The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLIX-B2-2026
XXV ISPRS Congress 2026 “From Imagery to Understanding”, Commission II, 4–11 July 2026, Toronto, Canada

Mobile Multi-camera System Performance for Photogrammetric Road Surface 3D Measurements – Assessment the Effect of Driving Speed

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Keywords: Mobile mapping, Photogrammetry, Multi-camera system, Road surface, Point clouds.

Abstract

Mobile mapping systems usually include cameras designed for 360° imaging and laser scanning point cloud coloring. However, the multi-camera systems are rarely optimized for producing photogrammetric image-based point clouds in road environments. In this study, we built a mobile 5-camera system and assessed its performance in determining the 3D geometry of road surfaces. The evaluation was carried out in two parts: First, we examined how driving speed ranging from 3 to 20 km/h affect the quality of the point cloud produced by the mobile multi-camera system. We compared this data to reference measurements of road surface samples obtained using a laboratory-grade structured-light scanner. Second, we compared the point cloud produced by the mobile multicamera system to that generated by a terrestrial laser scanner from a 10-meter single lane road section. In the case of the driving speed tests, the point cloud comparisons resulted an average 3D distance from 0.09 mm to 0.31 mm, and a standard deviation from 0.29 mm to 0.50 mm. On the road section, the average 3D distance between the points clouds was 0.97 mm, with a standard deviation of 0.59 mm. These results demonstrate the capability of the mobile multi-camera system in 3D reconstruction of road surfaces and encourage further research into the feasibility of multi-camera system configurations for studying road surface quality parameters and identifying the dimensions of road damages.

1. Introduction

Ensuring reliable and efficient assessment of road surface conditions is vital not only for effective pavement management and maintenance prioritisation but also for ensuring road safety and preventing accidents. Traditionally, road surface inspections have relied on manual surveys and static measurement techniques. These methods are time-consuming, costly and often require partial road closures or traffic control, posing safety and logistical challenges (Ahmed et al., 2011, Putkiranta et al., 2021). In response, remote sensing and image-based methods — particularly photogrammetry and laser scanning — have emerged as promising alternatives for automating pavement distress detection.

Previous studies in close-range photogrammetry have investigated high-resolution 3D modelling of road surfaces using terrestrial and UAV-based imaging systems (Ruzgienė et al., 2015, Inzerillo et al., 2018, Tan and Li, 2019). When equipped with multiple calibrated cameras, these systems can generate dense 3D point clouds suitable for analysing surface defects such as cracks, potholes, rutting, and general wear (Fritsch et al., 2012, Knyaz and Chibunichev, 2016). Photogrammetry-based approaches have also been adapted to mobile mapping platforms, enabling continuous data acquisition usually for road and city environments (Navarro and Lerma, 2016, Farhadmanesh et al., 2021). However, many existing mobile systems rely on 360° panoramic imaging, which is optimised for environmental context mapping rather than the fine-grained surface detail required for quantitative pavement analysis (Cavegn and Haala, 2016, Wierzbicki, 2018).

In contrast, terrestrial laser scanning (TLS) and mobile laser scanning (MLS) have demonstrated high accuracy in measuring pavement distress features, such as rut depth and surface roughness (El Issaoui et al., 2021, Feng et al., 2022). While these systems are highly effective, they are often costly and less accessible, and they may still require stationary operation for high-resolution capture, which introduces the same operational constraints as traditional methods. Static measurements performed on the road often interrupt traffic flow and may require traffic management (Putkiranta et al., 2021), making mobile alternatives both more efficient and safer.

Thus far, accurate reference data on road pavement distress, including 3D geometry and metrics (such as volume, area, and maximum depth) of individual damages has been lacking. This is also a constraint on developing robust detection methods for MLS, as reference data are crucial for validating accuracy and providing training data for automatically detecting damages. One limiting characteristic of MLS data regarding road surfaces is the point spacing resolution along the driving direction. The MLS laser profile interval increases relative to the driving speed. Furthermore, current commercial mobile mapping camera systems, such as panoramic cameras, are mainly designed to capture 360° views of the environment. Thus, they are not optimised for photogrammetric 3D measurements of road pavement damage. As a result, cameras must be aimed at the road surface, and the same road defect must be visible in multiple images to calculate its 3D coordinate information.

Despite the progress in sensor and algorithm development, a notable research gap remains in photogrammetric multi-camera systems specifically designed for high-precision road surface measurement from moving vehicles. Existing multi-camera photogrammetry platforms have mainly been used for architectural modelling, environmental mapping (Fritsch et al., 2012, Hammoudi and McDonald, 2013), or general mapping tasks that do not require sub-millimetre precision for groundlevel surfaces. Photogrammetric methods for road condition assessment have largely been limited to either UAV-based systems, which suffer from limited resolution and control near the ground (Zhang, 2008, Díaz-Vilariño et al., 2016, Putkiranta et al., 2021), or to static close-range setups with constrained coverage and slow operation (Tiong et al., 2012, Marinello et al., 2017, El Issaoui et al., 2021).

In this study, we introduce a novel vehicle-mounted photogrammetric multi-camera system, specifically designed for high-resolution reference data of road surfaces. Unlike traditional mobile mapping systems that utilise panoramic cameras, our configuration features downward-facing cameras, optimised for capturing detailed ground features. This setup facilitates the generation of dense and accurate 3D point clouds suitable for analysing cracks, potholes, rutting, and general pavement conditions with precision comparable to static laser scanning. The system is designed to function effectively at low driving speeds, significantly improving data acquisition efficiency while reducing the need for traffic interference or closures. Our goal is to deliver a photogrammetric road surface monitoring method that combines the point density and precision of static methods with the speed, safety, and scalability of mobile mapping platforms. The purpose is to use the system to collect reference data for verifying data from operational mobile laser scanning systems.

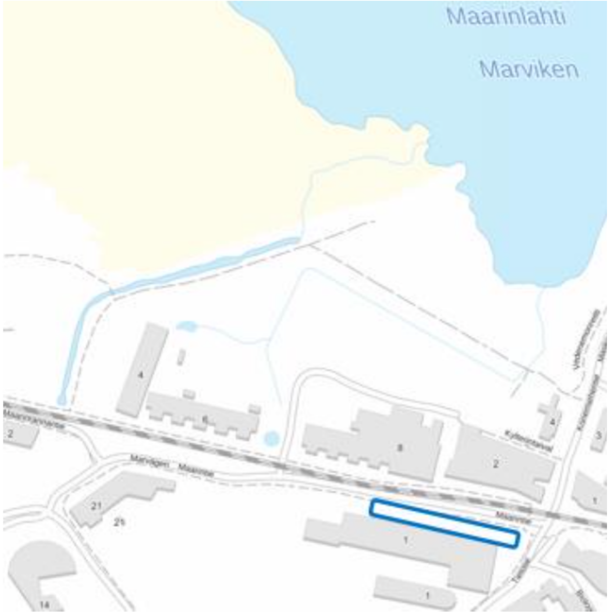

Figure 1. The parking area marked in blue (located in Otaniemi, Espoo, Finland) was used for driving speed tests. (Paikkatietoikkuna, November 2025)

Figure 2. The second test site included a measurement of approximately one kilometre (marked in blue) part of road in Röylä (Espoo, Finland). (Paikkatietoikkuna, November 2025)

2. Materials and Methods

2.1 Test sites

For the experimental part of this research, two test sites were selected, both located in Espoo, Finland. The first test site was located in a parking area in Otaniemi (Figure 1). This test site was enhanced with road surface samples as well as signalised ground control points (control targets). Various driving speeds were experimented with for data collection in this test site.

The second test site included 1 km of asphalt road, comprising a part of the Röyläntie road (Figure 2). The road segment was selected to ensure that there were open fields on both sides, which provided good satellite visibility and minimised potential shadows from the surrounding area. In this area, we performed road surface analysis using only one driving speed (approximately 12 km/h). In addition to photogrammetric data, TLS data was also collected from four smaller segments of the test area.

2.2 Mobile Photogrammetric Multi-Camera System

The multi-camera system consisted of five cameras mounted on a rig, which was attached to the coupling hook Figure 3. The cameras captured images with an oblique view directed downward. An overlap of approximately 80% on the road surface was ensured between each pair of cameras. All cameras were Sony α1 ILCE-1 models equipped with 14 mm SEL14F18GM lenses. The shutter synchronisation was implemented using an external laptop, connected to the cameras using a local area network. All five cameras were set to capture images of the road surface at 10 Hz, resulting in a total of 50 images captured by the system per second. The ground sample distance, computed as

$$\mathrm{GSD} = \frac{h\,p}{f}, \tag{1}$$

of $\approx$0.4 mm was estimated for a single camera using a camera height (h) of 1.3 m above the road surface, a pixel size (p) of 4.16 µm, and a focal length (f) of 14 mm. The system did not have an onboard GNSS/IMU system, but control targets were used for georeferencing Figure 5.

2.3 Road Surface Samples for the Speed Tests

The purpose of the field test, carried out in a separate parking area in Otaniemi (Test site 1), was to evaluate the effect of the

Figure 3. Mobile multi-camera system for photogrammetric road surface 3D measurements.

driving speed of the mobile multi-camera system on the point cloud quality by comparing the data with reference road surface samples. To ensure variation in terms of surface quality and road surface structure, five circular samples of road surface materials, ranging from 8 cm to 14 cm, were used Figure 4.

Figure 4. The reference road surface samples (S1-S5) were utilized for the speed test.

To obtain a reference, these road surface samples were digitized using a laboratory-grade structured-light scanner, the Konica Minolta VIVID 9i Non-Contact 3D Digitizer enabling a geometric precision of ±0.008 mm in the z-axis direction (Konica Minolta, 2005). All measurements were performed indoors under controlled temperature conditions, ensuring no exposure to natural light. Calibration was conducted using the Field Calibration System for the 744 mm TELE and 694 mm MIDDLE lenses, the latter being required for the largest road surface specimen. The scanner was operated in standard mode, and each sample was captured in four scans. Data were processed with the Polygon Editing Tool software, applying no hole filling and using a 1:1 reduction rate, after which the resulting mesh models were exported as OBJ files. Following the laboratory measurements, the road surface samples were arranged in sequence on an outdoor paved surface to replicate realistic field measurement conditions Figure 5.

The 3D coordinates of the 8 control targets in Figure 5 were measured using GNSS. The test area was driven over six times in one direction at different speeds. We selected all images from each run in which pavement samples were visible to calculate the photogrammetric point cloud. The speeds of each run and the number of images are presented in Table 1.

Figure 5. An example image of mobile multi-camera system on the speed test in Otaniemi parking area (Test site 1). The image includes road surface samples and control targets used for georeferencing.

Round №	**Approximate Speed** (km/h)	**№ of Images**
1	3	205
2	5	110
3	5	105
4	8	55
5	12	40
6	20	25

Table 1. The estimated driving speeds and number of images for each test run in Test site 1.

2.4 Terrestrial Laser Scanning

TLS data collection from the Röyläntie road experiments was conducted with a Leica RTC360 scanner. The driving line was blocked from traffic by two traffic controllers during the measurements. Two scans were taken, one on each side of the plot Figure 6, employing the medium setting which results in a point resolution of 6 mm at a distance of 10 m. Due to the close proximity of the two scan locations, the point resolution was significantly higher within the plot. The distance from the scanner to the plot area varied from about 1 to 5 meters. Images captured by the scanner’s integrated camera were used to both color the point cloud and georeference the photogrammetric datasets. The TLS point cloud was georeferenced using 19.9cm diameter target spheres on tripods. The locations of the tripods were measured using RTK-GNSS. The scan data for each four plot were registered in Leica Register 360, where automatic cloud-tocloud alignment was done using the target spheres in both scans. The point clouds were then segmented manually in CloudCompare 2.10.2 to separate the plot area from the other areas of the scan.

2.5 Post-Processing and Analysis of Photogrammetric Data

In the post-processing step, RealityCapture software (a proprietary package) was used to combine images and scans, and create an RGB-colored point cloud from the collected images. In the Röyläntie road area, the photogrammetric 3D point cloud was registered to the already georeferenced TLS 3D point cloud by utilizing the Iterative Closest Point (ICP) algorithm. In addition, the ICP algorithm was used to register the reference road

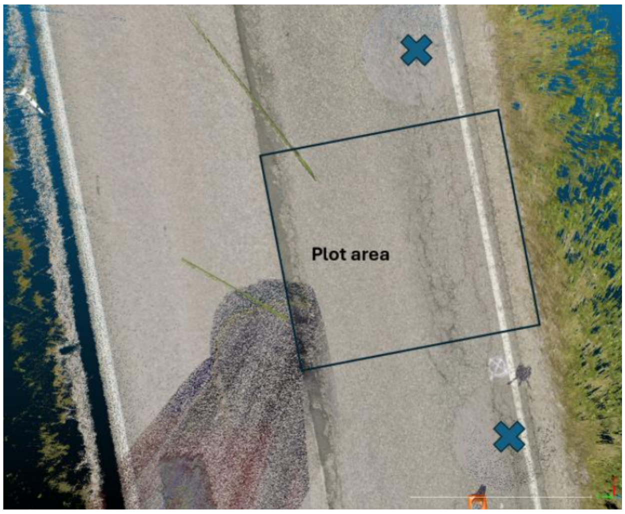

Figure 6. TLS scan station locations marked with blue crosses next to the study plot. The width of a single lane is approximately 3.5 meters.

surface samples measured at the Otaniemi parking area to corresponding samples measured in the laboratory using a Konica Minolta device. The Cloud Compare open source software was used to analyze point clouds using the Cloud-to-Cloud tool, which provided the average distance, standard deviation, and maximum distance for all comparisons. The distance is calculated as the Euclidean distance in 3D space. In addition, we evaluated the RMS values when the point cloud from the mobile multi-camera system was aligned to the reference data.

3. Results

3.1 Road Surface Sample Quality with Different Driving Speeds

The results of the road surface samples included an analysis of the number of points and point density with multi-camera images and laboratory measurements (Table 2). In addition, the RMS error for ICP registration, average distance, standard deviation and maximum distance values between the mobile multi-camera point cloud and reference data for each driving speed are presented in Figures 7 to 10.

	Number of datapoints		Point density	
Sample	Multicam	Laboratory	Multicam (pts /mm^2)	Laboratory (pts /mm^2)
1	75 699	141 953	13	24
2	80 179	150 969	12	23
3	75 213	145 495	11	21
4	69 570	131 221	13	24
5	187 951	107 943	12	7

Table 2. Statistics on the number of points and point density of road surface samples in the multi-camera system data with a driving speed about 12 km/h and in reference measurements performed in the laboratory.

3.2 Mobile Multi-Camera Point Cloud Comparison with Terrestrial Laser Scanning

The mean distance, standard deviation and ICP registration RMS values of the Röyläntie road point cloud comparisons are presented in Table 3. Figures 11, 12 and 13 show calculated cloud-to-cloud distances and a cross-section profile of the Röyläntie study plot 1 between mobile multi-camera point cloud measured with a driving speed about 12 km/h and TLS data. The comparison shows that most points have below 1 mm difference to the TLS data. Larger distances usually occur in deformations such as longitudinal cracks. The mean distance of the comparison is 0.97 mm and standard deviation 0.59 mm.

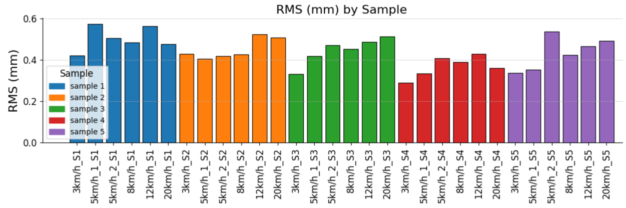

Figure 7. RMS error for ICP registration (Mobile multi-camera point cloud with reference) of different samples (S1–S5) with driving speeds 3–20 km/h varied between 0.29 mm and 0.57 mm.

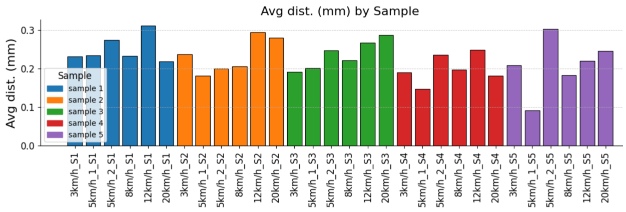

Figure 8. Average distance error between Mobile multi-camera point cloud and reference data of different samples (S1–S5) with driving speeds 3–20 km/h varied between 0.09 mm and 0.31 mm

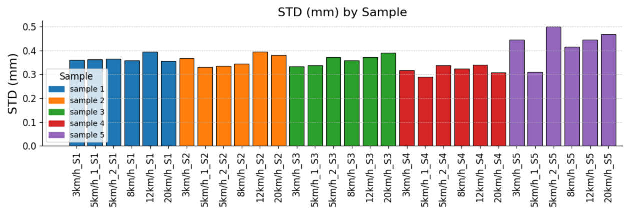

Figure 9. Standard deviation error between Mobile multi-camera point cloud and reference data of different samples (S1–S5) with driving speeds 3–20 km/h varied between 0.29 mm and 0.50 mm.

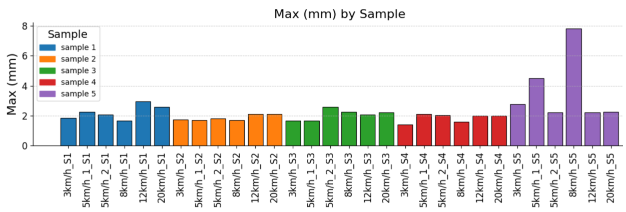

Figure 10. Maximum distance error between Mobile multi-camera point cloud and reference data of different samples (S1–S5) with driving speeds 3–20 km/h varied between 1.42 mm and 7.82 mm.

Plot	Mean distance (mm)	Standard deviation (mm)	ICP registration RMS (mm)
1	0.93	0.55	5.5
2	0.84	0.49	4.7
3	1.07	0.73	6.2
4	1.04	0.60	5.3
Mean	0.97	0.59	5.4

Table 3. Statistics of the cloud-to-cloud calculation and ICP registration of the Röyläntie plots.

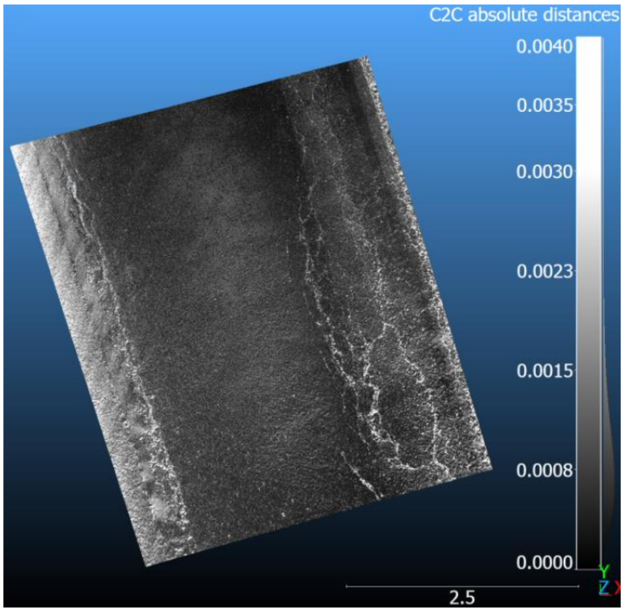

Figure 11. Cloud-to-cloud absolute 3D distances (unit in meters) between mobile multi-camera data and TLS data.

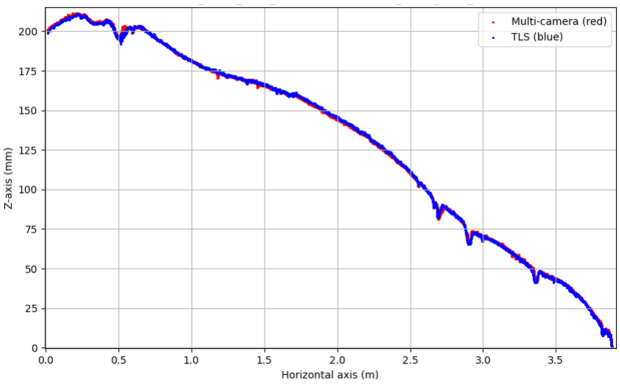

Figure 12. A 5 mm wide cross-section from the Röyläntie study plot area showing mobile multi-camera measurements in red and TLS data in blue.

4. Discussion

Our results from measuring road surface samples at different driving speeds showed great potential for utilizing the mobile multi-camera system to determine surface structure geometry with sub-millimeter precision. The preconditions were that the point clouds of the road surface samples were registered against the reference data using the ICP algorithm, with the RMS error varying between 0.29 mm and 0.57 mm. Subsequently, most of the measured pavement samples had less than 0.5 mm 3D distance difference to the reference. The average distance differed from 0.09 mm to 0.31 mm, the standard deviations from 0.29 mm to 0.50 mm and maximum error from 1.42 mm to 7.82 mm.

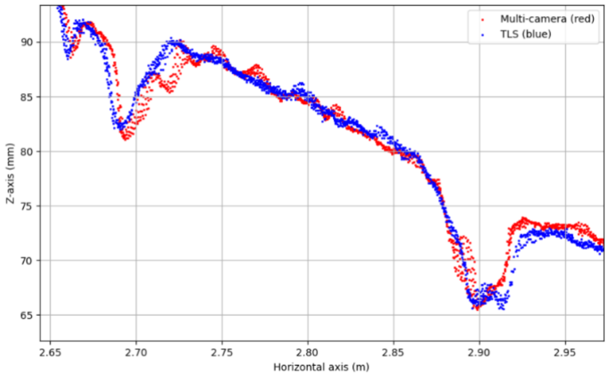

Figure 13. A zoomed section of the 5 mm wide cross-section from the Röyläntie study plot area shown in Figure X, enlarging the section between 2.65 and 2.95 m.

When the point cloud data collected by the mobile multi-camera system from a single lane of the road at a driving speed of 12 km/h was compared with TLS data, the average 3D distance difference was 0.97 mm and standard deviation 0.59 mm.

When examining the effect of driving speed on the results, only minor changes were observed as the speed varied between 3 and 20 km/h. In general, slower speeds yielded the most robust results. However, according to the findings, even the highest speed (20 km/h) did not significantly degrade the results. Based on these findings, further research is encouraged, particularly by increasing driving speed and optimizing the number of cameras, for example, by evaluating results using three cameras (the middle and the two outer cameras) instead of five.

When driving in a single lane, our multi-camera system has two or three cameras covering the sides. All five cameras capture the centre of the lane from optimal oblique angles. This can lead to uncertainty in detecting deep cracks at the edge of the road. However, the mobile multi-camera system was able to measure the sides of the pothole with a greater point density than the TLS. This is due to the better geometry of the mobile multicamera system. In addition, the point density is more consistent with the mobile multi-camera system. In our experience, the textures of asphalt-paved road surfaces in Finland contain many unique and individual features that are beneficial for photogrammetric point cloud calculation.

Our main purpose is to use the developed mobile multi-camera system to collect reference data on the road surface for the validation of operational mobile lidar systems. The aim is also to speed up reference measurements, which are currently performed on static platforms. Compared to mobile lidar-based systems, the proposed mobile multi-camera photogrammetric method offers several significant advantages for high-resolution road surface assessment. Although mobile lidar sensors are widely used for surveying road environments, their point density in the driving direction is limited by the vehicle’s speed, whereas a multi-camera system enables uniform, high-density image overlap and thus better spatial resolution for identifying various types of road damage. Our results also show that the precision of 3D range measurement using the mobile multi-camera system reaches the sub-millimeter level. Furthermore, the downward-facing camera configuration optimizes 3D data collection specifically for road surface analysis, for which the panoramic imaging systems used in conventional mobile mapping systems are often unsuitable. In our solution and results, it must be noted that we evaluated only relative 3D measurement accuracies; therefore, further research should include the integration of a GNSS/IMU solution for improving operational applicability.

By addressing the limitations of existing mobile photogrammetry systems and filling the gap between static precision and mobile efficiency, our approach contributes a practical and reproducible framework for large-scale pavement condition assessment. Furthermore, the high-fidelity 3D data produced by our system may serve as a reference dataset for validating other road monitoring technologies, including MLS and UAV-based systems (El Issaoui et al., 2021, Feng et al., 2022).

5. Conclusion

Mobile mapping systems, including laser scanners, cameras, and positioning systems, began to be developed for road environment surveying in the early 2000s. Nevertheless, the cameras used in mobile mapping systems have mainly been 360° solutions, whose images are mainly used to color laser point clouds but have been unsuitable for photogrammetric measurement. In this study, we built a photogrammetric mobile multi-camera system and investigated its feasibility for 3D measurement of road surface geometry. More specifically, we tested the effect of driving speed on the quality of the 3D point cloud geometry on road surface. The collected data was always registered to the reference data using the ICP algorithm. Our conclusion was that, with a five-camera system at speeds of 3—20 km/h, we achieved 3D distance errors of less than 0.5 mm when the data was compared to reference data measured from road surface samples. Furthermore, when data driven at a speed of 12 km/h from a single lane width was compared to TLS data, the 3D distance errors were less than 1 mm.

The results show that the method has great potential for producing sub-millimetre resolution and precision data on road surface damages, road roughness, and other road parameters. The purpose is to use the system to collect reference data for verifying data from operational mobile laser scanning systems. The system can also be installed on other platforms and applications. Further research will also include integrating a positioning solution into the system.

6. Acknowledgements

The authors would like to thank the Research Council of Finland for financial support through the projects “Towards automatic road inspection” (No. 365584 and 365583) and “Innovative methods for measuring and modelling the dynamic forest road quality” (No. 362926 and 362928), and the Flagship project “Forest-human-machine interplay – building resilience, redefining value networks and enabling meaningful experiences” (UNITE, 357906 and 359175).

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