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A COMPARISON BETWEEN 3D HIGH-DEFINITION MAPS CREATED BY PHOTOGRAMMETRY AND BY LASER SCANNING APPLIED FOR AN AUTONOMOUS VEHICLE

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Abstract. Seft-driving cars are a key innovation in the automotive industry with many benefits that can be achieved to reduce major current traffic problems such as accidents, jams, parking lots, and so on. Various researchers and companies, especially in developed countries, try to solve many problems such as developing the drive-by-wire system, making mathematical algorithms, applying artificial intelligence, with the hope of bringing autonomous vehicles to life. In order to step by step capture the technology and get ready for the test of autonomous vehicles, 3D high-resolution maps, as an important part of the vehicle's localization and path planning need to be studied in depth. In this paper, based on the selected mathematical algorithm, the performing of two methods for building 3D high-resolution maps will be analyzed to find out the advantages and disadvantages of each one. The results show that the high-resolution map constructed by using lidar is more accurate and detailed, whereas the map constructed by using images with coordinates is more intuitive. Therefore, to be able to develop autonomous vehicles with high accuracy for the whole city, a mapping method using lidar-camera fusion is essential in which map of the detailed roads is created by Lidar and map of the rest areas is built by optical imaging method.

Keywords: Autonomous vehicle, Point cloud map, Velodyne, HD map.

Classification numbers: 5.3.6, 5.10.2.

1. INTRODUCTION

The autonomous vehicle (AV) industry is rapidly developing in recent years. According to SAE (Society of Automotive Engineers) [1], autonomous vehicles are classified into 6 levels: from 0 which is no automation up to 5 which is full automation without a request of driver on the vehicle. Nowadays, most worldwide autonomous vehicles are on level 2 and level 3, or semi-autonomous. According to the Mesinsights, Waymo, General Motor, Argo, Tesla, Baidu could reach level 4, but only for R&D purposes. AV is more and more becoming a focusing topic of leading companies and researchers, and also a comprehensive research venture involving interdisciplinary study. Based on some reports [2], commercial automated cars will be soon accessible on the market in the coming years with the maturity of autonomous vehicle technology such as perception, localization and mapping, path planning, decision making, and drive-by-wire. Therefore, 3D high definition (HD) map data for navigation purposes need to be ready for market soon.

There are several approaches for 3D HD map creation, which could be used in AV industry. A list of currently available methods is shown in Table 1. The main differences between photogrammetry and 3D laser scanning are shown in Table 2. Because of more accurate and robust than visual SLAM, the lidar-scan-data based mapping has been using popularly in the industry. In this study, a novel comparison between two approaches, photogrammetry and laser scanning, is focused on producing HD maps, which would be tested at Phenikaa University.

Table 1. Methods for 3D point cloud mapping generation.

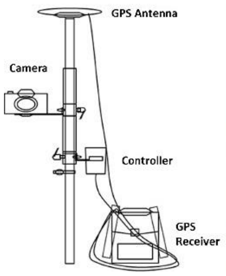
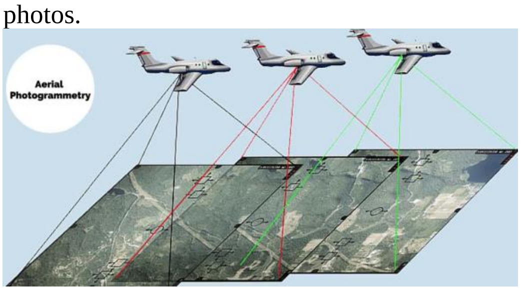
	Method	Principal	Advantage	Weakness
1	Infrared scanner	Thermal analysis	- Cheap - Suitable for small area	- Not high quality - Relatively short range
2	Photogrammetry	Image analysis	- Be able to control cost and quality - Large area coverable	- Require high resources for post-processing - Quality depends on camera and sampling technique - No real-time view
3	Laser scanning (LIDAR)	Lightwave analysis	- High quality - Real-time	- Require high resources for post-processing - Expensive equipment - Relatively short range
4	Radar	Radio wave analysis	- Not affected by surrounding environment - Suitable for internal structure check	- No color
5	Sonar	Sound wave analysis	- Suitable for underwater structure check	- Not suitable for street mapping

Table 2. Comparison between photogrammetry approach and 3D laser scanning.

Method	Photogrammetry	3D laser scanning
Principal	Image analysis	Lightwave analysis and 3D point matching
Output data	3D colored point-cloud	3D point-cloud with intensity
Advantage	- Coverable large area - Cost and quality controllable	- High quality - Real-time processing
Tools	Aerial photogrammetry, Terrestrial photogrammetry	Lidar-based mapping systems (pack back/ rover/ vehicle…)
Application	Survey, construction, mineral, 2D and 3D street-view map, HD map for self-driving car…	

Photogrammetry is the science of making measurements from photographs [3]. The input of the photogrammetry consists of photographs (with GPS coordination integrated), and the output is typically a map, a drawing, a measurement, or a 3D model of some real-world object or scene. There are two approaches to photogrammetry: terrestrial photogrammetry based on imaging of ground systems, and aerial photogrammetry with an aircraft (manned or unmanned controlling). The difference between the two methods is shown in Table 3.

Table 3. Terrestrial and aerial photogrammetry.

	Terrestrial photogrammetry	**Aerial photogrammetry**
Method	The camera is located on the ground, and hand held, tripod or pole mounted.  	The camera is normally vertically mounted towards the ground in an aircraft (manned or unmanned vehicle) to take multiple overlapping photos. 
Main component	- Camera (one or a set) with mounting system - GPS receiver with antenna (integrated or external antenna) - Control unit - Base chassis (optional)	- Camera (one or a set – normally up to 5 for oblique photography) with mounting system - GPS receiver with antenna (integrated or external antenna) - Control unit setup on a plane/an UAV with autopilot and camera trigger mechanism.
Output	Normally non-topographic like drawings, 3D models, measurements, or point clouds only.	3D models or topographic maps depends on purpose and photo technique
Advantage	- Easier and safer to deploy measurement system, not require special operating skills. - Be able to carry out a better camera, usually provide better photos. - Normally not require special permits for mapping.	- Can make large maps efficiently. - Better GPS signals. - Do not capture environment noise (sky, far-field objects…) in photos.
Weakness	- GPS signals are affected by surrounding environment. - More noise in photos (sky, far-field objects…)	- Require special equipment, operation skills and work permit for flying UAV. - Camera quality is limited by UAV takeoff weight.

On the other hand, laser scanning (LIDAR) uses controlled laser beams together with a laser range finder, which is based on light wave analysis. Measuring distance in 360 degrees or in some specific field of view, the sensor can quickly capture the surface shape of objects or buildings. The construction of a full 3D point cloud map needs a matching procedure between multiple captures while moving the laser scanner. The sensor also can be mounted on the ground vehicles such as an automobile or motorbike for terrestrial mapping of streets and roads, or be carried on an UAV in the case of large surveying area. The point cloud data would be processed simultaneously by an embedded computer connected to the sensor during the scanning or processed later on a high-performance computer for point cloud matching and 3D map generation with point intensity.

In the literature, there are two basic methods for point cloud matching during scanning to create 3D maps. The first approach is the iterative closest point (ICP) method [4]. This is a well-known, robust, reliable and simple method but requires powerful computation and implementation time in the case of real-time applications, and it would be sensitive with rotation movement during data collection process. The second approach, Normal Distributions Transform (NDT) [5 - 8] transforms reference point cloud into fixed 2D cells and converted to a set of Gaussian probability distribution before matching the scan data to the set of normal distributions. The matching time of the NDT approach is faster than ICP since it does not require point-to-point registration. This algorithm is good for path planning or change and loop detection, however it is sensitive to initial guess and uncertainty may be caused by moving objects.

2. MATERIALS AND METHODS

2.1. Overview of the comparison method

For accuracy and comparable purposes, 05 ground checking points (GCPs) are used in this study for both approaches (Figure 1). The list of checking points is shown in Table 4. The coordination of the points was measured with Real-Time Kinetic (RTK) accuracy (10 cm accuracy level). GCP size for photogrammetry will follow the requirements of Pix4D software, which is 30 × 30 cm black and white squared targets. The GCPs in this case are used for increasing the accuracy level of photo processing and for comparison purposes. GCPs for laser scanners are placed in the same location as GCPs of photogrammetry. However, GCPs for laser scanner were black-painted cylinder objects with dimension of 30 cm height and 10 cm diameter. As a result, the GCPs would appear as a 10 cm radius dark area in the resulted point cloud, as shown in Figure 2. In this case, the GCPs were used only for quality checking and comparing purposes.

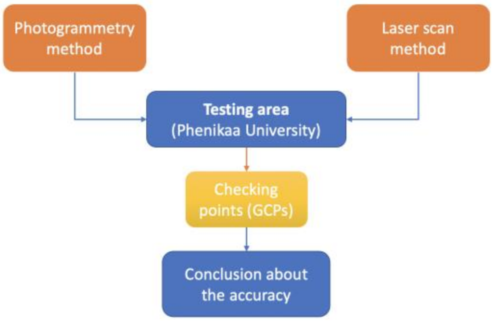


Figure 1. Comparision method overview.

Table 4. Ground Control Points.

Point	Latitude	Longitude	Altitude
1	20.96155475	105.7465387	-20.91229316
2	20.96129979	105.7460934	-20.82127908
3	20.96083384	105.7453303	-20.85566319
4	20.9603937	105.7456928	-20.90419309
5	20.96098268	105.746138	-20.81554716

Two methods for building a map will be applied for creating an HD map, and then, using GCPs point to check the accuracy.

2.2. Testing area

In this study, the survey area was a 0.013 km2 triangle area of the Phenikaa University main campus, located in Viet Nam. The 2D map of the campus is shown in Figure 2. The testing area covers asphalt roads with sidewalk, office buildings and plants, which perfectly reproduces a common transportation infrastructure in Viet Nam.

Figure 2. Testing area.

2.3. Creating HD map by photogrammetry

For hardware, an aerial photogrammetry approach was applied using a DJI Mavic 2 Pro quadcopter. The drone has a 1-inch CMOS F2.8-F11 20MP camera sensor with a 3-axis gimbal to maintain the capturing angle of each photo. The UAV can operate for 30 minutes in the air and cover an area of 1 km^2 with a single take-off. Since the GNSS sensor of the Mavic 2 Pro is a typical M8 GNSS, which only has the accuracy of up to 2.5 m, therefore Ground Control Points (GCPs) are used to increase the accuracy of the 3D point cloud map. For this study, more than 600 photos were taken at altitude of 60 m with a capturing angle of 80 deg.to capture the testing area with good 3D visualization and an average ground sampling distance down to 1.45 cm/pixel.

For creating a map through the pictures, we applied the same technique as Nang et al. [9] by converting the image with GPS information to the point cloud, and then connecting all of point cloud in different images together using an interactive closet point algorithm [10]. By comparing the point cloud, two continuous pictures will be connected as one, and it continues until the end by using a well-known application such as Pix4D.

2.4. Creating HD map by laser scanning

In this study, a laser scanning system, developed by PRATI team for autonomous vehicle testing purposes, is used, as shown in Figure 3 [11]. The system was created by combining the Velodyne VLP-16 (16 lidar lines; 100 m range, proven 905 nm tech) with an IMU whose primary purpose is to reduce noise from movement. A camera is also included in this system with the main purpose of reviewing information after collecting data.

In this study, we applied the same technique as Takeuchi [7] with the following equation:

$$\boldsymbol{p_k} = \frac{1}{M_k}\sum_{i=1}^{M_k} \boldsymbol{x_{ki}} \quad (1)$$

$$\Sigma_k = \frac{1}{M_k}\sum_{i=1}^{M_k}(\boldsymbol{x_{ki}} - \boldsymbol{p_k})\,(\boldsymbol{x_{ki}} - \boldsymbol{p_k})^T \quad (2)$$

where $\boldsymbol{x_i} = (\boldsymbol{x_i}, \boldsymbol{y_i}, \boldsymbol{z_i})^T$ with i = 1:M;

Denoting R as the rotation matrix and $\boldsymbol{t'}$ as the translation vector, the $\boldsymbol{x'_i}$ can be calculated by:

$$\boldsymbol{x'_i} = \boldsymbol{R}\boldsymbol{x_i} + \boldsymbol{t'} \quad (3)$$

The pose translation and rotation parameters to estimated are

$$\boldsymbol{t} = (\boldsymbol{t_x}, \boldsymbol{t_y}, \boldsymbol{t_z}, \boldsymbol{t_{roll}}, \boldsymbol{t_{pitch}}, \boldsymbol{t_{yaw}})$$

$$\boldsymbol{E}(\boldsymbol{X}, \boldsymbol{t}) = \sum_i^N \exp\frac{-(x'_i-p_i)^T\,\Sigma_i^{-1}(x'_i-p_i)}{2} \quad (4)$$

E(X,t) represents the matching or the well-aligned.

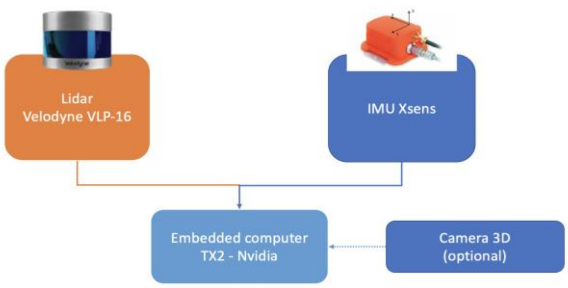


Figure 3. PRATI mapping systems.

3. RESULTS AND DISCUSSION

3.1. HD map

HD map general specifications produced by laser scanning approach and photogrammetry approach are shown in Table 5. As seen in Figure. 4 (left side), the point cloud map by laser scanning approach shows better detail in low levels of the road such as trees and cars, while that by photogrammetry (Figure 4, right side) has better coverage of buildings and other objects at all angles. However, it should lead to unnecessary data capturing, which may not be suitable for use for AV purposes. In fact, both the number of points and the storage size of the 3D point cloud in the photogrammetry case are twice that of the laser scanning case for the same survey area (Table 5).

Table 5. HD map information.

	Laser scanning	Photogrammetry
Number of points	25.087.783	47.145.780
Size (MB)	784	1.500

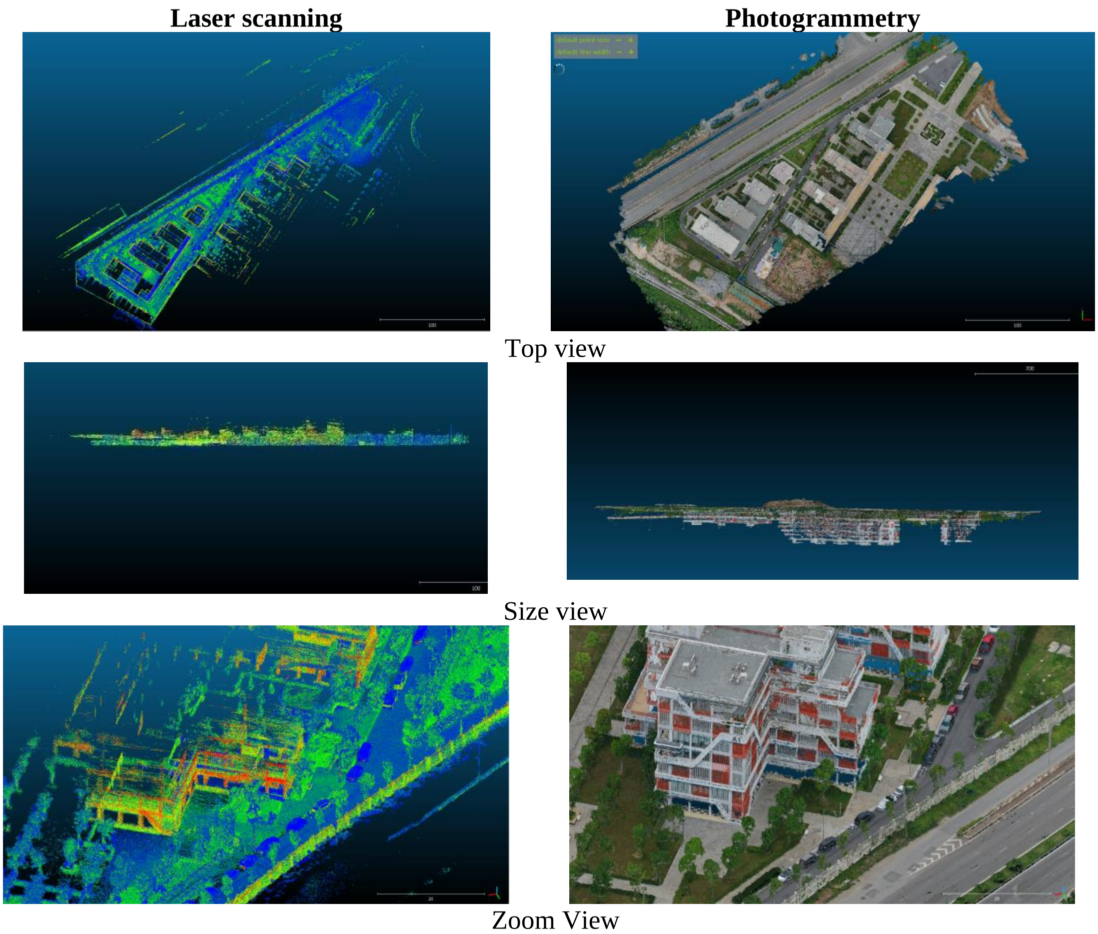


Figure 4. Point cloud by a laser scanner (left) and by photogrammetry (right).

3.2. The matching between two methods

The matching between the two maps is graphically shown in Figure 5. Furthermore, the data matching measurement between two 3D mapping methods is shown in Table 6 by comparing the distance between the same GCPs in both 3D point cloud maps. The results show a good agreement between the two maps, since the average errors of all distances in these maps are lower than 10 cm when comparing with RTK-measured geography data. Moreover, (4/5) 80 % of distance have an error lower than 10 cm - RTK accuracy, which confirmed a good accuracy level of both methods.

Figure 5. Matching demonstration between point cloud map of laser scanning and photogrammetry.

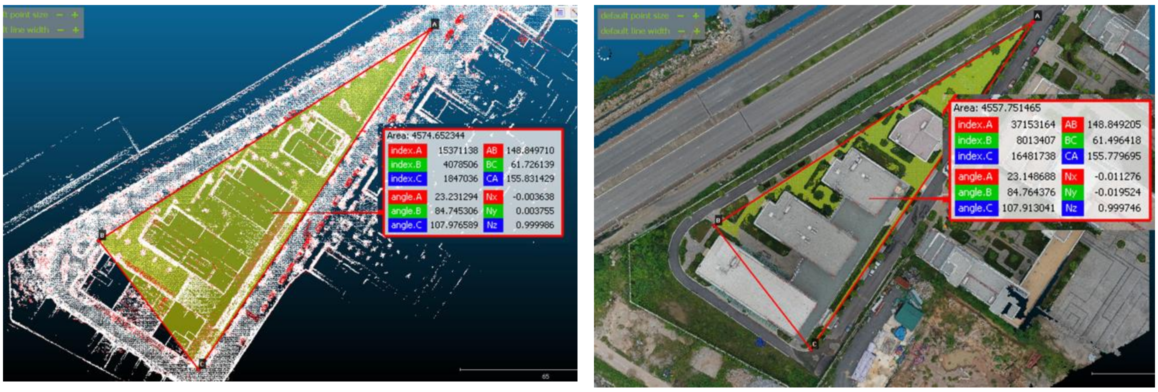
Table 6. Distance comparison between geography data and 3D point cloud maps.

Distance	Geo distance (m)	3D scanning (m)	error (cm)	error (%)	Photo-grammetry (m)	error (cm)	error (%)
point 1 to point 2	54.24	54.22	2.43	0.04 %	54.23	0.91	0.02 %
point 2 to point 3	94.67	94.69	1.77	0.02 %	94.64	3.49	0.04 %
point 3 to point 4	61.74	61.72	1.75	0.03 %	61.71	2.58	0.04 %
point 4 to point 5	80.16	80.06	9.81	0.12 %	80.07	8.59	0.11 %
point 5 to point 1	76.01	75.83	18.42	0.24 %	75.75	26.30	0.35 %
		Average error	6.84		Average error	8.37	
		SD error	7.31		SD error	10.42	

Additionally, distortion of two point-cloud maps was considered by measuring a triangle formed by 03 GCPs at three corners of the testing area, as shown in Figure 6. The data also exhibit a similar shape between the two maps since the average angle errors in both cases are lower than 0.2 deg (Table 7).

Table 7. Distortion comparison between geography data and 3D point cloud maps

Angle	Geo angle (deg.)	3D scanning (deg.)	error (deg.)	error (%)	Photo-grammetry (deg.)	error (deg.)	error (%)
A (point 1)	23.203	23.231294	0.03	0.12%	23.148688	0.05	0.23%
B (point 3)	84.958	84.745306	0.21	0.25%	84.764376	0.19	0.23%
C (point 4)	108.161	107.976589	0.18	0.17%	107.913041	0.25	0.23%
		Average error	0.14		Average error	0.17	
		SD error	0.11		SD error	0.12	



a. Laser scanning b. Photogrammetry

Figure 6. GCPs at laser scanning and photogrammetry map.

3.3. Discussion

The completed HD map database is the essential part to realize autonomous vehicles in Viet Nam. Therefore, the development of a low-cost 3D mapping device would be the first step to start this ambition. Firstly, the real-time decision-making capability of an autonomous vehicle in driving and navigation is more and more dependent on the quality of HD maps. For example, any driving cases such as stopping at the appropriate location, where to locate for a traffic signal at the crossroads, or to avoid passages in non-standard crossing, become exceedingly difficult for AV to make without having a proper HD map. So, as a part of the decision-making process, mapping becomes a key factor of helping the AV make the correct decisions at the right time. Secondly, personal portable mapping devices such as laser scanning backpacks are especially suitable for Vietnamese traffic condition, where motorbike traffic is the majority. An engineer wearing a mobile mapping backpack on a motorbike can reach many difficult locations such as city-center streets in Viet Nam. Fusing with UAV for large scale HD maps of highway and mobile mapping system for outer city roads, a complete solution for 3D and HD map making tools should become essential to realize Viet Nam HD maps database.

In the world, there are several algorithms to build high-resolution 3D maps from lidar information such as using normal distribution transform (NDT) [6 - 8], Graph SLAM [12], matching point to point [13], iterated closest point [14 - 15]. Each method has its own advantages and disadvantages. The technique from Takeuchi [7] which was used by Tier IV Company (Japan) is one of the successful algorithms to localize the vehicle. In this paper, we once again confirm that the method using NDT proposed by Takeuchi works well in a small area in terms of the required accuracy. For big areas, the photogrammetry method helps to correct the map obtained by the NDT one. Therefore, a combination of the two methods is a necessary and suitable solution which can help to improve the vehicle localization for more accuracy.

Moreover, the research also confirmed that our mapping is suitable for autonomous purposes, which will open for various future directions in research related to improving map accuracy, localization, and path planning for autonomous vehicles. On the other hand, the research also creates a possibility of developing other variations of the device such as a laser scanning mobile (mounting on an automobile) or an aerial laser scanning device (mounting on UAV), which would increase the efficiency of 3D mapping performance.

4. CONCLUSIONS

Comparing the results of two methods, we can conclude that the 3D laser scanning method could be used for building 3D HD maps for autonomous vehicles with low-cost and accepted accuracy (lower 10 cm - RTK accuracy).

Furthermore, based on the advantages of each method, for creating a 3D map for the whole city, a combination between the two methods is necessary, where a detailed map could be created by Lidar and a larger scale by photogrammetry.

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Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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