cm. Fig. 1a) shows the profilometer illumination principle and a photographic image of line profiler realization. The laser transmitter uses cylindrical optics to produce the laser fan. The receiver collects the backscattered photons using optics with a narrow vertical field of view and an optical band-pass filter to reduce the effect of background radiation. Only the rows (in the vertical direction) illuminated by the laser signal are enabled, so that as little background light as possible is measured. The electronic elements of the transmitter and receiver are on a single small sized printed circuit board (5 x 7.5 cm) located behind the opto-mechanics. The device operates with no moving parts and utilizes the movement of the excavator and its positioning sensors to increase the field of view. A plastic case (Fig. 1b) was designed to protect the profilometer from adverse weather conditions such as rain, dust, and sand. A compressed air and wiper cleaning system can also be integrated into the profilometer window. Technical details of the TOF profilometer can be found in Keränen and Kostamovaara (2019a, 2019b).

Excavator with control system

The profilometer scans in two dimensions; for the purposes of this study, the excavator boom's natural motion was utilized to produce a three-dimensional image. We used a Bobcat E85 commercial excavator (8.5 tons), which was modified for automation and fitted with electrohydraulic controls, a suite of sensors and an on-board computer. The control system's personal computer requested the profilometer's local coordinates and orientation data, which were timestamped. Fig. 2 shows the configuration of the boom, arm, and bucket, which were controlled by a Novatron Xsite system. The hydraulic system of machine valves was retrofitted for precise electrical control. The sensor system was based on the newly developed Novatron IMU G2 sensor, which can operate at frequencies of up to 200 Hz with a dynamic angle measurement error of less than 1.0˚. The Bobcat was equipped with both a radio receiver and a wireless data connection, enabling it to receive real-time kinematic correction data under different site conditions. The RTK-corrected GNSS positioning data are precise enough to enable movements that achieve close to centimetre accuracy. The sensors are connected to a controller area network (CAN) bus, which reduces the need for wiring; all sensors can be set on the same bus.

The laser profilometer was enclosed in a plastic case and attached to the excavator arm, using rubber pockets to damp any vibrations. As the profilometer has no moving parts, it can be used in harsh outdoor conditions. The computer collects the required data automatically. Using the mathematical procedure in Fig. 3, the position of the vector can be represented as

$$\boldsymbol{P}_{\mathbf{prof}} = \boldsymbol{T}_{\mathbf{1}} \times \boldsymbol{T}_{\mathbf{2}} \times \boldsymbol{P}_{\mathbf{m}} = \begin{bmatrix} R_{\mathrm{ORI}} & A_{\mathrm{P}} \\ 000 & 1 \end{bmatrix} \begin{bmatrix} R_{\mathrm{Prof}} & 0 \\ 000 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ me \\ 0 \end{bmatrix} \quad (1),$$

where $\boldsymbol{T}_1$ and $\boldsymbol{T}_2$ are the transformation matrices (implemented using quaternion algebra); vector P_{m} is the profilometer measurement; vector $\boldsymbol{A}_{\mathbf{P}}$ represents the scanner position in the workspace coordinate system; and R_{ORI} represents profilometer orientation. Further details of the calculation routine can be found in Niskanen et al. (2020). Technical details of the line profiler are described elsewhere (Keränen and Kostamovaara 2019a, 2019b; Kostamovaara et al. 2020).

Measurements

While we hope to extend the use of the profilometer to other applications beyond everyday visualization of soil materials at road construction sites, the present study focused on application-oriented measurements to demonstrate the nature and potential of the measurement chain. In the first place, we demonstrated the system’s accuracy by measuring the volume of a rectangular truck container. The 3D measurement system was then used to determine the volume of a soil stockpile. It is convenient to be able to measure the volume of small soil stockpiles directly from the working excavator, as the contractor can use this information for near real-time monitoring of changes in soil stockpile volume and management, handling, and storage of various bulk materials. The third test measured the thickness of base layers of sand and gravel. On construction sites, a surveyor typically uses a total station to measure the thickness of soil layers. While this is an accurate method, it only provides coordinates for a few manually measured points. Laser scanners can measure a surface's 3D profile, but these devices have to be moved around the site to capture the region of interest. Instead, we propose to perform 3D scanning from the excavator itself, utilizing the excavator arm's movement to scan the scene in the vertical direction while the solid-state 2D profilometer measures the 3D ground profile in the horizontal field of view. Finally, we also used the profilometer to identify soil materials based on signal intensity data. Information about object reflectivity was obtained from the profilometer signal strength readings incorporated in the point cloud coordinates. These measurement cases were selected because they are commonplace at road construction sites, further confirming the potential of the proposed approach.

Volume measurement accuracy

Field testing of the proposed setup was conducted at an earthmoving site with the assistance of a unit from Haukipudas Vocational College. To begin, we assessed the dimensional accuracy of the profilometer and other instrumentation by determining the volume of a truck container. A mechanical calliper with a reading accuracy of 1 mm measured the container's dimensions as 650 cm (length) by 186 cm (height) by 250 cm (width), yielding a volume of 30.22 m^3.

The reflective tape was then affixed to the container. The highly reflective yellow crosses and lines were easily distinguished from the blue-painted surface of the container, which had a low reflection coefficient. The reflective surface markings allowed the container to be identified by text. By combining the profilometer data and the GNSS/RTK data collected through a socket connection from the excavator, X, Y, and Z coordinates were calculated for each point using the transfer matrix formula (1). Using Matlab software, the control system computer synchronized the two sets of data by their timestamps. The excavator boom movements adjusted the joint angle between boom and arm from −120° to −45° (Fig. 5) at seven different locations on the outside of the container.

The number of points in a single 3D cloud was approximately 222,000, and the total measurement time was about 34 seconds. The 3D point clouds were imported into CloudCompare software (Oniga et al. 2016) and were combined into a single cloud. The 3D point cloud was manually edited to eliminate irrelevant objects that might affect volume estimation. The final model was composed of 470,000 points. The results in Fig 6a show the 3D point cloud for the truck container; the colour indicates signal intensity (i.e. signal photon detection probability per laser pulse). The form of the truck container is recognizable in the 3D image, but some details (especially at the back of the container) cannot be seen.

The volume of the truck container was calculated using the Matlab alpha shape function (Matlab 2020), which creates a bounding volume that envelops a set of 3D points based on a Delaunay triangulation. Alpha shape implementation is straightforward and can be automated for rapid processing of large datasets. The alpha shape is created by a radius that sweeps across the points. The parameter alpha’s radius dictates the level of refinement, ranging from coarser (larger alpha) to finer (smaller alpha) (Gardiner et al. 2018); the extreme values of alpha are convex hull and empty. Alpha values can be determined experimentally to balance size and shape/volume contours (Maddah and Cao 2017). The alpha parameter value is correct when the bounding shape fits all sample data within a tight bounding box that contains no other points, where the squared radius is equal to or smaller than the alpha radius (Bonneau et al. 2019). As the point cloud contained gaps, the selected alpha radius was approximately the width of the object divided by two to ensure the most uniform overall shape for triangulation (Matlab 2020). The resulting surface reconstruction is shown in Fig. 6b. This calculation yielded a volume of 29.45 m^3 (including overhangs). Compared to the actual volume (30.22 m^3); our 3D measurement system (profilometer combined with GNSS/RTK and IMU sensors) returned an error of less than 3%.

Determining the volume of a soil stockpile

For the first field test, a conical soil stockpile was prepared. The stockpile comprised 25 excavator buckets; given a bucket volume of 0.37 m^3, the total volume was estimated as 9.25 m^3. The volume was also estimated by measuring the radius and height from the bottom of a cone, yielding a value of 9.54 m^3.

The volume of the stockpile was then measured with the profilometer attached to the excavator by adjusting the angle between boom and arm from −140° to −65° (see Fig. 5) from three scanning locations beside the stockpile. The number of points in each of these 3D clouds was approximately 209,500, involving a total measurement time of about 32 seconds. Using reflecting tape, the stockpile was labelled PILE 1 (Fig. 7).

Using CloudCompare software, the three point clouds were then combined into a single point cloud of 489,300 points. The projected 2D map (XY) of the point cloud is shown in Fig. 8. In Fig. 8 inspection 2D map indicates that reflection tapes stand out from other materials due to the high reflection. The resulting 3D surface reconstruction is shown in Fig. 9. As shown in

Fig. 9a, the reflective intensity of the tape-based text is high when compared to the other materials in the 3D image of the stockpile (as in Fig. 7). The stockpile's volume was calculated from the point cloud in Fig. 9a. Using Matlab's alpha shape function, the surface reconstruction (Fig. 9b) yields a volume of 9.42 m^3. Using the Trimble RealWorks program to generate a pillar-mesh image from the 3D point cloud (Fig. 9c), a further calculation of the stockpile's volume yielded a value of 9.77 m^3. One possible explanation for this larger estimate is that the pile bottom was not quite flat; in any event, the pile's asymmetric shape made it difficult to accurately determine its volume, and estimating the amount of soil in terms of buckets is also difficult. Based on the image analysis results and given that the actual volume could not be precisely determined, the error in profilometer estimates for Matlab and Trimble RealWorks was 1.5–2.0% and 2.5–5.5%, respectively, as compared to estimates based on radius and height (9.54 m^3) and number of buckets (9.25 m^3)—a difference of 0.35 m^3 between the two programs.

Determining soil layer thickness

The second field test involved building a road comprising base, sand and gravel layers. The base layer dimensions were 250 by 250 cm while the sand and gravel layers had thicknesses of 11 cm and 10 cm, respectively. In addition, to demonstrate the measurement system's ability to identify small objects within the working area, a plastic pipe was laid on top of the base layer (length 218 cm, diameter 11 cm). Using white paper, the layers were labelled LAND, SAND and GRAVEL; the photographs in Fig. 10 (left) show this layer structure. The excavator boom movement adjusted the angle between boom and arm from −120 ° to −45 ° for each layer from two adjacent locations (as in Fig. 5) to bring the whole road into view. Measurement time per layer was about 48 seconds, capturing approximately 313,000 3D points in total.

The 3D point clouds were again imported into CloudCompare software. Measurement results for the different layers are shown in Fig. 10 (centre); the point clouds are good, and layer shapes can be roughly discerned. The white paper letters reflected the laser light well; it appears as the yellow letters in all the layers. The reflective papers help to identify the layers, and the tapes on the traffic cone offer good reflection. As shown in Fig. 10 b, the utility pipe can also be detected, again confirming the system's high performance. Additionally, the results confirm that the profilometer can handle challenging geometry and sharp edges and can capture small objects at centimetre level.

Finally, we assessed the accuracy of layer measurements by taking a cross-section of the road from the centre of the plastic tube. As shown in Fig. 10 (right), there are ditches on both sides of the road, and the base layer is not quite flat (Fig. 10c). At road construction sites, layer thickness is typically measured after levelling by a compaction roller. In some cases, however, it would be useful to be able to measure layer thickness directly from an excavator.

Using the Matlab image analysis tool to process 10 observations, the thicknesses of the sand and gravel layers were estimated as 11.5±0.4, and 8.2±0.5 cm, respectively. These results indicate a potential profilometer error of 2 cm when compared to the measured thicknesses. Measurement of the gravel layer may be unreliable because the lower sand layer and the upper gravel layer were not quite smooth, and the grain size was about 10 mm.

We also assessed the profilometer's ability to distinguish earth materials based on reflection intensity data was studied. The results are shown in Fig. 11.

As shown in Fig. 11, base and sand layers are very difficult to identify from the profilometer intensity data because these adjacent layers are partly constituted by the same material (clay/sand mixture) and have similar reflectivity characteristics. The measurement resolution means that the gravel’s larger grain size can be distinguished from sand. Furthermore, as dark objects absorb more light, gravel has a lower reflection intensity than sand or clay. In addition, signal intensity (detected signal photons per laser pulse) depends on the material’s reflection coefficient and several other factors, including scanning geometry, atmospheric effects (weather), surface properties (roughness), distance to the object, and laser wavelength. For that reason, applications should calibrate intensity values to render them usable (Tatoglu and Pochiraju 2012; Bolkas and Martinez 2018).

Discussion

Reliable real-time information about soil materials is a key factor in road construction, planning and decision-making; in economic terms, prediction and appropriate timing depends on accurate data capture and analysis. The present study demonstrated that a low-cost 2D TOF profilometer can be used to estimate soil layer thicknesses and soil stockpile volume from an excavator using 3D point cloud data. Integration of the profilometer into an excavator equipped with IMU sensors and GNSS enabled the automation of onsite data collection. At road construction sites, automated data collection plays an important role in site management, control and environmental quality management and can detect and eliminate human error and other problems before they affect the ongoing workflow.

The study has several important implications. First, the proposed measurement system facilitates soil layer thickness monitoring and soil stockpile management on road construction sites. The proposed method is sufficiently precise to guard against excessive road layer thicknesses, so improving efficiency and profitability. The results indicate that the method can distinguish soil layer thicknesses and shapes in real time, ensuring that layers remain within tolerance limits without being too thin or too thick. A road layer that is too thin may lack durability while an excessively thick layer increases material costs, leading to significant accumulated costs, especially on long stretches of road. The ability to monitor these issues can also reduce the need for expensive manual checks by a surveyor.

Second, the comparisons of stockpile volume results show that measurement errors fell within a few percent of the estimated true value (where actual volumes could not be precisely determined). In general, material inventory specification requirements allow for an error level of ~5%. On the other hand, the estimated thickness of soil layers achieved two centimetre-level accuracy, with average errors 4% and 3% for sand and gravel layers, respectively. An accurate and complete 3D multi-point cloud of a large object like a soil stockpile requires multiple scans from different locations around the target object, and the number of scans required depends on the object's distance from the excavator. At present, our profilometer's field of view is quite limited (+-20 degrees horizontal, maximum range 10 metres in daylight conditions for low reflectivity targets). Any unnecessary scan overlap can reduce the sharpness of the 3D image, increasing computation complexity and time (Prokop et al. 2019). Multiple-point clouds may also be impaired by noise and outliers due to profilometer limitations, positioning accuracy, lighting or surface reflections (Han et al. 2017). Movement of the objects in view may also cause localized distortions in the point cloud image. In our sample cases, the objects remained static. However, GPS/GNSS positioning and angle measurement inaccuracies led to mismatching of point clouds collected from different positions and angles. Angle measurement is based on the mathematical integration of IMU sensor outputs, and accumulated errors can cause drift in angle measurement results (Al Hage et al. 2019). Boom vibrations and point cloud density may also affect volume measurement accuracy. The profilometer has a frame rate of about 25 Hz in sunny conditions, and that rate can be increased by lowering ambient light conditions or by improving the laser transmitter to provide more laser pulse energy

(Kostamovaara et al. 2020). Computation accuracy is likely to be influenced by the number and accuracy of acquired points and the complexity of target surfaces (Tucci et al. 2019). This implementation of road construction layers and volume of soil stockpiles can be updated in near-real-time compared to the UAV system. In addition, the coordinates of the profilometer's point cloud can readily be integrated into Building Information Modeling (BIM) data. To some extent, intensity information can be used to distinguish soil materials and surface markings with numbers and text. However, it should be noted that reflection intensity and therefore material identification is affected by factors like surface smoothness and moisture (Kaasalainen et al. 2010). The proposed method can also be utilized to gather information about the location of underground cables and pipes. While the profilometer can be operated during the day and at night, limitations include bad weather conditions such as fog, heavy rain and snow, and data cannot be received if objects in the front of the excavator obscure the view.

Conclusion

This paper describes the use of a low-cost 2D TOF profilometer to estimate soil stockpile volumes and road layer thicknesses based on near real-time multi-point 3D cloud data collected directly from an excavator. Our results indicate that the method can be used for onsite 3D measurement. The most promising finding relates to the estimation of soil stockpile volumes. The main advantages of the method are robustness (because the devices have no moving parts), relatively low costs, computation speed, no control point requirements, compact size, and direct mounting on the excavator's vibrating arm (which can cause mechanical stress in commercial scanners with a moving mirror and reduced image quality if using a stereo- or mono-camera), with no need for calibration following installation. Permanent installation of a profilometer control system on the excavator eliminates the need for drones or other SLAM devices. Among practical challenges for the proposed method, one major issue is the profilometer’s short measurement range (1–10 metres) and the narrow field of view (currently 40 degrees). Finally, the excavator needs GNSS, IMU, and a machine control system to implement the 3D scanning process, which increases investment costs.

Using a profilometer for road construction projects can increase efficiency and accuracy when measuring materials, surfaces, heights, and volumes and can help to reduce soil and labour costs. The proposed system is likely to prove useful in settings where practicality and robustness are more important than perfect accuracy. In addition, the method has great potential for documenting surface structures during road construction projects. In future studies, we plan to investigate the effects of harsh weather conditions on the profilometer's performance. Our long-term aim is to develop an integrated sensor system for intelligent autonomous excavator systems.

Data Availability Statement

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Table

Table 1. Summary of the main features of methods used to determine volume of soil stockpile ([1]Keränen and Kostamovaara 2019b, [2] Galanakis et al 2021, [3] Zhou et al. 2021 and [4] Gillan et al. 2021) .