TRAFFIC MONITORING FROM AIRBORNE LIDAR – FEASIBILITY, SIMULATION AND ANALYSIS

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ABSTRACT:

Automatic acquisition and analysis of traffic-related data has already a long tradition in the remote sensing community. Similarly airborne laser scanning (ALS) has emerged as an efficient means to acquire the detailed 3D large-scale DSMs. The aim of this work is to initialize research work on using ALS to extract the traffic-flow information focusing on urban areas. The laser data acquisition configuration has firstly to be analyzed in order to obtain the optimal performance with respect to the reconstruction of traffic-related objects. Mutual relationships between various ALS parameters and vehicle modeling in the laser points are to be elaborated. Like other common tasks in object recognition, vehicle models for detection and motion indication from the laser data are presented; moreover, an ALS simulator is implemented to clarify and validate motion artifact in laser data. Finally, a concept for recognizing vehicles are proposed based on a vehicle and context model, which establishes a direct working flow simulating the human inference routine.

1. INTRODUCTION

Automatic traffic monitoring has evolved to an important and active research issue in the remote sensing community during the past years, as indicated by the special issue of ISPRS Journal in 2006 - "Airborne and spaceborne traffic monitoring" (Hinz et al., 2006). Transportation represents a major segment of the economic activities of modern societies and has been keeping increase worldwide which leads to adverse impact on our environment and society, so that the increase of transport safety and efficiency, as well as the reduction of air and noise pollution are the main task to solve in the future.

On the one hand, today's road monitoring systems are mainly equipped by a series of sensors like induction loops, overhead radar sensors and stationery video cameras, etc. They all deliver accurate, reliable, timely, yet merely point-wise measurement. On the other hand spaceborne and airborne sensors can complement the ground-based collection and give us synoptic views of complex traffic situations. With the recent advances in sensor technology, a number of approaches for automatically detecting vehicles, tracking vehicles and estimating velocity have recently been developed and intensively analyzed, using different air-and spaceborne remote sensing platforms, e.g. Synthetic aperture radar (SAR), infrared(IR) cameras, frame and linear pushbroom optical cameras. However, so far there have been few works conducted in relation to traffic analysis from laser scanners.

The most relevant and up-to-date research to our work is, according to our knowledge, from Toth & Grejner-Brzezinska (2006), Grejner-Brzezinska et al., (2004) and Toth et al., (2003). In this work an airborne laser scanner coupled with digital frame imaging sensor was adopted to analyze transportation corridors and acquire traffic flow information automatically. They have tried to extract traffic-related static and dynamical data as part of the regular topographic mapping. Vehicle velocity can be estimated either by analyzing motion artefacts in the laser data or by vehicle tracking in image sequences with reasonable acquisition rate. The experiences gained so far by their test flying-campaigns showed that the two sensors have different strengths and weakness for the various data processing tasks and, in most cases, they complement each other. It can be declared that the combination of airborne laser and imaging sensors can provide valuable traffic flow data that can effectively support traffic monitoring and management. But the extensive testing of this system is limited to highway, freeway and other heavily travelled roads where occlusions cast by buildings, vegetations and some other anomaly objects (e.g. guild rails) are rare in the image and laser data.

Another important category of research field related to our scope is 3D object recognition from laser radar data, which is primarily dedicated to the military Automatic Target Recognition (ATR) application (Grönwall et al., 2007; Steinvall et al., 2004; Grönwall, 2006; Ahlberg et al., 2003). The scene can be scanned from different platforms and perspectives, such as terrestrial or airborne platforms. The biggest difference distinguishing the use of laser sensor for urban traffic analysis from for the military application lies in data coverage and the application objective. The military applications feature small field of view (FOV) and very high-resolution (very high density of laser points) of laser data recording. The data acquisition process is target-orientated and limited to a relative small coverage, the interest region or object is scanned with very high resolution and concentrated energy. Most of algorithms developed within this scope aim at recognition of the object type (e.g. classification of tank) and pose estimation (e.g. orientation of a tank); some even tried to detect fine sub-structures of object (e.g. barrel and turret of a tank). Among these algorithms, model-based shape matching or fitting strategies have been most frequently applied to the laser data in order to find and recognize the corresponding object class and its status (Koksal et al., 1999; Zheng & Der, 2001; Johansson & Moe, 2005).

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Contrarily, for the urban traffic monitoring, in order to ensure the system efficiency and derive the traffic flow information, a much broader area is needed to be covered by laser scanner surveying and multiple instances of vehicle object have to be recognized and located from there simultaneously. It requires more advanced algorithms to separate 3D vehicles laser points from complex clutter surroundings. Under this situation, some operations used for pose estimation or geometric inference are not crucial as semantic decision of whether a vehicle exists or not (vehicle counting).

In this paper we will study the feasibility and characteristics of using ALS data to analyze vehicle activity in urban areas. Since urban areas usually characterize dense road networks, vegetation occlusion and anomalies (e.g. irregular structures like wire, pole or flowerbed), we try to find out the optimal laser data acquisition configuration for traffic monitoring in view of reliability and efficiency, and propose conceptual design of approach for vehicle detection and motion indication. In this work initial research efforts are made to explore the capability of solely using state-of-art commercial airborne laser scanner for the task. The general and boundary conditions of traffic analysis based on ALS are to be examined and outlined. The purposed concepts and algorithms methods will initially be assessed empirically in terms of accuracy and recognition rate. Different impact factors on the results should be studied. Moreover, an improved completeness of vehicle detection can be expected due to penetration of laser ray through tree canopies. The modeling of object under volume scatters is an important issue for the recognition task in the 3D laser data. The goal is to diagnose to what extent vehicles under trees can be hit and sampled by penetrating laser rays, and further be recognized and reconstructed by computer operations, even if human inspection also cannot.

This paper is structured as follows: first, the configurations of laser data recording in view of urban traffic analysis are discussed and the vehicle models for stationary and moving ones are introduced; next, general approaches for detecting vehicle from urban laser data tending to derive traffic flow parameters are proposed and analyzed; and finally, the conclusions are presented.

2. LASER DATA ACQUISITION FOR URBAN TRAFFIC ANALYSIS

Usually, traffic monitoring using LiDAR, as mentioned here, refers to the direct collection of 3D information from airborne platform rather than from ground-based sensor. Deriving the traffic flow parameters statistically demands a certain spatial coverage of data acquisition. Currently, ALS systems show a great variability and flexibility concerning data acquisition strategies; we want to first compare and analyze different scanning configurations and attempt to qualitatively evaluate results on the traffic analysis depending on different factors. Generally, traffic - related information are expected to be extracted as add-ons of regular LiDAR mapping systems, together with topography and city models, so that current laser surveying systems could be adapted to the solution to traffic monitoring at no extra efforts. However, in the long term, one may also think of operational traffic monitoring systems based on ALS.
Current ALS systems work almost solely in the pulse time-of-flight measurement principle for ranging, detecting a representative trigger signal for multiple echoes in real time using analogue detectors (Pfeifer & Briese, 2007). The direct objective of ALS is to reconstruct 3D geometric model of sensed environment as accurate as possible. Various system specifications and relations have been examined in order to clarify the scanning process and related impact factors on the range accuracy (Baltsavias, 1999). However, via taking a deep look into them, some parameters are also considered as being relevant and sensible for the traffic-related analysis using ALS data, which are listed as follows:

1. View angle, namely the angle between the scan plane and the horizontal level
2. Surface sampling capacity ─ Footprint size, which is affected by laser beam divergence and flight height and Point density, namely point spacing which can be decomposed into along-track and across-track components
3. Field of view, namely swath width which is determined by flight height and range of scan angle
4. Scan pattern and relation between flight path and vehicle queue
5. Minimum detectable object/energy

Being different from freeway and other open areas, such as rural areas, urban areas face a more complex situation concerning the traffic analysis from ALS due to dense road networks, numerous buildings and vegetations, anomaly structures. Any adjustment of sensor configurations can easily lead to change of data characteristics, which may be exploited for specific applications.

2.1 View angle. Concerning the view angle of ALS, normally, it amounts to 90 degree, perpendicular to flight line, forming the most common scanning geometry: nadir-view; if not perpendicular, it then refers to forward - or backward looking ALS. In case of oblique view (Hebel & Stilla, 2007), a side of vertical structures such as building façade is recorded whereas another side would cast a big shadow causing loss of information about surrounding objects (Fig.1c, d). The oblique view of ALS can also lead to abnormal incidence angle of laser ray interacting with the illuminated surface, which has been proven to be adverse to laser backscattering mechanism. Most incident laser energy is scattered away in this case, especially for vehicle surfaces which are constituted of mental (Fig.1a, b). Moreover, the travel path of emitted laser ray becomes longer due to inclination. It is crucial for detection of those vehicles beneath the vegetation, because the penetration rate of the laser ray decreases and we can receive even fewer laser pulses backscattered from the vehicle surface. Overall, to avoid the missing laser data and consider material properties related to laser incidence angle, the scan geometry of nadir-view is required.

2.2 Surface sampling capacity. The footprint size and the point density seem to be two most relevant parameters among system configurations. But they are determined by independent factors which can be selected before flight. Nowadays, most commercial systems can achieve the point density of about 1-10 pts/ m^2 with a footprint diameter of up to 50cm increase per 1000m distance. According to experience it seems to get better detection results when the laser point density increases. Normally only the object model, which is represented by laser point samples with certain level of detail, can be found and recognized. Furthermore, laser footprints should not be overlapped with each other in order to ensure that the captured surface information carried by each laser echo are not mixed.

Therefore a laser point cloud of high density usually demands a very small footprint to accomplish the surveying task. As we have mentioned above, the vegetation occlusion is a key factor for vehicle detection in laser data of urban areas, the penetration ability of the laser sensor against vegetation has to be examined by registering multi-return-pulses in one echo signal. Meanwhile, another type of commercial ALS systems, named full-waveform LiDAR, has been developed recently (Jutzi & Stilla, 2006; Wagner et al., 2007). The entire analogue echo waveform, i.e. the time-dependent variation of received signal power, for each emitted laser pulse is digitized and recorded. This new sensor technique was recently employed to analyze and estimate the biological volume of vegetations, whose internal structures are partially penetrated by the laser beam and can be reconstructed. It can be inferred that penetration rate of single laser pulse is proportional to the footprint size. Thus in case of vehicle detection, a certain diameter of laser footprint is necessary to enable the emitted laser pulse to penetrate the vegetation and hit the potential interest objects beneath it. Considering other demands mentioned above, a compromise between footprint size and point density should be made in the mission plan to achieve the optimal configuration of ALS data acquisition for traffic analysis. Another two extra products derived by waveform decomposition - pulse width and intensity, which describe physical reflection properties of the illuminated surface other than geometric information, could also provide us useful clues to the existence of vehicles.

2.3 Field of view. The FOV of laser scanning, namely swath width, is the extent of data coverage perpendicular to the fight path. It depends on the flight height and scan angle which refer to the application – specific parameters and can be selected in view of project objectives to optimize the system performance. For traffic monitoring applications we assume that the FOV can be chosen without special restriction.

2.4 Scan pattern. Scan pattern of laser data acquisition is generated by deflecting the laser beam using an oscillating or a multi-faceted rotating mirror. Parallel line and z-shaped are two most common scan patterns used by current commercial systems. The point distribution on the ground of z-shaped can be less homogeneous in the along-track direction than parallel line. The orientation of the flight path with respect to the main street of test site plays a role in the quality of acquired laser points used for object recognition, especially for vehicle queues. When a vehicle queue spreads parallel to the flight path, the point distribution of single vehicles is homogeneous among the vehicle queue model; the illuminated surface model depends uniformly on the scan angle. When a vehicle queue spreads perpendicular to the flight path, the point distribution of single vehicles is not homogeneous any longer due to the varied incidence angle; the illuminated surface model of each single vehicle depends on its relative position to the nadir. It seems that both modes of data recording can not prevail over each other towards traffic analysis. It has to be further verified by quantitative analysis.

2.4 Minimum detectable object/energy. The minimum detectable object/energy within the laser footprint does not depend on the object size, but primarily on its reflectivity, when ignoring other factors that influence detectability. This expression has signified that the comprehensive knowledge of analysis and modeling of material properties of vehicle surfaces play a key role in case of traffic objects acquisition and recognition from ALS. The effect of occlusions due to vegetation because of the minimum detectable object/energy is also needed to be studied exactly.

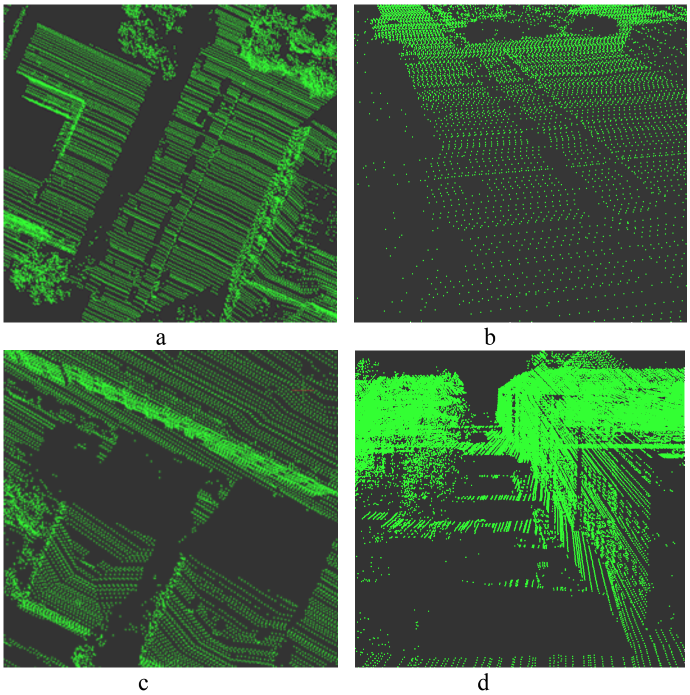

Figure 1. Characteristics of forward-looking laser data. a,b) pulse dispersed by vehicles; c,d) shadow cast by buildings

3. VEHICLE MODEL

Research works on vehicle detection using the imaging sensors, such as optical camera, IR camera or SAR, usually are distinguished based on the underlying type of modeling. There are generally two types of vehicle models – appearance-based implicit model and explicit model in 2D or 3D represented by a filter or wire-frame (Hinz, 2004). Some authors have also modeled queue as global feature for vehicles and made use of it and local vehicle features in a synergetic fashion for vehicle detection from various kinds of remote sensing platforms. For the purpose of better understanding of the sensor mechanism und data characteristics, it is assumed that the vehicle modeling is equally required for vehicle detection in the context of traffic monitoring from ALS systems, although the consistent object modeling in the laser data seems to be very difficult.

3.1 Stationary vehicle

Here the stationary vehicle model refers to the parking vehicles and temporarily motionless ones (mainly cars in urban areas), which comprises an important category of vehicle status for deriving traffic parameters.

The typical object model usually compiles knowledge about geometric, radiometric, and topological characteristics. The geometric property is considered to be the essential part of the vehicle model (Fig.2), which is used to support the recognition task in the laser data. The intensity of received laser pulses is so far hardly utilized due to lack of the calibration and the insight into physical background. The model represents the *standard case*, i.e. the appearance of vehicles is not affected by relations to other objects, e.g. shadow cast by buildings and vegetation occlusion. Moreover, since the detection of vehicles beneath the vegetation is, from our viewpoint, also very important, a new modelling scheme for such vehicles is needed to cope with the appearance variety.

For 3D laser data the implicit model can be regarded as 3D point pattern (set) of vehicles, whereas the explicit model of the vehicle uses the surfaces plus their boundaries or height discontinuity as 3D representation. It seems difficult to strictly distinguish between two models and to make a choice concerning their performance at first glance. Both models focus on the geometric features without radiometric properties, and in terms of our research objectives and test data characteristics, the fundamental and robust features of cars are not always summarized by only using the vehicle models due to random reflection property of the laser pulse against car surfaces. It demands incorporation of more advanced knowledge, such as context relations to roads, intensity or global model, into the detection strategy.

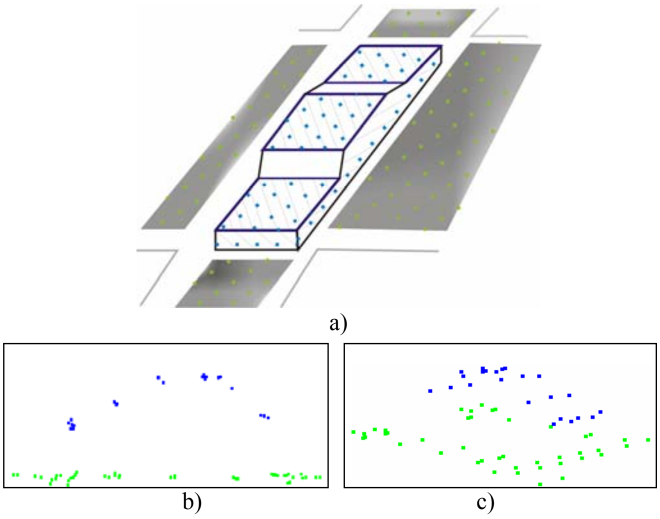

Figure 2. Vehicle model (red: ground, green: vehicle) a) schematic 3D representation. Measured point cloud in b) side view and c) oblique view.

3.2 Moving vehicle

The moving vehicle here refers to the instantaneous moving cars when the scanning pattern sweeps over them. This category comprises the essential part of dynamical information for traffic flow analysis while another part of traffic dynamics caused by temporally motionless vehicles could not be considered.

The fundamental difference between scanning and the frame camera model, with respect to the moving objects, is the presence of motion artifacts in the scanner data (Toth & Grejner-Brzezinska, 2006). The frame imagery preserves the shape of the moving objects because of the relatively short sampling time (camera exposure). But if the relative speed between the sensor and the object is significant, the motion blurring may increasingly occur. Contrarily, the scanning mechanism always produces motion artifacts; moving objects will be deformed and have a different shape in the recorded data, depending on the relative motion between the sensor and the object and sampling frequency. Usually in the laser scanning data, the moving object would be projected as stretched, compressed or skewed compared to the original one and its 2D shape distortion can be summarized in Eq.1 and 2. In order to illustrate this effect we have designed an ALS simulator for moving object indication according to sensor parameters of riegl laser scanner LMS-Q560. Fig. 3 depicts the mutual relationships of moving vehicle under ALS and an example in the simulated laser data.

$$l_s = \frac{l_v \cdot |\mathbf{v}_L|}{|\mathbf{v}_L| - |\mathbf{v}| \cdot \cos(\theta_v)} \tag{1}$$

$$\alpha_v = \arctan\left(\left(w_v \cdot \sin(\theta_v) \Big/ \left(|\mathbf{v}_L| - |\mathbf{v}| \cdot \cos(\theta_v) \right) \right) \cdot |\mathbf{v}| \cdot \frac{1}{w_v} \right) \tag{2}$$

θ_v : angle between the fight path and the vehicle trajectory

$\mathbf{v}$: vehicle velocity

$\mathbf{v}_L$, $v_{l-along}$, $v_{l-along}$: laser scanner velocity and its across- and along-track component

l_s : sensed vehicle length; l_v : true vehicle length

w_v : true vehicle width

α_v : skewing angle of vehicle form, $90^\circ \pm \alpha_v$ = angle of parallelogram deformed vehicle shape

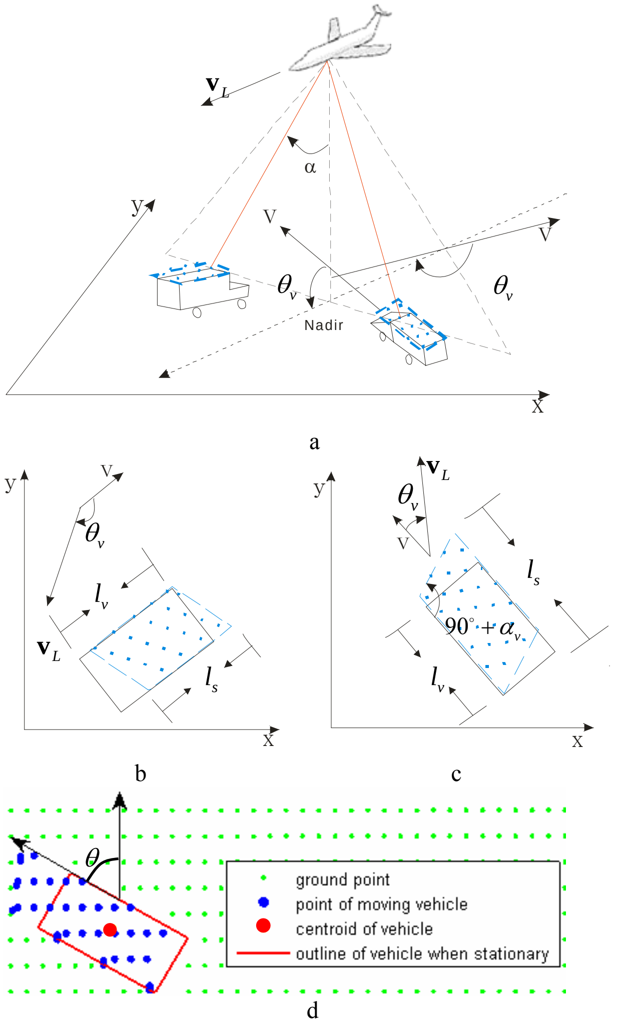

Figure 3. Moving vehicle in the ALS data. a) schematic description of mutual relations, b,c) 2D top-view, d) simulated laser data

Generally, a vehicle is assumed to be a rectangle surface in the object space. Following conclusions can be obtained from the simulation results: the along-track ($\theta_v = 0^\circ/180^\circ$) motion leads to stretch or shrink of the vehicle length (l_s) in the scanning data, whereas the across-track motion ($\theta_v = 90^\circ/270^\circ$) leads to skewing (α_v) of the vehicle shape. Therefore, for the most cases the vehicle will appear as deformed parallelogram in the scanning data – combination of both motion effects. In principle the shape deformation of the vehicle can be used to quantitatively derive the motion status, but a prerequisite must be fulfilled that the true vehicle length is known and its accuracy and sensitivity depend strongly on various impact factors, such as point density, horizontal position error, or physical properties of surface. In practice it is firstly not easy to access the performance of this approach; a great amount of test data is required to prove the feasibility and robustness.

4. GENERAL APPROACHES AND ANALYSIS

In the last two decades general approaches of 3D object representation and recognition have been widely investigated in the computer science community (Arman & Aggarwal, 1993; Besl & Jain, 1986). Being different from the classical object recognition, different methods, such as graph-based shape matching/fitting and point pattern matching were developed to directly conduct recognition process in the 3D range data. Formerly, the most developed methods used to deal with the small-scale dataset of reverse engineering. Due to the high level of detail the smoothness, or curvature-based segmentation algorithms are adopted to facilitate the recognition process; ALS data over urban areas characterize the large coverage, very complex scene and low LoD concerning the shape fidelity. Rather than generic, application-specific methods have been widely employed for object extraction, e.g. for building, road and tree. The almost unique standard operation to ALS data is filtering of non-ground points, motivated by topographical mapping applications, to obtain the DEM.

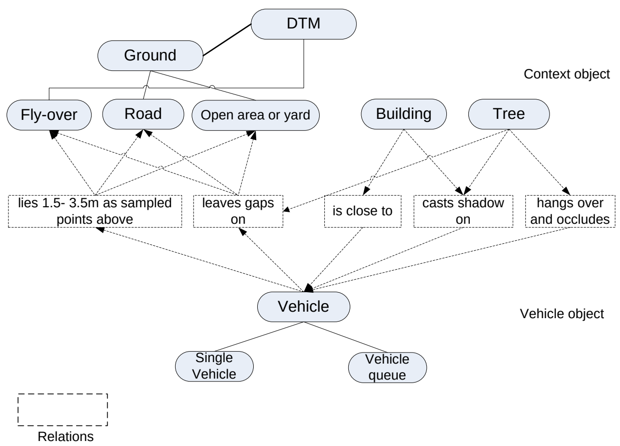

Figure 4. Context-relation model

A progressive processing strategy is proposed here to tackle the problem of traffic monitoring using ALS data: by exploring context relations. It is a direct processing chain being in accordance with human inference. The structure of this algorithm is organized based on the context-relation model (Fig.4) retaining the knowledge of various object relations in the urban area, where the dotted arrow indicates relation direction. It is executed in a progressive and hierarchical way controlled by our strategy for vehicle detection (Fig.5).

The algorithm starts with raw 3D point cloud of urban area. Some basic operations for preprocessing laser data could be run beforehand, like outline remove and hole filling. Then, a rough separation of ground points and non-ground points is to be carried out, using the height histogram thresholding or building

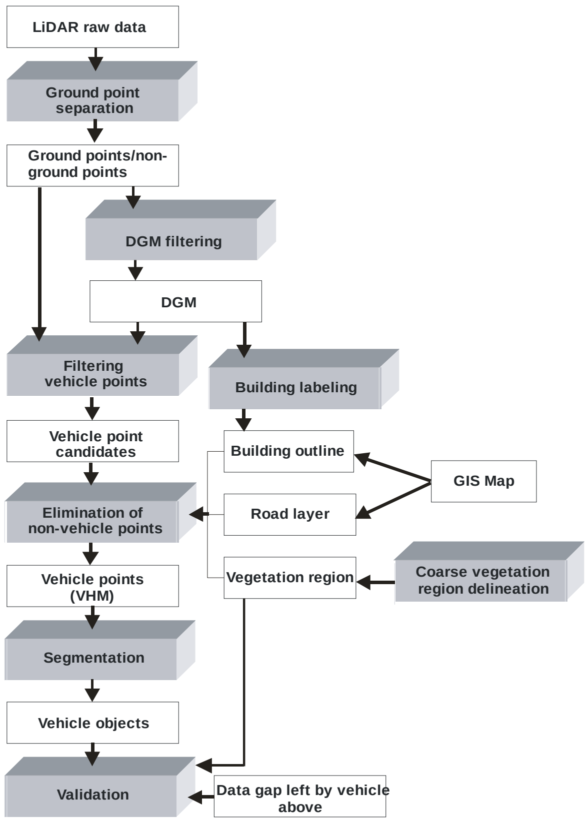

Figure 5. Flow chart of method

labeling algorithm; the objective of this step is to mask out non-ground points or man-made objects like buildings where the vehicle is assumed not to appear. The ground points are viewed to build ground level surface in the urban which consist of not only road but also courtyard. A smooth and continuous surface could be imagined to be generated from the ground points as the reference surface for ground level, being like the terrain surface (DTM) after filtering, which can be represented in the form of point cloud, surface meshing or analytical function. A height interval of 0.5 to 2.0m over this ground surface is set to slice a laser data layer S_1 including all laser points p_k regarded as vehicle hypotheses (Formula.3). Afterwards, the vehicle candidate points are delivered to the process eliminating disturbing objects like tree points, wire pole, parterre or some anomaly points. In order to distinguish between different confused objects, various extern information sources such as GIS/map can be used to mark building and road regions. Vegetation regions can also be first delineated, beneath which potential vehicles are to be searched and validated with special efforts. The remaining laser points are transformed to vehicle height model (VHM) in regular grid – normalized DSM for vehicle, based on which single vehicle extraction and modeling is to be carried out. Laser point gaps (holes) on the ground surface left by impervious vehicles provide us another clue to the presence of vehicle. All laser points belonging to or lying within certain buffer interval ($\pm$0.05m) of ground surface are projected into a 2D plane regularly gridded, where cell size is selected according to the laser point density. Each cell is assigned with a value indicating either whether there are points fall into the grid representing a small neighborhood, so the gap will be retained as small dark area in this image. Some experimental results are illustrated in Fig.6

$$S_1 = \left\{ p_k \in S : z_k - z_{S_r(x_k, y_k)} < \Delta h_{\max} \right\} \qquad (3)$$

The vegetation region is critical for vehicle detection due to variation of the penetration rate of laser pulse energy. Laser point gap model for vehicles assumed above works no longer on its own, and we have to combine both clues to generate and validate vehicle hypotheses. Further measurement provided by ALS systems or a-prior knowledge, e.g. pulse intensity and width, GIS data, could be exploited jointly to reinforce the use of weak object model for vehicle recognition.

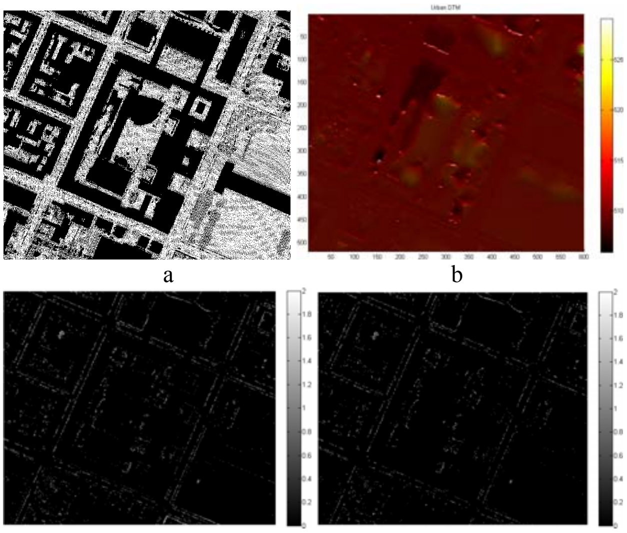

Figure 6. Experimental results: a) ground points-white, b) DTM, c) vehicle candidate points, d) VHM

In further steps we will extend the above concept by clustering the pre-selected laser points and filtering (mode-based) geometric primitives to the clusters. A combination of these bottoms-up and top-down procedures is necessary. On the one hand, due to the specialty of laser data, the exclusive adoption of model-based matching could reduce the algorithmic efficiency by exhausted searching in huge data amount; on the other hand, some spatial features and constraints in the data indicating the vehicle presence could firstly be extracted and used to support subsequent procedures of recognizing vehicles. Moreover, by selecting and devising different feature values from ALS data and other co-registered bands to build the feature space, the statistical classification and machine learning scheme can be utilized to accomplish the recognition task (Barnea et al., 2007).

5. CONCLUSION

Thanks to modern airborne LiDAR techniques, being able to acquiring the detailed 3D large-scale city model, ALS is applied to traffic monitoring in (sub-)urban areas. The problem can be subdivided into two stages — vehicle detection and motion estimation. The configuration of laser data acquisition should be optimized in view of maximal capability of vehicle representation and modeling by discretely sampled 3D points. Vehicle model has been abstracted from the laser data which focused on the geometric information. A new approach has been proposed among which context relations play key role and are firstly used to guild vehicle detection progressively.

Motion artifacts in the LiDAR data in principle allow us to discern moving vehicles, but in practice are suspect; so they need to be analyzed thoroughly and validated by great amount of test data.

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