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Next generation gravel road profiling – The potential of advanced UAV drone in comparison with road surface tester and rotary laser levels

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ABSTRACT

Over the last decades, significant progress has been made and new approaches have been proposed for efficient collection of road condition data. Gravel roads are crucial for connecting urban and rural areas in Sweden, constituting a significant portion of the road network. Therefore, this study addresses the use of a developed Unmanned Aerial Vehicle (UAV)-based digital imaging system focusing on efficient collection of surface condition data over gravel roads.

The study focuses on *in-situ* profile measurements of a gravel road located in Trosa, Sweden, using three different profiling methods: UAV drone with RTK technology, Road Surface Tester (RST), and Rotary Laser Level (RLL) to explore the agreement between these methods.

The UAV drone, equipped with Real-Time Kinematic (RTK) technology, captures high-resolution images to produce detailed 3D surface models, overcoming the challenges posed by adverse weather conditions. Notable outcomes reveal RTK technology's stability, maintaining a steady 3D position accuracy below 2 cm. To enhance synchronization and comparison between different profiling methods, efforts should be made to standardize coordinate systems and measurement analysis software.

Minimum average absolute differences of 1.1 cm, 1 cm, and 0.7 cm were recorded for all profiles (from 1 m left to 1 m right of the road centerline) in the comparisons between UAV drone – RST, UAV drone – RLL, and RST – RLL methods, respectively. This underlines the significant advancement in UAV drone technology, enabling remarkably accurate measurements of vertical offsets for profiling the tested gravel road despite the high altitude at which the UAV drone operates.

1. Introduction

Aggregate surfaced roads are referred to as unpaved roads[1,2]. Unpaved road structure consists of an aggregate layer directly placed over the natural soil subgrade [3,4]. Gravel roads are designed not only to bear traffic loads but also to exhibit resistance to shear deformation and wear, ensuring they possess ample strength and durability [5]. Additionally, these gravel roads can endure the stresses imposed on the underlying layers of the pavement. In contrast to paved roads, unpaved roads experience a rapid rate of deterioration due to various factors such as weather, heavy traffic, driver behavior [6], and other influences that can readily impact their condition. Under wet weather conditions and/or heavy traffic, gravel roads may experience deterioration issues like rutting and the formation of potholes [7–10].

Gravel roads play a central role in transport networks, serving as essential links between urban and rural areas [11,12]. In many developing countries, more than 75 % of the road network consists of gravel and earth roads [13]. According to a global study conducted by [14], approximately 80–85 % of the world's road network consists of unpaved roads. In both India [15] and the USA [16,17], 35–50 % of the road network is unpaved. In the state of Wyoming in USA, gravel roads make up around 90 % of the local road network, as highlighted by Huntington and Ksaibati [18]. In Sweden, approximately 76 % of the road network is made up of unpaved roads that serve as major arteries in rural areas [19]. Countries with large territories and a strong presence of agricultural, forestry, and mining activities usually have a substantial unsurfaced gravel road network.

The quality and durability of gravel roads are of paramount importance in ensuring safe and efficient travel. Local authorities overseeing gravel roads are advised to establish not only an effective management

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Fig. 1. The DJI M300 Drone with RTK used in the project, photo by Dina Kuttah.

Fig. 2. An Orthophoto taken during the gravel road profiling for visual inspection and interpretation.

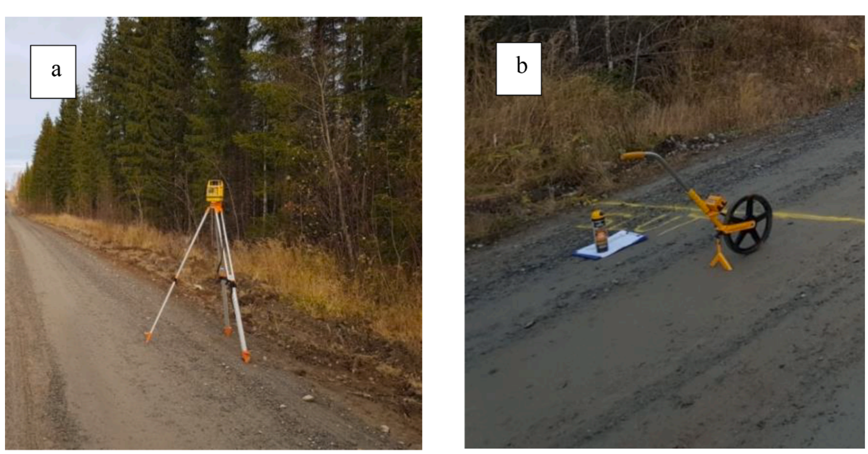

Fig. 3. (a) The rotary laser level, (b) the distance measuring wheel used in the study.

system, but also methodologies for assessing the operational efficiency of these roads [20,21]. The last decade has seen a significant increase in the number of studies focusing on gravel roads [22–27]. This growth can be attributed to an increased awareness of the problems associated with inadequate gravel road networks, such as traffic operational challenges, health concerns and environmental impacts. As a result, consistent

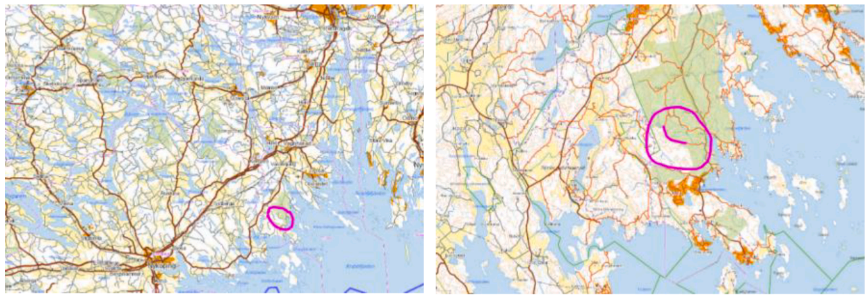

Fig. 4. Location of the forestry road tested in the current study.

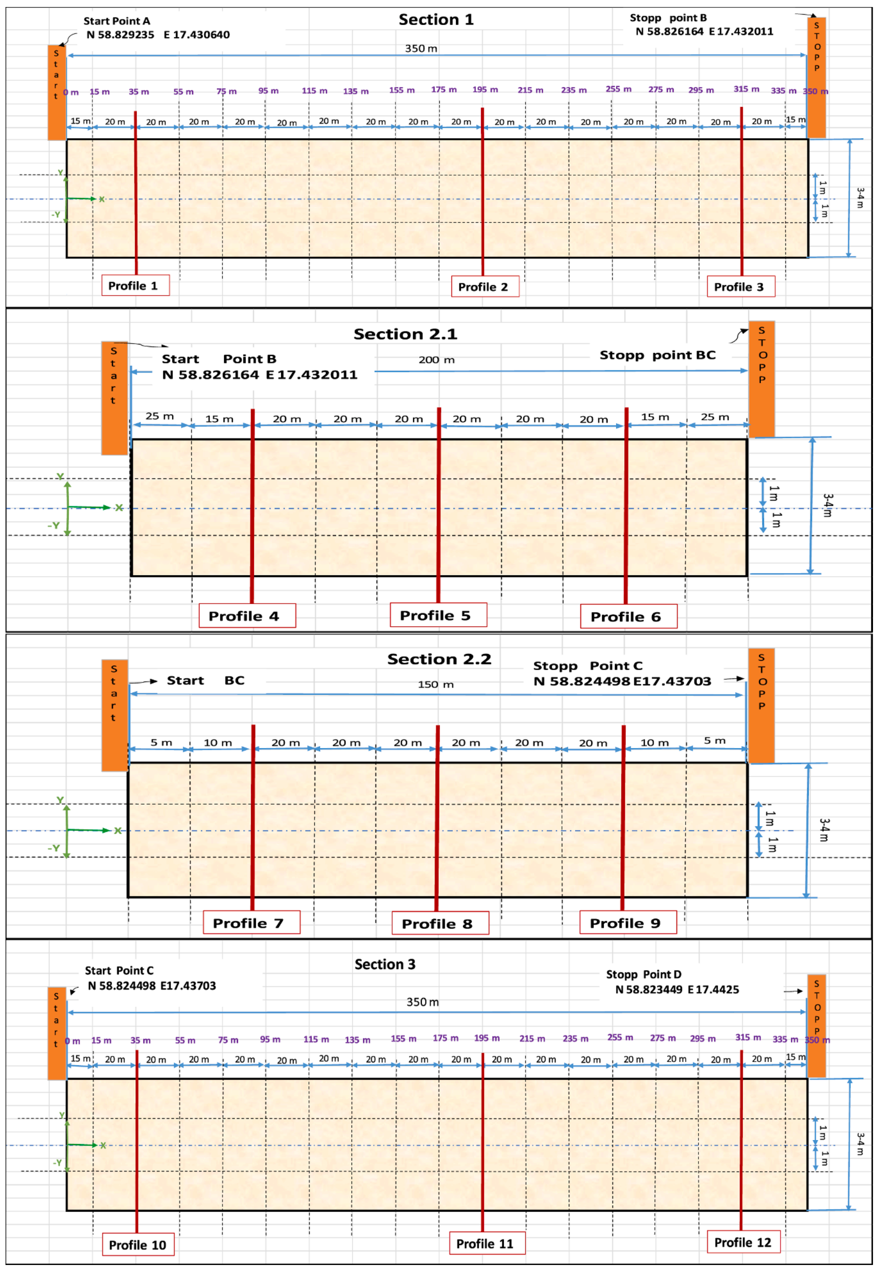

Fig. 5. Testing profiles layout.

maintenance is essential to ensure the continued optimal functionality of these built roads. Therefore, road condition assessment is a critical task in road monitoring and maintenance [28].

The predominant method of surveying and analyzing gravel roads is still largely based on extensive field observation by experienced assessors, who characterize the road using visual inspection, simple

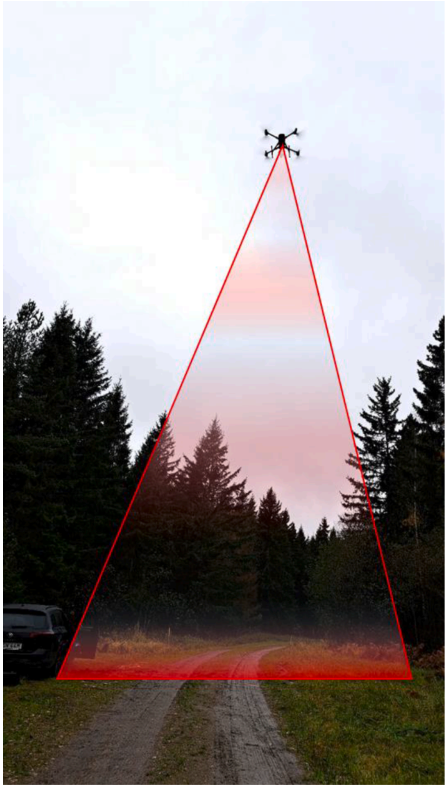

Fig. 6. Profile measurements with DJI M300 Drone.

measuring tools. In such cases, Engineers either traverse the entire length of the road on foot or remain in their vehicles to perform windshield inventory and road surface surveys, a method that occasionally overlooks certain defects due to oversights.

Profiling, which involves the measurement and analysis of road surface characteristics, is a critical aspect of assessing and improving the performance of gravel roads. This can be done using a rotary laser level (RLL) and a distance-measuring wheel. Nevertheless. it is well known that laser-level profiling is time-consuming and raises safety concerns even under normal traffic conditions. In addition, this method does not provide an adequate survey of the entire area of the gravel road or the surrounding terrain. This is because profiling is carried out at a number of selected points, which limits the survey.

To overcome the problems associated with manual measurements, vehicles are being fitted with cameras and various sensors for the detection, measurement and analysis of road distress. This approach facilitates road condition assessment using survey vehicles, such as a road surface tester (RST), to collect pavement images and other data on surface roughness and rut depth [29,30]. However, these vehicles have certain drawbacks, including a complex structure, high cost and susceptibility to weather conditions [31].

For centuries, the practice and acceptance of manual road surface condition surveys prevailed until the introduction of photogrammetry to facilitate data collection and analysis.

In recent years, technological advances have introduced new methods for road profiling that offer improved accuracy and efficiency. Unmanned Aerial Vehicle (UAV)-based imaging systems and image processing techniques have been used for road inventory [32–35]. The use of UAV-based digital imaging and image processing technologies for the assessment of unpaved roads has been investigated. Zhang and Elaksher [36] conducted a quantitative evaluation of the system using markers and traffic cones of known sizes. They found that the system is capable for providing 3D information on surface distresses for road condition assessment purposes. As these studies collectively advance the comprehension of individual technologies, there arises a crucial need for a comprehensive comparative analysis to discern the nuanced strengths and limitations of advanced UAV drones in contrast to traditional tools, namely, Road Surface Tester and Rotary Laser Level. To the authors' knowledge, no quantitative assessment has been carried out to demonstrate the concordance and synchronization of on-site manual measurements, RST and UAV drones with RTK technology for gravel road profile measurements. This is particularly important as these methods differ significantly in terms of measurement procedures, coordination systems, and data analysis and processing software.

Correspondingly, this study aims to fill this gap by conducting a comprehensive evaluation of the capabilities of each method concerning profile measurements. This endeavor seeks to provide valuable insights for making informed decisions in infrastructure maintenance and development.

2. Equipment used and methodology

2.1. Advanced drone: DJI M300 with RTK

In this investigation, an advanced Unmanned Aerial Vehicle (UAV)-

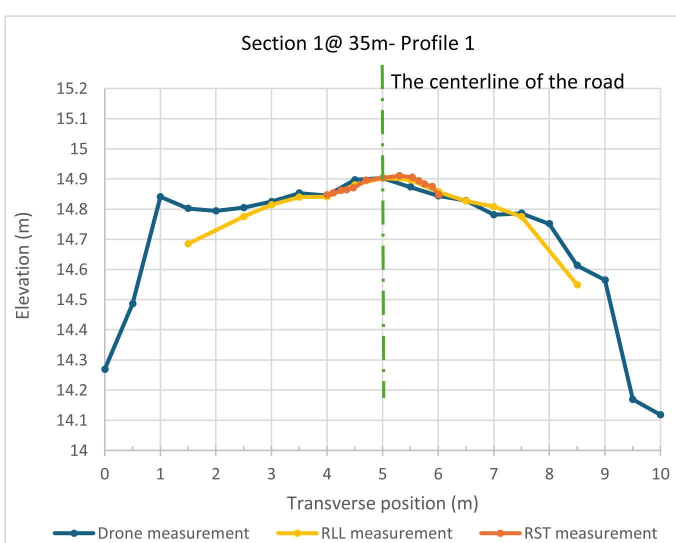

Fig. 7. Mmeasurements of Section 1 @ 35 m- Profile 1, using the three selected methods.

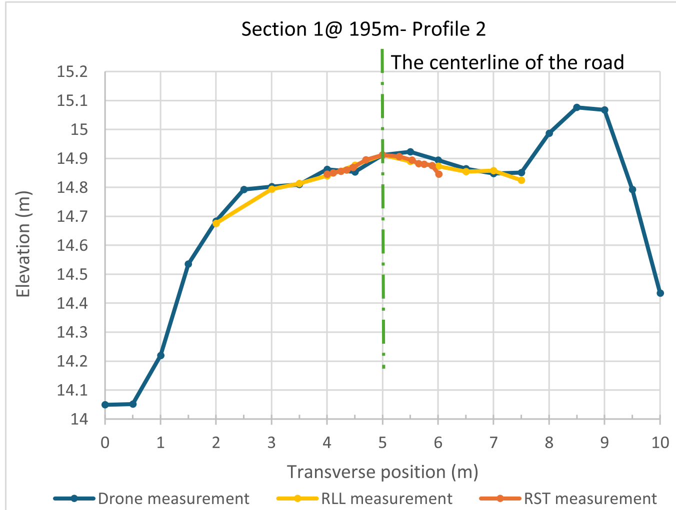

Fig. 8. Measurements of Section 1 @ 195 m- Profile 2, using the three selected methods.

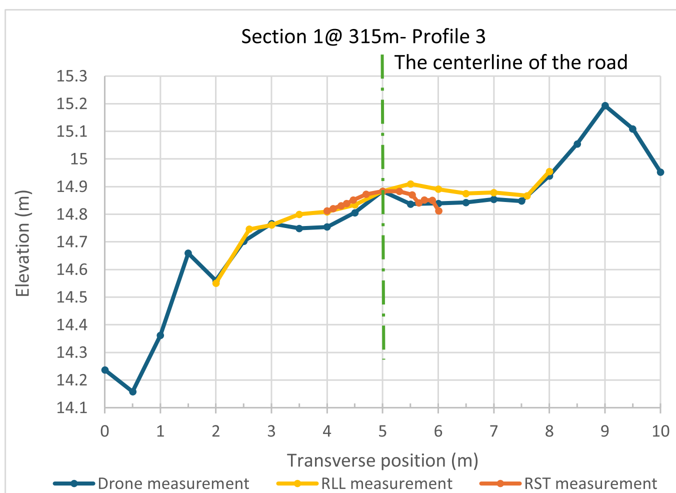

Fig. 9. Measurements of Section 1 @ 315 m- Profile 3, using the three selected methods.

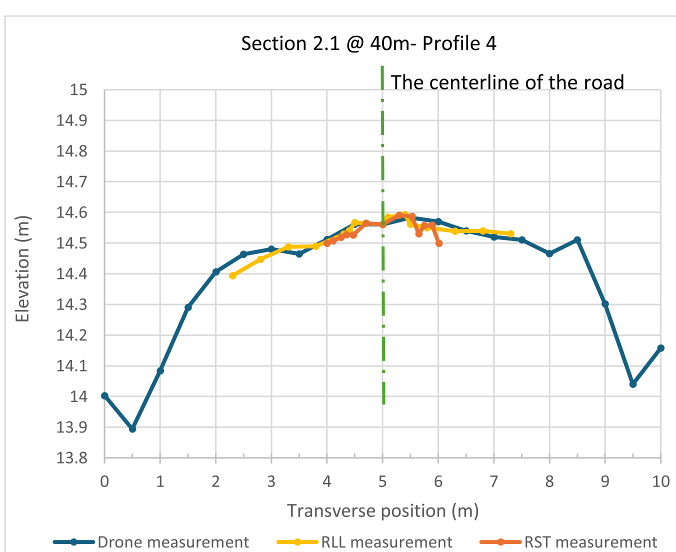

Fig. 10. Measurements of Section 2.1 @ 40 m- Profile 4, using the three selected methods.

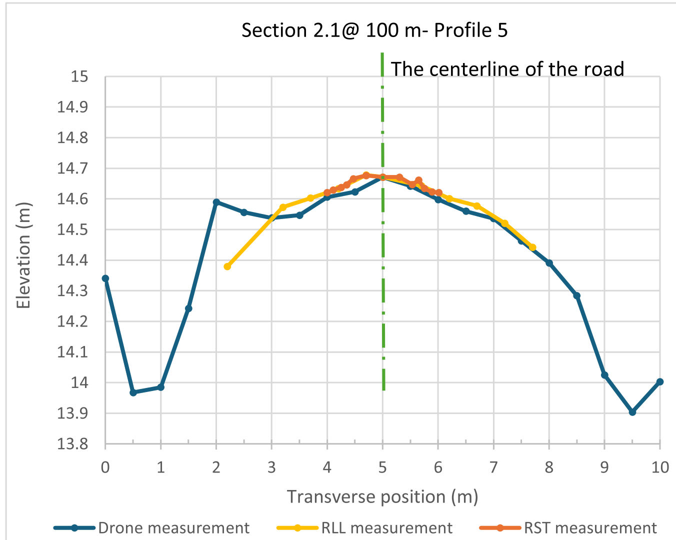

Fig. 11. Measurements of Section 2.1 @ 100 m- Profile 5, using the three selected methods.

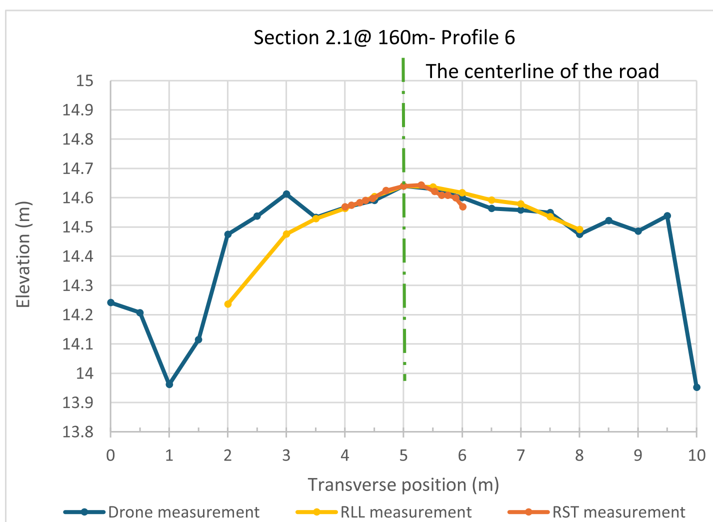

Fig. 12. Measurements of Section 2.1 @ 160 m- Profile 6, using the three selected methods.

based digital imaging system has been employed to efficiently gather surface condition data over gravel roads. The approach involves utilizing aerial imagery acquired from an unmanned platform to generate a three-dimensional (3D) surface model for assessing road distress. The system comprises a DJI M300 drone equipped with RTK technology, along with DJI P1 and DJI L1 cameras, and leverages Pix4D Mapper (P1 Photogrammetry) and DJI Terra (L1 LiDAR) software, see Fig. 1.

Photogrammetry involves capturing multiple overlapping images and using software to generate a 3D model by triangulating points between these images. On the other hand, LiDAR uses laser pulses to directly measure distances to the ground, creating a highly accurate point cloud with precise elevation data. The integration of RTK technology into the DJI M300 drone played a crucial role in establishing accurate Ground Control Points (GCPs), thereby enhancing georeferencing. The Real-Time Kinematic technology (RTK) exhibited remarkable stability, maintaining a consistent 3D position accuracy below 2 cm per pixel throughout the survey. Real-time precision and efficient GCP establishment were identified as key advantages of integrating RTK technology into the UAV survey.

The DJI P1 Photogrammetry, utilizing Pix4D Mapper, captured high-resolution imagery that facilitated the creation of a detailed point cloud. Meanwhile, the DJI L1 LiDAR sensor, coupled with DJI Terra, generated a precise 3D point cloud, providing crucially accurate elevation information for road surface analysis. In addition, TIFF orthophotos were taken for visual inspection and interpretation. To achieve high accuracy geometric feature extraction of road surface automatically from UAV based images, the ortho photo is first imported and placed in the drawing with the correct scale and position. Then, a surface model is created from the point cloud by importing the point cloud, filtering out non-ground points, and spacing the remaining points by 200 mm, which helps to eliminate non-ground points. Next, a TIN surface is created by adding the filtered point cloud. The road centerline is drawn on the ortho photo using the polyline tool, and then an alignment is created along the road centerline. Afterward, sample lines for cross-sections are created by selecting the alignment and placing sample lines at intervals or specified locations based on VTI marking in the ortho photo. Finally, the alignment and sample lines are selected, the settings are configured, and the section views are generated see Fig. 2. It should be noted that the orthophoto data processing achieved a resolution of less than 2 cm per pixel.

Concerning the vertical offset, an average elevation difference of 0.059 m was observed between the P1 photogrammetric point cloud and

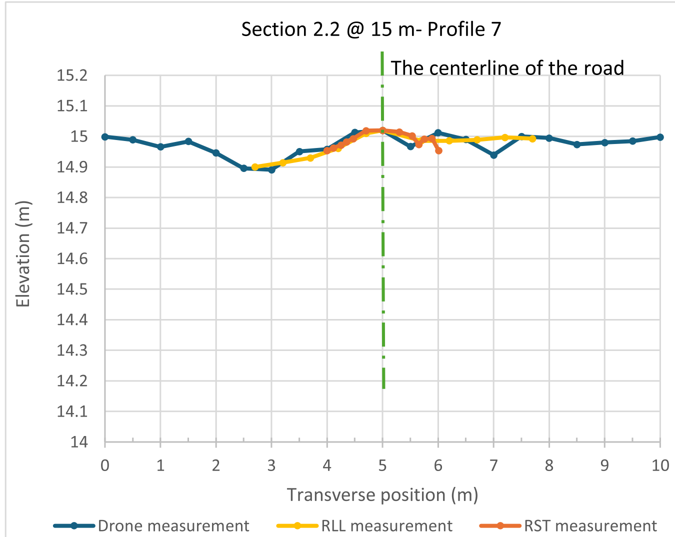

Fig. 13. Measurements of Section 2.2 @ 15 m- Profile 7, using the three selected methods.

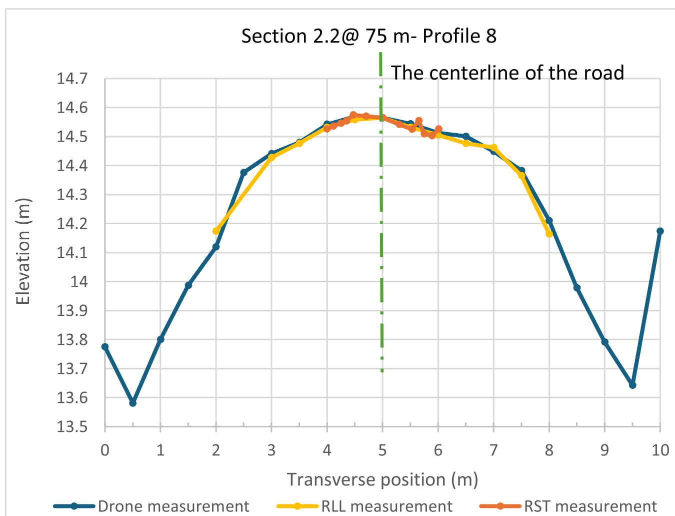

Fig. 14. Measurements of Section 2.2 @ 75 m- Profile 8, using the three selected methods.

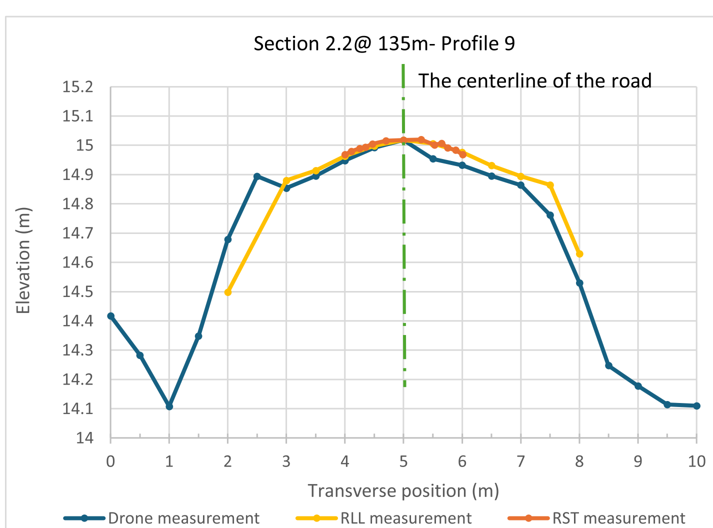

Fig. 15. Measurements of Section 2.2 @ 135 m- Profile 9, using the three selected methods.

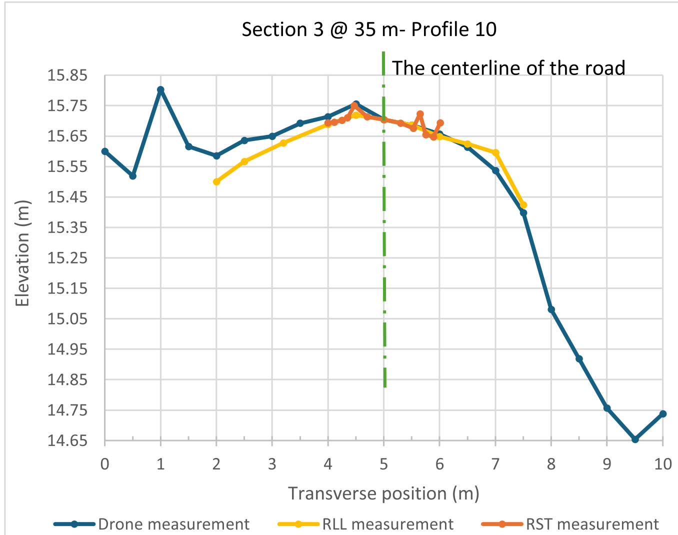

Fig. 16. Measurements of Section 3 @ 35 m- Profile 10, using the three selected methods.

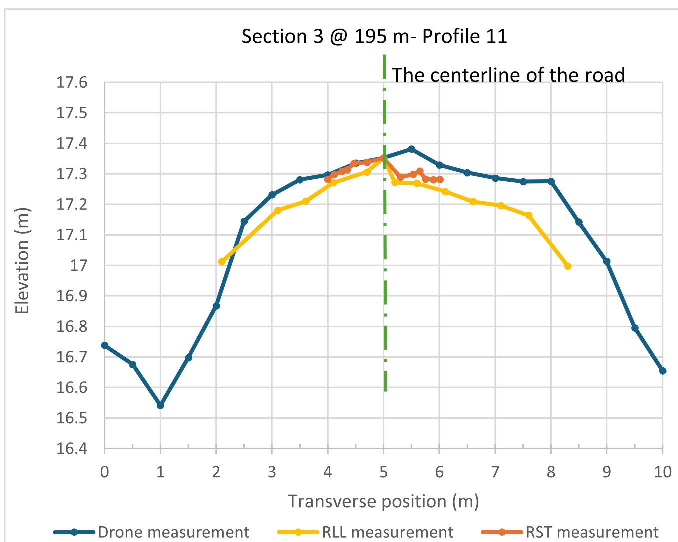

Fig. 17. Measurements of Section 3 @ 195 m- Profile 11, using the three selected methods.

the L1 LiDAR point cloud, significantly impacting the analysis of the road surface. The offset between the P1 and the L1 was primarily due to differences in the underlying technologies and methodologies used by the two systems for capturing and processing elevation data. Photogrammetry (used by the DJI P1) and LiDAR (used by the DJI L1) each have their own specific characteristics and inherent limitations. Photogrammetry can be affected by lighting conditions, shadows, and the texture of the surface being imaged. The accuracy of photogrammetry can vary based on these factors, potentially leading to slight vertical inaccuracies. Also, photogrammetric models can exhibit minor discrepancies in elevation data due to the nature of image-based reconstruction. On the other hand, LiDAR is generally less affected by lighting conditions and can penetrate vegetation to some extent, making it particularly useful for obtaining accurate terrain data. LiDAR typically provides very precise elevation measurements, which can result in differences when compared to photogrammetry-based data

In terms of surface-specific analysis, variations in the offset were detected across different surface types, including roads, gravel areas, grass, and regions with trees. Notably, the mean offset value remained consistently uniform throughout the entire road area, indicating a systematic discrepancy rather than random errors. The offset between the P1 and L1 data could not be entirely eliminated due to the fundamental differences in their data acquisition and processing techniques. This consistency in vertical offset prompted the decision to prioritize the utilization of the LiDAR point cloud due to its higher specification. Despite acknowledging the quality of the P1 point cloud, the superior capabilities of LiDAR technology were deemed indispensable for this particular project, especially in achieving precision over the road surface.

Hence, the choice to prioritize the LiDAR point cloud for road surface analysis in this study was motivated by its precision and accuracy in providing elevation data. The DJI L1 LiDAR camera, when used in conjunction with DJI Terra software and an RTK (Real-Time Kinematic) DJI drone, leverages several advanced mathematical techniques to achieve precise 3D mapping and modeling. The key mathematical components involved in this process are LiDAR Data Acquisition (Time-of-Flight and Point Cloud Generation), RTK GNSS for Georeferencing (RTK Positioning), LiDAR and Camera Integration (Sensor Fusion), Simultaneous Localization and Mapping (Pose Estimation), Point Cloud Processing in DJI Terra (Point Cloud Filtering and Surface

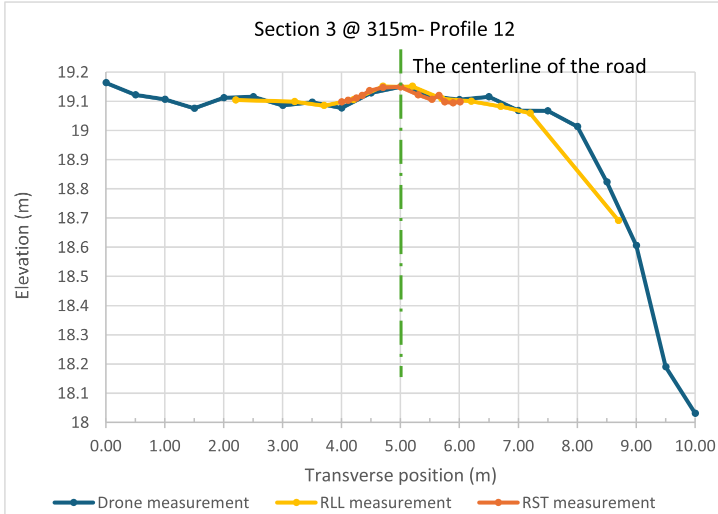

Fig. 18. Measurements of Section 3 @ 315 m- Profile 12, using the three selected methods.

Table 1
The differences in profile measurements conducted by the three methods for Section 1.

Section	Profile no.	Position with respect to the road centerline	Absolute Difference Drone -RST (in cm)	Absolute Difference Drone -RLL (in cm)	Absolute Difference RST-RLL (in cm)
1	1	@ 1 m from the road centerline (left)	2.5	0.4	2.9
		@ 0.5 m from the road centerline (left)	0.2	1.7	1.5
		@ 0.5 m from the road centerline (right)	3.7	2.4	1.3
		@ 1 m from the road centerline (right)	6.1	1.3	4.8
		Average difference (From 1 m left to 1 m right)	**3.1**	**1.5**	**2.6**
	2	@ 1 m from the road centerline (left)	0.7	2.2	2.9
		@ 0.5 m from the road centerline (left)	4.3	2.3	2.0
		@ 0.5 m from the road centerline (right)	1.7	3.3	1.6
		@ 1 m from the road centerline (right)	0.0	2.1	2.1
		Average difference (From 1 m left to 1 m right)	**1,7**	**2,5**	**2,1**
	3	@ 1 m from the road centerline (left)	9.8	5.5	4.3
		@ 0.5 m from the road centerline (left)	6.6	2.8	3.8
		@ 0.5 m from the road centerline (right)	4.6	7.3	2.7
		@ 1 m from the road centerline (right)	3.2	5.2	2.0
		Average difference (From 1 m left to 1 m right)	**6.0**	**5.2**	**3.2**

Reconstruction), Orthophoto Generation (Orthorectification).

The examination of surface models and orthophotos was conducted using Civil 3D software, which offers sophisticated tools for cross-section analysis, volume calculations, and precise georeferencing. The outcomes derived from Civil 3D were cross-validated against the initial UAV survey data, thereby ensuring the accuracy of interpretations and analyses.

2.2. RST (Road surface tester)

The Laser RST (Road Surface Tester) is a testing system designed to measure various road surface properties at normal traffic speeds [37]. It operates largely independently of speed variations in the testing vehicle, ensuring that the testing process does not disrupt the quality of the test or impact other road traffic.

The testing is conducted without direct contact with the test object. This eliminates the need for precise calibration and minimizes wear and tear on the testing equipment. Measurement positioning relies on the Global Navigation Satellite System (GNSS) and the distance rolled. This means that data is accurately positioned using coordinates. The sensor for measuring the rolled distance is situated on the free-rolling front-left wheel, allowing it to gauge the distance rolled at the center of the road.

Laser RST can measure various properties, including the longitudinal profile, cross-profile, camber, curvature, rise and fall, megatexture, and macrotexture. Based on the mentioned properties, the system allows for the calculation of measurements such as rut depth, rut area, theoretical water depth, the distance between rut bottoms, verge depth, fill volumes, irregularities (using a simulated straight edge), megatexture International Roughness Index (IRI), Mean Profile Depth (MPD), and more. Among the road characteristics that can be assessed using RST, the present study focuses on the cross profile.

Table 2
The differences in profile measurements conducted by the three methods for Section 2.

Section	Profile no.	Position with respect to the road centerline	Absolute Difference Drone -RST (in cm)	Absolute Difference Drone -RLL (in cm)	Absolute Difference RST-RLL (in cm)
2.1	4	@ 1 m from the road centerline (left)	1.4	2.9	1.5
		@ 0.5 m from the road centerline (left)	0.3	0.5	0.2
		@ 0.5 m from the road centerline (right)	0.8	0.2	0.6
		@ 1 m from the road centerline (right)	1.7	2.3	0.6
		Average difference (From 1 m left to 1 m right)	**1.1**	**1.5**	**0.7**
	5	@ 1 m from the road centerline (left)	6.0	2.7	3.3
		@ 0.5 m from the road centerline (left)	5.4	5.5	0.1
		@ 0.5 m from the road centerline (right)	2.9	0.1	2.8
		@ 1 m from the road centerline (right)	5.0	0.3	4.7
		Average difference (From 1 m left to 1 m right)	**4.8**	**2.1**	**2.7**
	6	@ 1 m from the road centerline (left)	3.1	0.3	3.4
		@ 0.5 m from the road centerline (left)	3.5	1.4	2.1
		@ 0.5 m from the road centerline (right)	1.3	0.6	0.7
		@ 1 m from the road centerline (right)	2.1	1.7	0.4
		Average difference (From 1 m left to 1 m right)	**2.5**	**1.0**	**1.7**
2.2	7	@ 1 m from the road centerline (left)	3.5	0.3	3.2
		@ 0.5 m from the road centerline (left)	0.6	0.3	0.9
		@ 0.5 m from the road centerline (right)	4.8	1.9	2.9
		@ 1 m from the road centerline (right)	1.0	2.6	1.6
		Average difference (From 1 m left to 1 m right)	**2.5**	**1.3**	**2.1**
	8	@ 1 m from the road centerline (left)	3.2	1.0	4.2
		@ 0.5 m from the road centerline (left)	0.1	1.1	1.2
		@ 0.5 m from the road centerline (right)	0.2	1.2	1.0
		@ 1 m from the road centerline (right)	1.2	0.8	2.0
		Average difference (From 1 m left to 1 m right)	**1.2**	**1,0**	**2.1**
	9	@ 1 m from the road centerline (left)	5.7	1.5	4.2
		@ 0.5 m from the road centerline (left)	2.4	0.6	1.8
		@ 0.5 m from the road centerline (right)	6.6	5.2	1.4
		@ 1 m from the road centerline (right)	6.9	4.4	2.5
		Average difference (From 1 m left to 1 m right)	**5.4**	**2.9**	**2.5**

2.3. *A rotary laser level and a distance-measuring wheel*

A rotary laser level (RLL) represents an advanced laser level that achieves a full 360-degree horizontal or vertical plane by rapidly rotating the light beam. This unique feature enables the illumination of not just a fixed line but an entire horizontal plane [38]. Additionally, the study incorporates a distance-measuring wheel, also referred to as an odometer, as depicted in Fig. 3. This wheel operates concurrently with the rotary laser level measurements, aiding in pinpointing the position of the profiles of interest based on the layout of testing points shown in the figure. Each turn of the wheel corresponds to a specific measured distance, and the wheels on this surveying equipment contribute to achieving an acceptable level of precision.

3. Case study

To ensure the accuracy and reliability of the current gravel road profiling comparison study, a test methodology was developed that involved the simultaneous application of three different measurement methods, namely UAV drone technology, road surface tester, and rotary laser level. The aim was to carry out all measurements on the same day, thereby reducing the potential variation in road profiles due to daily traffic fluctuations.

The point-by-point methodology described below provided a comprehensive and accurate comparison of the three profiling methods under consistent conditions. This approach ensured that any observed differences in road profiles could be attributed to the inherent characteristics of the measurement methods, rather than to external factors such as varying weather or traffic conditions.

3.1. *Site selection and preparation*

A gravel road in Trosa, Sweden, surrounded by dense forest, was chosen as a representative site for this study, taking into account factors such as traffic volume, road conditions, and accessibility. The road extends over 1 km from its starting point at N 58.829235 E 17.430640 in the north to its endpoint at N 58.823449 E 17.4425 in the south (see Fig. 4). This forest road is owned by Holmen. The test road was systematically divided into three main sections - Sections 1, 2 and 3, each 350 m long. Section 1 starts at N 58.829235 E 17.430640, followed by Section 2, which is further divided into Sections 2.1 and 2.2. The final section of the test road is Section 3, which ends at N 58.823449 E 17.4425. The division of the main test road into these sections facilitates the seamless integration of parallel studies. Different research teams or

Table 3
The differences in profile measurements conducted by the three methods for Section 3.

Section	Profile no.	Position with respect to the road centerline	Absolute Difference Drone -RST (in cm)	Absolute Difference Drone -RLL (in cm)	Absolute Difference RST-RLL (in cm)
3	10	@ 1 m from the road centerline (left)	3.6	2.6	6.2
		@ 0.5 m from the road centerline (left)	4.2	3.7	0.5
		@ 0.5 m from the road centerline (right)	0.7	0.0	0.7
		@ 1 m from the road centerline (right)	1.8	0.9	2.7
		Average difference (From 1 m left to 1 m right)	**2.6**	**1.8**	**2.5**
	11	@ 1 m from the road centerline (left)	3.7	2.6	6.3
		@ 0.5 m from the road centerline (left)	0.3	2.9	3.2
		@ 0.5 m from the road centerline (right)	9.2	10.9	1.7
		@ 1 m from the road centerline (right)	3.1	6.0	2.9
		Average difference (From 1 m left to 1 m right)	**4.1**	**5.6**	**3.5**
	12	@ 1 m from the road centerline (left)	5.9	2.8	3.1
		@ 0.5 m from the road centerline (left)	1.9	2.3	0.4
		@ 0.5 m from the road centerline (right)	0.4	3.4	3.0
		@ 1 m from the road centerline (right)	0.1	0.4	0.3
		Average difference (From 1 m left to 1 m right)	**2.1**	**2.2**	**1.7**

projects can focus independently on specific sections, allowing concurrent investigations without compromising the integrity of either study. This approach was particularly important as the test road is being used simultaneously in a parallel study, necessitating the consistent use of sections observed in the current research.

The three selected profiling methods were used to test twelve selected profiles divided into three main sections, namely Sections 1, 2 and 3, see Fig. 5. Note that Section 2 is subdivided into two sub-sections, for each of which three profiles were tested.

3.2. Data collection and processing

On the appointed day, all three measurements were carried out at predetermined intervals along the selected gravel road. The day begins with profile measurements using the laser level. After two hours, scanning of the gravel road using the UAV drone was started to capture aerial images and data of the road surface. Careful flight planning covered the entire gravel road, optimizing altitude, speed, and imaging settings for both cameras to capture detailed data in varying terrain conditions. Flight altitudes ranged from 50 to 100 m above ground level, see Fig. 6. However, wet and dark weather conditions with light rain during the tests posed a challenge.

Later in the same day, the road surface tester was used to obtain accurate profiling measurements and assess other distress characteristics of the gravel road.

3.3. Synchronization of measurements

Measurement synchronization is the most important and critical aspect of this study, particularly for the three methods selected. It acts as the lynchpin, ensuring the precise alignment and simultaneous data collection of the UAV drone, the surface tester, and the rotary laser level. Coordinating these measurements at the exact location is essential to maintain consistency, eliminate external variables, and facilitate comprehensive and reliable comparative analysis between the methods. Careful synchronization of measurements is the cornerstone that ensures the integrity and validity of study results across all profiling techniques. Therefore, a comparative framework was developed to assess the similarities and differences between the road profiles obtained by the UAV drone, the road surface tester, and the rotary laser level measurements.

Initially, the data collected by each method was processed and analyzed separately. Concerning the UAV drone, the test point layout shown in Fig. 5 was used to collect profile data as close as possible to the twelve profiles given in the test point layout and matched to LAS files containing LiDAR point cloud data for detailed terrain analysis. Challenges were encountered in delivering results compatible with ArcGIS, requiring data conversion and collaborative communication for successful integration. Fortunately, the drone data could be converted to Excel format something essential to compare the drone data with the data collected using RST and RLL methods. The drone used the Sweref 99 18 00 coordinate system and the RH2000 height system. Consequently, all data delivered to VTI was presented in terms of road profile cross sections, with a defined road centerline versus the elevation of the measured points. Elevations were calculated from a starting point to the left of the road towards the centerline and extending to the opposite edge. Measurements along the cross sections covered a 10 m width of each profile. For the road surface tester, the profile data was subdivided based on measurements taken from north to south and vice versa. The profile measurements taken as the road surface tester moved from north to south were aligned with the other measurements in the current study. This choice of direction was made to avoid mirror image problems in profile comparisons between the three methods. The main challenge in synchronizing the profile measurements collected by the drone and the pavement tester was the difference in the adopted coordinate system, particularly along the z-axis (i.e. the vertical offset). This difference is critical because the pavement tester measures depths in relation to a beam mounted on the vehicle at a height of approximately 50 cm. In terms of profile measurements using the rotary laser level and the distance measuring wheel, similar challenges were encountered due to the use of different systems to define profiles along the z-axis. The rotary laser level measures the vertical offsets relative to fixed reference points, such as a large rock or a wooden stick fixed in the ground.

Fortunately, all three methods accurately defined the road centerline, enabling the synchronization of measurements across the road section. This was achieved by adjusting the y-axis of the profiles collected by the three methods to align with the same defined road centerline. The same approach was applied to synchronize the profile measurements along the z-axis. This involved aligning the z-coordinate of the centerline points from data collected by the rotary laser level and the RST with the drone-measured elevation at the centerline of each profile. This enabled a comparison without impacting the relative measurements.

4. Results and discussions

Figs. 7-18 show the profiles obtained using the three methods employed, namely, UAV drone technology, Road Surface Tester (RST), and Rotary Laser Level (RLL) technology. In these figures, each horizontal line represents a 10 cm distance in elevation. The orange curves depict profiles conducted by the RST, covering a road width of 2 m, while the yellow curves represent measurements taken by the rotary laser level with a coverage width of approximately 6 to 7 m. The broadest profile measurements, spanning about 10 m in width, are represented by the blue curves from the UAV drone technology in the figures below. The green line denotes the road centrelines in Figs. 7-18.

It is evident that the profile measurements from the three methods closely align with each other. In Figs. 10 and 14, profiles 4 and 8 exhibit nearly identical measurements on both sides of the road (i.e., from 1 m left to 1 m right of the road centreline). However, for profile 3 in, there is mismatching among the measurements from the three methods from 1 m left to 1 m right of the road centreline. The remaining profiles measured by the three methods show a better match than profile 3 for measurements taken from 1 m to the left and 1 m to the right of the road centreline. The other measurements taken by the drone and RLL for the distance between 1 m and 3.5 m from the road centreline to the left and right are not compatible due to the presence of vegetation in the ditches on both sides of the road in these areas, which may have affected the drone measurements.

Tables 1–3 show the absolute differences in profile measurements taken by the three methods for each section. The data show that the variations between the drone and RST measurements, and between the drone and RLL measurements, are similar to those observed between the RST and RLL methods. Notably, this similarity in differences occurred despite the drone flying at heights ranging from 50 m to 100 m above ground level, while the other two methods were conducted at/close to ground level. This indicates that the used UAV drone with RTK technologies can be employed for profile measurements on gravel roads with sufficient accuracy.

Based on the data presented in Table 1 to 3, the best agreement between the UAV drone and RST measurements was reported for Profile 2 at 1 m from the road centreline (to the right) and for Profile 8 at @ 0.5 m from the road centreline (left) with almost zero difference in measurements between these methods at the given points.

The optimal agreement between UAV drone and RLL measurements occurred for Profile 4, positioned 0.5 m to the right of the road centreline, and for Profile 7, located 0.5 m to the left of the road centreline. Minimal differences in measurements were observed between these methods at the specified points.

The RLL and RST measurements exhibited the best agreement for Profiles 4 and 5 both at 0.5 m to the left of the road centreline. Negligible differences in measurements were noted between these methods at the designated points.

According to the absolute difference measurements provided in Tables 1 to 3, maximum average absolute differences of 6 cm, 5.6 cm, and 3.5 cm were recorded for all profiles (ranging from 1 m left to 1 m right the road centreline) in the comparisons between UAV drone – RST, UAV drone – RLL, and RST – RLL methods, respectively. Minimum average absolute differences of 1.1 cm, 1 cm, and 0.7 cm were recorded for all profiles (ranging from 1 m left to 1 m right the road centreline) in the comparisons between UAV drone – RST, UAV drone – RLL, and RST – RLL methods, respectively.

This underlines the significant advancement in UAV drone technology, enabling remarkably accurate measurements of vertical offsets for profiling the tested gravel road despite the high altitude at which the UAV drone operates (ranging from 50 to 100 m above the ground surface). In most cases, this high altitude is crucial for avoiding obstacles such as trees lining both sides of the gravel roads. In cases where it is possible to operate the drone at lower altitudes, it is expected that even greater accuracy in UAV drone measurements can be achieved.

5. Conclusion and recommendations

In this study, a comprehensive assessment of gravel roads was conducted using three profiling methods: UAV drone technology, Road Surface Tester (RST), and Rotary Laser Level (RLL). The road condition profiling is crucial for effective maintenance, especially for gravel roads that play a vital role in connecting urban and rural areas, comprising a significant portion of the Swedish road network.

The integration of advanced technologies such as UAV drone with RTK, Laser RST, besides the Rotary Laser Level has demonstrated the potential for accurate and efficient profiling of gravel roads. The study compared these methods and revealed that despite the distinct measurement procedures, coordination systems, and data analysis approaches, the results obtained from the three methods showed a substantial level of agreement.

The used UAV drone technology showcased its capability to capture high-resolution imagery and generate a detailed 3D surface model. The integration of RTK technology ensured accurate Ground Control Points (GCPs), enhancing georeferencing and providing real-time precision. The vertical offset analysis revealed the precision of the LiDAR point cloud generated by the DJI L1 LiDAR sensor, making it preferable for road surface analysis.

Of course, for the recent decades, the Laser RST has proven to be an efficient testing system for measuring various road surface properties. Its independence of speed variations in the testing vehicle and ability to operate without direct contact with the test object make it a valuable tool for road condition assessment. Also, the Rotary Laser Level, with its 360-degree horizontal plane capability, provided good insights into road profiles. Coupled with a distance measuring wheel, it demonstrated acceptable precision in measuring distances.

To enhance synchronization and comparison between these profiling methods, efforts should be made to standardize coordinate systems and data processing software. This standardization will facilitate seamless integration and interpretation of data obtained from these sources.

Overall, this study provides valuable insights into the potential of next-generation profiling for gravel roads and sets the foundation for further advancements in road condition assessment methodologies.

CRediT authorship contribution statement

Dina Kuttah: Writing – original draft, Validation, Supervision, Project administration, Methodology, Formal analysis. **Andreas Waldemarson:** Investigation.

Declaration of competing interest

The authors declare that there is no conflict of interest regarding the current manuscript "**Next Generation Gravel Road Profiling- The Potential of Advanced UAV Drone in Comparison with Road Surface Tester and Rotary Laser Levels**" sent to your Transportation Engineering Journal.

Data availability

Data will be made available on request.

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