On Construction and Applications of High-Definition (HD) Maps

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ABSTRACT

High-definition (HD) maps have recently become so important for automated driving applications. These new maps contain a significantly higher density of information than traditional maps to provide high precision instructions for automated driving software agents. However, building and maintaining HD maps up to date have introduced several research challenges. Besides, with the unprecedented level of detailed mapping information and high-precision geo-referenced information extraction, new potential applications have been motivated. This paper gives an overview of the rich literature of HD maps. We classify the major tasks in the literature into eight main sub-areas that span research work on constructing, maintaining, and using HD maps in various applications. We highlight major directions in each sub-area and discuss related challenges. We also highlight potential future directions to use HD maps in a wider variety of applications.

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1 INTRODUCTION

Digital maps, e.g., Google Maps, Bing Maps, and Apple Maps, are being extensively used in various applications by hundreds of millions of users every day. All traditional digital maps are designed and developed for human-to-machine interaction. So, there is an implicit assumption that a human user is consuming the mapping information, such as in using maps in driving or searching for points of interest (POIs). Recently, major applications, such as autonomous driving, have invalidated this fundamental assumption and introduced the need for digital maps that are designed and developed for machine-to-machine interaction. In autonomous driving, maps are used for the perception of distances that are beyond the sensors' ranges. In this case, the consumer is not a cognitive human, but an automated software driver. Other applications that use automated map consumers include motion planning [31] and 3D object detection [42].

The significant need for automated map consumers has introduced the concept of high-definition (HD) maps. HD maps are digital maps that include much more high-resolution details compared to traditional maps. The additional details are designed to enable automated map consumers, e.g., an autonomous driver software, to recognize surrounding information that is usually recognized by a human user, such as lane boundaries, directions, road obstacles, traffic lights, road signs, etc. HD maps use methods of vectorizing most of the structure of all surrounding context beyond the conventional map and making on-map computation of precise displacement and angles possible.

The applications of high-resolution maps are popular in indoor environments. Specifically, in the robotics field, robots use detailed maps in combination with sensors to navigate in smart factories and workshops, smart health facilities, smart homes, etc [36, 37].

However, such indoor environments are usually small and controlled environments. The recent literature of HD maps is mainly motivated by outdoors autonomous navigation for self-driving vehicles [19, 38]. Moving from indoor spaces to outdoor spaces has fundamentally changed major assumptions on the surrounding environment, which posed several research challenges and triggered all the existing rich research in this area.

It is very expensive to build and maintain changes in HD maps depending only on specialized equipment. In fact, we do not have the HD map of the whole world, it is still being developed. So, building and using HD maps is an open area of research and still has several technical challenges to address to partially automate the exploitation of available big spatial data for HD maps. Several works have addressed research challenges on developing and maintaining such highly detailed maps on a large scale.

In this paper, we provide a lengthy glimpse of the literature on building, maintaining, and using HD maps. It is extremely challenging to cover the whole literature of such a rich topic. Nevertheless, due to the importance and richness of the topic, there is a need for research efforts to summarize the current status and discuss research opportunities. Our objective in the paper is to take a middle position, we outline the main sub-areas of research in this literature, pointing out some of the existing challenges and future directions. Yet, we encourage readers to refer to the whole literature for a deep coverage for all existing research in one of these sub-areas.

We classify the literature into two main categories that are outlined in Table 1: (1) *HD maps design and construction* (Section 2). This category is corresponding to the first three rows in Table 1 and highlights techniques that model, design, and build HD map content. It is further categorized into: (1.1) *Modeling and design* (Section 2.1) that highlights data models and design schemes that are used to represent HD mapping data. (1.2) *Map creation* (Section 2.2.1) that highlights major directions to build HD map content. (1.3) *HD map maintenance and update* (Section 2.2.2) that highlights major directions to keep HD maps up to date despite having a significantly higher change rate compared to traditional maps. (2) *HD maps applications* (Section 3). This second category has discussed five sub-areas that are branched from autonomous navigation in both outdoor and indoor environments. The five applications sub-areas are corresponding the last five rows in Table 1, and summarized as follows: (2.1) *Localization* applications that use HD maps to position objects with high accuracy in real time. (2.2) *Pose estimation* that uses HD maps to understand a detailed view of the surrounding environment. (2.3) *Path planning* techniques and subroutines that generate end-to-end high-precision routes to be consumed by machines for routing. (2.4) *Perception* that uses HD maps to improve real-time accuracy of information perceived about the surrounding elements. (2.5) *Automated transfer vehicles (ATVs)* that use HD maps in indoor environments, e.g., smart factories. The rest of this paper discusses each category and its sub-areas.

2 HD MAPS DESIGN AND CONSTRUCTION

HD maps introduce fundamental changes to existing mapping frameworks. So, a significant portion of the current efforts is being made in designing new data models for HD maps and new frameworks to automate collecting high-resolution mapping data from various data sources. This section presents three sub-categories: *HD maps modeling and design* (Section 2.1), *HD map creation* (Section 2.2.1), and *HD map maintenance and update* (Section 2.2.2).

2.1 HD Maps Modeling and Design

Navigation Data Standard (NDS) [26] is a leading data format in the industry of creating high-resolution maps for autonomous navigation. In [16], HiDAM focuses on designing a data model for road networks on HD maps that extends the node-edge structure to model the new rich mapping information. It mainly addresses some limitations in the NDS format. The new mapping information includes the lane system and various types of landmarks. Compared to the traditional node-edge model, each road segment (edge) is represented by a multi-directional lane bundle, where each lane bundle consists of a set of parallel lanes. A road segment is also associated with on-road and off-road landmarks, that represent various 3D objects, such as road signs, traffic lights, buildings, parking lots, etc. HiDAM also discusses the compatibility of the model with existing applications, potential simplifications to the model, and further applications for HD maps beyond self-driving cars.

In [3], designing a Weighted Mode Filter (WMoF) for Full-HD Depth Map using a VLSI architecture is the key contribution. It proposed a WMoF engine to take in the different levels of external memory to construct the Full-HD Depth Map of architecture to include the architecture benefits of each circuit or major leak.

The contributions in [18] is inspired by the robotics field, which used to develop high-detailed mapping models for the surrounding environment to enable robotic navigation. In [18], they proposed the usage of a *semantics map* for robotics tasks. The semantics map is another form of HD map due to its defined property in the paper: "The world W is a physical space defined as tuple W = $\langle$Y, P,$\Sigma\rangle$, where Y is a set of entities, P is a set of poses and Σ is a set of attributes. Each entity y $\in$ Y will be associated with one pose p $\in$ P by a function p : y –> p. Furthermore, each entity y can be associated with a Σ subset of attributes by a function a : y –> 2" [41]. The vectorized elements in the map definition are the same as the vectorized road defined in HD maps. Harsha Vardhan in [39] discusses a globally accepted definition of HD map in what, how, and why terms. The article states if a map contains only vectorized elements and can achieve the precision of less than 1 meter of error in the real life can be considered as HD map basically. However, satisfying the basic needs can not ensure the quality of HD maps since more processing techniques, e.g., the accuracy of localization, are considered in the process of evaluation.

HDMI-Loc [13] uses one 8-bit image as an HD map design. It uses patches to represent the road. Patches also include the global coordinate of the vehicle pose, with the last frame as the center point. Each patch also has a transformation relative to the previous patch. Using this HD map can significantly reduce the storage space and alleviates the cost of updating and transmitting the map.

Lanelet2 [29] is a layered open-source mapping framework that is designed for typical isolated applications such as localization or motion planning as well as highly automated driving. The map is divided into three layers: (1) a physical layer, which contains the usual real observable elements. (2) a relational layer in which the elements of the physical layer are connected to lanes, areas, and

Table 1: Taxonomy of the Presented HD Maps Literature

		2009-2015	2016	2017	2018	2019	2020
Design & Construction	Map Modeling & Design	[18]	[3, 26]	[39]	[29]		[13, 16, 41]
	Map Creation	[4]	[24, 25]	[6, 30]	[17]	[10, 35, 44]	[11, 23, 40]
	Map Maintenance & Update				[15, 37]	[22, 27]	[28, 36]
Applications	Localization		[2]	[45]	[8, 9]	[7, 14]	[33, 34, 41]
	Pose Estimation						[13, 41]
	Path Planning		[32]	[20]	[5, 21]	[14]	[28]
	Perception				[42]		[33]
	ATVs				[12]		[36]

traffic rules. (3) a topological layer, which is implicitly inferred from the contexts and neighborhood relationships of the relational layer.

2.2 HD Maps Construction

This section highlights methods to construct HD maps. HD maps creation and update are among the most, if not the most, challenging tasks in the literature of HD maps. As previously introduced, HD maps provide significant additional content compared to traditional maps to enable machine-to-machine information consumption. Collecting and organizing such new content is very costly on a large scale. Thus, several research efforts are being made, by both academic and industrial researchers, to enable building HD maps worldwide. Several data sources and different computational techniques are being used to automate or semi-automate this process. We highlight methods for *map creation* in Section 2.2.1 and methods for *map maintenance and update* in Section 2.2.2.

2.2.1 Map Creation. Dabeer et al. [6] proposes combining crowdsourcing with cost-effective sensors for building HD maps. They propose an end-to-end HD mapping pipeline in global coordinates in the automotive context using cost-effective sensors. The crowdsourcing aspect is used to exploit the crowd capacity in producing a plethora of mapping information. The sensors are used to triangulate both road signs and road lane markings Triangulation results are continuously enhanced using corrective feedback mechanisms to keep improving the mapping accuracy. Crowdsourcing is also used to add additional layers to existing maps as proposed in [17]. The main contribution of this paper is the generation of new feature layers in the accuracy level of the HD map using the existing HD map and crowd-sourced information without additional costs, human resources, or latency. Decoupling the layers allows enriching map content through separate crowdsourcing applications. In addition, it isolates human inaccuracy problems from one layer to another, so it is possible to improve error-prone layers in later stages if needed.

This idea of using sensors in building high-resolution mapping has been used by Chen et al. [4] to enable large-scale map creation using ground-level LiDAR devices. LiDAR is used to automatically detect geo-referenced navigation attributes. The advantages of using such specialized equipment are: (1) Direct acquisition of 3D coordinates once the objects are detected, which reduces error margins and improves overall accuracy, especially in map-based

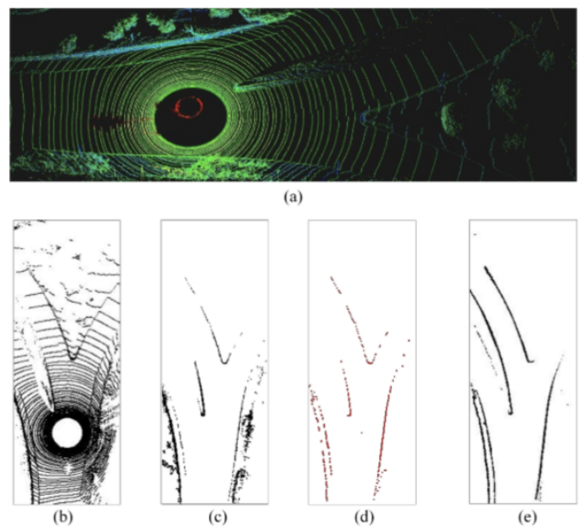

Figure 1: LiDAR-based Road Boundaries [44]

localization applications. (2) Less redundancy for processing compared to video-based object detection, which enables large-scale support. (3) Invariant to lighting conditions and shadows, in contrast to camera-based systems. (4) Robust for irregular shapes (e.g., partially occluded signs, sharp lane curves, etc). (5) Robust for distinguishing objects at different distances, so it accurately distinguishes background and foreground objects.

LiDAR is one of the most popular technologies that are used solely to collect 3D mapping data. In [44], LiDAR is used to recognize road boundaries using a five-step procedure that is depicted in Figure 1. Firstly, the 3D point cloud of one scene is generated. Then, it is converted into a 2D projection. After that, the ground is eliminated from the 2D projection and only the non-ground data is further processed. The road boundaries are extracted from the previous results. Finally, a probabilistic fusion model is applied to the boundary extraction to build final HD map boundaries.

As LiDAR is not a cheap technology, some methods try to make use of existing LiDAR sensors in on-road vehicles to piggyback building high-definition 3D maps on vehicles' operational processing. Ilci and Toth [11] assess the feasibility of this idea using only

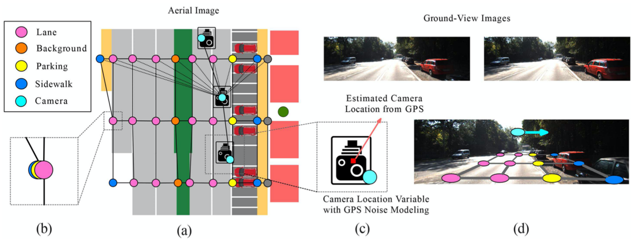

Figure 2: Image-based lane extraction [25]

auto industry-grade mobile LiDAR sensors. It is common in autonomous vehicles to combine HD maps with sensor-based localization techniques to simplify the perception and scene-understanding problem. Since autonomous vehicles cannot detect distant objects or objects blocked by obstacles in real time, using HD maps can help overcome these limitations and offer a detailed representation of the surroundings of the vehicle, and thus, the perception task of vehicle systems is significantly assisted.

Using specialized equipment is not always affordable or needed, so combining cheaper methods for map creation has got considerable attention in the literature. Hirabayashi et al. [10] provides an accurate method to extract road traffic lights from images with the help of a fusion technique between a camera and 3D information. The implementation of the method includes three parts: Autoware implementation, where the author describes how to use Autoware to implement the traffic light recognition module; SSD implementation, where the author realizes color state training and recognition; and finally, the implementation of the inter-frame filter.

Another method that combines cheap data sources to improve the accuracy and scalability of map creation is proposed in [25] to extract high-resolution road information from both aerial images and ground images. The four phases of the proposed technique is depicted in Figure 2. It decodes the aerial image of the road and utilizes ground-level high definition images to cooperatively create an HD map of a gridded view of road conditions. The precision evaluation shows a great improvement in the alignment of road centers and different ground portions, resulting in 6 seconds per km of road inference time and overall 0.57 meters of an error on average compared to 1.67 meters of an error on average using GPS+IMU. In [30], HD maps are directly used on a pilot emulator project to harness the power of precision produced by HD maps. The pilot model is based on the conventional training experience in the previous work, but in the model the use of HD map is crucial in providing a more accurate relationship between the pilot and the actual environment.

Machine-crowd crowdsourcing is also proposed to create HD maps through crowdsourced probe data from connected vehicles [24]. By 2019, ~28.5 million connected vehicles are in operation [40], which generates millions of terabytes of vehicular probe data. This is automatically vehicle-generated data that provides information about surrounding vehicles, road conditions, and traffic situations to road users and road operators. The paper [24] introduces a scalable infrastructure, which supports the ingestion, management, and analysis of huge amounts of probe data to build layered HD maps as proposed in Figure 3. It supports an iterative process to

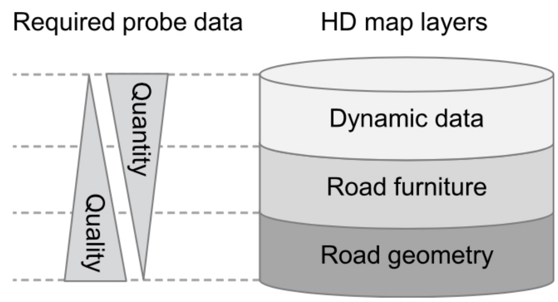

Figure 3: HD Maps Layered Design [24].

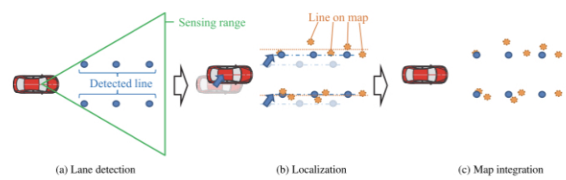

Figure 4: Camera-based Localization and Lane Extraction [23]

develop, assess, and tune methods for generating HD maps from probe data. They developed two approaches to derive HD maps from vehicle probe data. The first approach assumes limited probe data (GPS information only). It has been shown that the quality of the inferred map, in terms of geometric accuracy, is limited. The second approach requires additional sensor data that can be retrieved from series vehicle sensors. Thus, neither extra sensors nor extra onboard data processing capabilities are required.

Camera data is also used to generate HD maps as a cheap and available data source [23]. In this technique, cameras are used to localize one driving car inside the road through a lane detection algorithm. Detected lane information are then integrated with the lines information on HD map as depicted in Figure 4. It aims at applying a map construction method that does not require the high cost of precise and expensive sensors on former creation of HD maps. So, it piggybacks lane extraction overhead on the localization process and adds mapping lines with much lighter overhead compared to dedicated HD map construction methods.

Using smartphones in building HD maps is discussed in [35]. The Kalman filter is used in order to filter the measured data and to provide those state variables that are needed in each time step. The lane detection of HD map from sensors of a smartphone was based on the fusion of deep neural network and the combination of color and gradient approach as depicted in Figure 5.

2.2.2 Map Maintenance and Update. As HD maps include plenty of information about the surrounding space, their content encounters much more changes compared to traditional maps. Thus, updating frequent changes to maintain map accuracy represents a major challenge in constructing effective HD maps without significantly increasing the cost. Some methods that are proposed in the literature to handle map updates are actually used in building maps in the first place before putting the update mode into action. This can

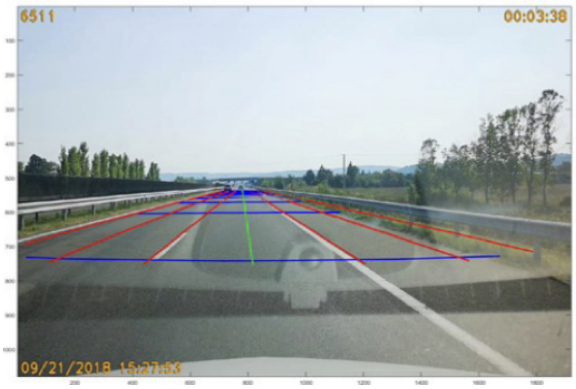

Figure 5: Smartphone-based Lane Markings Detection [35]

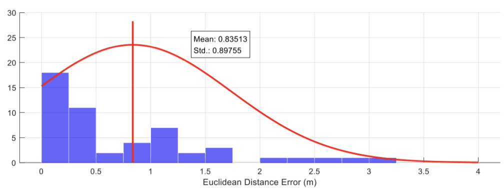

Figure 6: SLAMCU mapping error for the position estimation of new map features [15]

be accomplished by combining the update methods with traditional maps as a preliminary map version, or a lower-cost HD map that did not capture all the necessary details. In all cases, map update methods represent core techniques either to build or to maintain accurate HD maps.

SLAMCU [15] proposes a simultaneous localization and map change update algorithm to detect and update the HD map changes. SLAMCU depends on a dynamic Bayesian network (DBN) to detect changes. The DBN is represented as an inference graph structure with known nodes as input, estimated nodes, and unknown nodes to be estimated. The known nodes are input actions or physical changes that are solicited from a measurement model that solves a localization problem with data association. The DBN employs an inference method with edge constraints to transfer nodes from unknown to estimated status, exploiting the known input nodes. The detected and updated map changes by SLAMCU are reported to the HD map database in order to reflect the changes and share them with other autonomous cars or beneficiary systems. SLAMCU is empirically evaluated on HD map data of traffic signs in real traffic conditions along 20km on a highway in France. The reference position of the new map features for the evaluation obtained by the GraphSLAM based post-processing with real-time Kinematics RTK-GPS. An average position error is 0.8m with a 0.9m standard deviation (as depicted in Figure 6). The overall accuracy is 96.12% for the estimated map changes.

Pannen et al. [27, 28] from the BMW group presents a map change detection system that processes crowdsourced floating cars data (FCD) that are collected from cooperating autonomous vehicles fleet in a machine-crowd crowdsourcing system. They propose

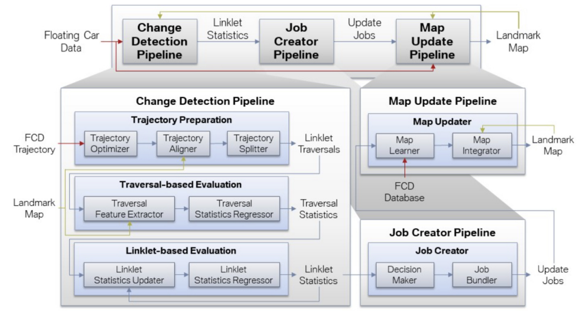

Figure 7: System overview with the three major pipelines: change detection, job creation, and map updating [27, 28].

techniques within this system that run in real time as part of a back-end stream processing pipeline. The proposed technique makes reliable prior information on lane markings and road edges available to automated driving functions. The central idea is estimating the probability of change based on FCD and updating the map when required. Figure 7 depicts the system overview. The system has three major pipelines: change detection, job creation, and map updating. To scale up, they introduced a partitioning approach to tackle smaller areas and aggregate results for larger areas effectively. Each of the three pipelines employs a set of utility and core components, including a novel map learning component that exploits FCD data and real-time trajectory statistics to learn new map updates incrementally. The learner applies two-particle filter setups simultaneously for increased robustness during localization. Based on the results from the localization process, it calculates different metrics and applies a variety of classifiers. By applying boosting to these classifiers, it further improves the classification performance. The techniques are applied on 300 traversals of seven different construction sites and the classifier performance is evaluated both on a single traversal as well as on multi-traversal classification. It is shown that the multi-traversal classification significantly outperforms the single traversal classification with a sensitivity of 98.7% and specificity of 81.2%.

Tas et al. [36, 37] proposed an HD-map update methodology for Autonomous Transfer Vehicles (ATVs) that operates in smart factories. The proposed update methodology is based on visual simultaneous localization and mapping (SLAM) with visual object detection and localization to keep the HD map up to date. The main contribution is the detection of a new or disappearing safety sign or orientation sign in the environment by simultaneously comparing the valid HD map information and virtual HD map information constructed from visual sensors. A grid map that is improved with visual SLAM and object detection and localization framework is used to update the HD map information. The detected objects are laid over the grid map for accurate positioning, then they are batched as map updates. Figure 8 summarizes the procedure that incrementally senses the surroundings with improved object detection, and compares newly sensed objects with existing data.

Liu et al. [22] proposed an incremental technique that improves HD map content through combining historical data with updated sensor measurements as depicted in Figure 9. It depends on a fusion

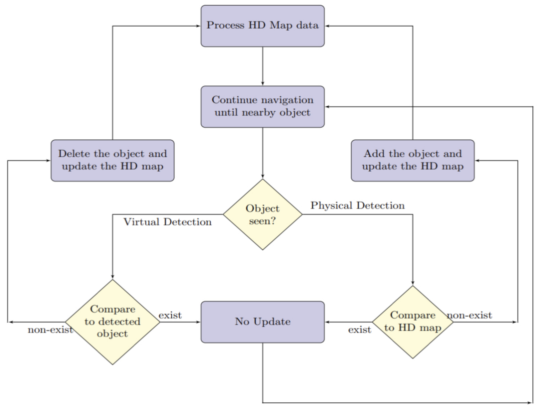

Figure 8: ATV-based HD map update flow chart [36].

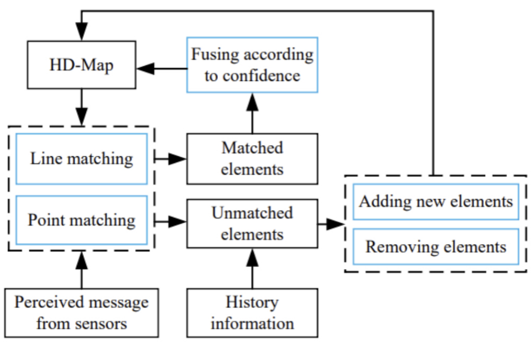

Figure 9: Fusion-based HD map updates [22].

algorithm based on the Kalman filter to match map elements' geometry with perceived sensor data. The fusion algorithm improves the position and semantic confidence of the map element. At the same time, the time decay term is included in the fusion algorithm. When the actual environment changes slightly, the mapping element can be closer to the true value faster. Unmatched elements are returned back in a feedback loop, along with historical information, to be checked for matching in the following cycles. Figure 9 shows an overview of this process.

3 HD MAPS APPLICATIONS

The applications of high-resolution maps are popular in indoor environments, e.g., for robots in smart factories and workshops [36, 37]. However, autonomous navigation for self-driving vehicles [19, 38] in outdoor environments has introduced fundamentally different challenges. The studied indoor environments are usually small and controlled environments. So, major assumptions on the surrounding environment have been challenged, which posed several research challenges and triggered rich research in this area. Despite the potential of several HD map techniques to be used in a wider variety of applications, as discussed in Section 4, the existing literature mainly focuses on outdoor autonomous navigation.

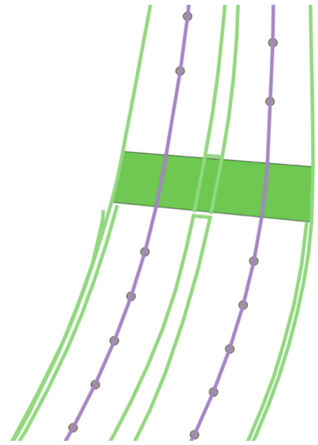

Figure 10: A detailed view of a road segment in HD map [1].

Outdoor autonomous navigation is a challenging application that is divided into several subordinate applications. In this section, we highlight research methods that are proposed for four categories of subordinate applications, namely, *localization*, *pose estimation*, *path planning*, and *perception*, in addition to methods for *automated transfer vehicles (ATVs)*. The rest of this section highlights each of these categories.

(1) Localization. Localization is by far the most popular application that uses HD maps in autonomous driving. Localization is used to position an object, mainly the vehicle itself but could be also a road object such as a sign or an obstacle. Positioned objects are used by the automatic driver software in taking real-time decisions. A road segment in an HD map is detailed into multiple components including line making, centerline, pedestrian crossing, signs, and obstacles, as depicted in Figure 10. Thus, localizing an object within these close components accurately with a centimeter-level error margin is a challenging task that is fundamental to facilitate real-time autonomous driving decision making.

Ghallabi et al. [8] have proposed a map-based localization using a multi-layer LiDAR sensor. The method mainly relies on road lane markings and an HD map to achieve lane-level accuracy. In order to detect lane markings, it is necessary at first to segment road points from the whole point cloud since road markings are located on the road surface. Once road points have been segmented, the intensity of LiDAR data is used to extract marking points. Then, the extracted markings are matched with the map data to localize vehicles. The lane marking detection is implemented in two different steps: road segmentation and Hough transform on an intensity image. Road segmentation is based on ring geometric analysis which measures the discrepancy of real local geometric features with expected features on the road surface. This is particularly useful to remove environment regions where surfaces are not smooth and are discontinuous, e.g., vegetations and gravel. Furthermore, a Hough line transform using an apriori information on the environment is applied to detect lane markings. Finally, a map-matching algorithm has been implemented to validate the detection phase.

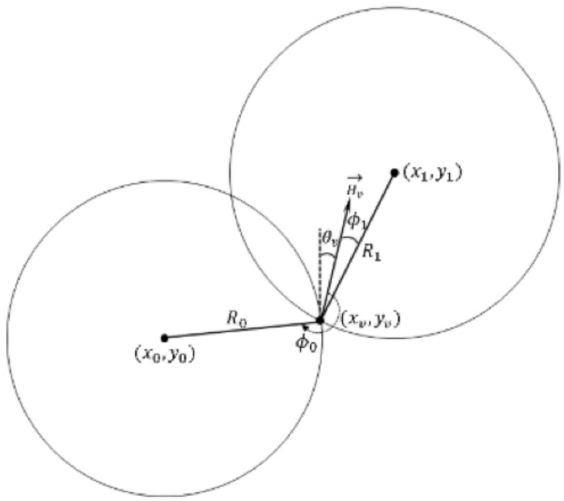

Figure 11: Angular triangulation for landmark-based localization [14]

(a) Linear Road Surface (b) Intersection Road Surface

Figure 12: Lane-based localization using particle filter [2]

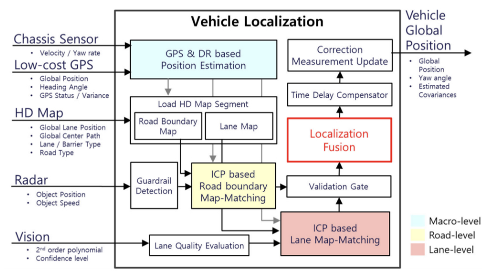

Figure 13: ADAS-based localization [34]

The presented results are promising and sufficient for highway use cases.

Jian [14] uses on-road landmarks in HD maps to facilitate localization. It uses triangulation methods, similar to angular triangulation in Figure 11, to locate vehicle location with the pre-knowledge of locations of signs in an HD map. It proposed one landmark detection method which uses LiDAR scans in terms of size, shape, reflectivity, and height to determine which landmark it is. The landmark has fixed size, shape, reflectivity, and height which gives the determined output. Other work extends using landmarks in localization to using High Reflective Landmarks (HRL) [7]. HRL is also used as new 3D information to be stored in HD maps. In [7], LiDAR data is used for HRL detection to perform a map matching algorithm based on Markov localization. The reflectivity of HRL is highly unique. Its localization approach is based on the implementation of a particle filter which is a non-parametric implementation of a recursive Bayes filter.

Geometry influence of sign detection on localization is discussed in [45]. It aims at designing a high precision and reliable localization system using HD map. Geometric strength is evaluated under different scenarios considering three factors including feature distribution type, feature number, and distance between vehicle and feature. The results are mostly affected by feature number and distance between vehicle and feature. Random distribution, more detected features, and close distance between the host vehicle and the features may all contribute to good quality of vehicle position estimation.

Bauer et al. [2] proposes lane-based localization using the particle filter aided with the road surface to bound the particle, as depicted in Figure 12. Each particle state has to be evaluated against the HD map. After it left one road surface area, the new lane should be found. The road surface at the other side of the targeted accessor is the only candidate in order to speed up the process. Except for the road area, there is also lane surface area. The particle is mainly staying on the lane surface area.

Han et al. [9] proposes a map matching technology for robust vehicle localization. The technique proposes a new line segmentation matching model and a geometric correction method of extracted road marking from an inverse perspective mapping (IPM) for robust map matching. The technique has been tested on real autonomous vehicles and successfully acquired the autonomous driving license of the Republic of Korea.

HD map-based localization is also proposed using advanced driver assistance system (ADAS) environment sensors for application to automated driving vehicles [33, 34]. ADAS uses several hardware sensors (as shown in Figure 13 and Figure 14), including LiDAR, RADAR, vision, and GPS sensors in addition to vehicular sensors that provides information on vehicle speed, acceleration, steering angle, etc. Using low-cost sensors and high-definition maps, the proposed positioning algorithm includes the following parts: environmental feature representation with low-cost sensors, digital map analysis and application, location correction based on map matching, designated verification gates and extended Kalman Filter positioning filtering and fusion. An overview about the proposed localization scheme is depicted in Figure 13. The localization task is used in a higher-level application to control the vehicle motion and facilitate autonomous driving using ADAS systems as depicted in Figure 14.

MLVHM [41] proposes segmentation of the HD map properties as small monoculars for vehicle localization. The proposed technique is a low-cost localization method that integrates camera images and HD maps to localize objects. The technique includes two modules, an image processing module and an HD map module. The image processing module extracts visual and geometric features that are combined with key points features from HD maps

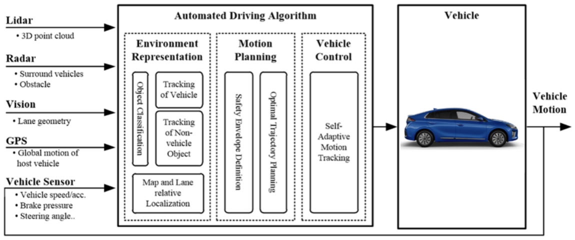

Figure 14: ADAS-based autonomous vehicle motion [33]

Figure 15: 6-DoF global pose estimation [13]

to perform initial pose prediction. The initial pose associates frame motion information with objects to output object locations. Pose estimation techniques are highlighted later in the section.

(2) Pose estimation. Pose estimation is an orthogonal task from localization and aims to automatically understand a wider view of the surrounding scene instead of just localizing objects at a certain point. Although this understanding is helpful for multiple purposes, pose estimation is majorly used in this literature as a helper utility for localization, as in MLVHM [41]. A few research efforts have focused on pose estimation as a separate task. In fact, pose estimation can output much wider views for the surroundings than the view needed for high-precision localization, which is usually a few meters around the object. For example, HDMI-Loc [13] proposes a full six degree of freedom (6-DoF) global pose estimation exploiting semantic road information obtained from HD maps and query stereo images. First, using the particle filter, it estimates the 4-DOF partial pose (i.e., 3-DOF translation and heading) of the vehicle through image matching of the patch. After that, roll and pitch are additionally calculated which gives 6-DOF pose with regard to the HD map. An example of multi-block pose estimation is depicted in Figure 15.

(3) Path planning. Path planning applications go beyond the localization and pose understanding and provides full path generation based on HD maps. They provide detailed routing directions to machines (i.e., automated drivers) similar to traditional routing directions that are provided to humans in existing routing applications, e.g., Google Maps and Apple Maps. Li et al. [21] propose a low-cost vector map-based navigation framework for automatons vehicles. By recording the vector map offline, the framework initializes an optimal global route by giving any starting and ending position on the map. Conventional HD maps have stringent requirements on storage. For instance, Pannen et al. store 20,000 miles of roads in 200GB of space through data compression technology [28], which corresponds to 10MB per mile. The proposed vector map in this work uses high-precision DGPS to extract latitude and longitude information, remove large-scale laser point cloud data, and achieve accurate navigation by marking essential information such as lanes and links, speed limits, traffic signs in the map. The total mileage of 26 lanes, 3 miles distances only occupies about 300KB of data storage (100KB per mile), which dramatically reduces the storage size by two orders of magnitudes while providing enough information for navigation.

Jian et al. [14] use semantic road information for path planning. The algorithm is divided into two parts. The first part is the path set generation, and the second part is the path selection. The path set generation reflects the vehicle kinematics parameters to the lane coordinate. Then, it performs path set generation with optimization according to the reflection results and lane information provided by the HD map. The path selection is based on their proposed inertia-like path selection algorithm to perform a stable path for obstacle avoidance.

Chu et al. [5] develop a Predictive Cruise Control (PCC) based on HD map information. The contributions of this study are summarized as follows. First, the problem of the PCC is formulated as a nonlinear MPC, and a fast solver is proposed. Second, a novel shift-map is constructed to define different working regions from the perspective of the application. Third, HD map information is integrated into the PCC system in the form of a dynamic map. Fourth, the total fuel consumption obtained with the proposed PCC system and factory-installed ACC system over a 370 KM route is compared. The proposed PCC system can obtain an average fuel savings rate of as high as 8.73%.

At a micro-level, HD path planning provides high-resolution details to provide, for example, lane-level directions and not only a bird's-eye or road segment view of the route. To provide such details, path planning techniques must combine both road segment-level routing with lane-level techniques, including lane-level localization and map matching. One of the most promising strategies for providing this is *simultaneous localization and mapping* (SLAM) algorithms that are used in [32]. The reconciliation of real-time gathered data from onboard sensors with cloud-based HD map data provides a virtual image of the car's vicinity to landmarks. This allows an exact determination of location and relation to other road users. Another method for a lane-level map matching using a particle filter is used in [20]. The main steps to implement efficiently the map matching method includes loading the whole map information once when starting, as its size is relatively limited. The initial filter sample set is populated and matched to the road network to finalize the initialization process. The filter then runs the real-time execution loop.

(4) Perception. A typical classification of tasks in the autonomous driving pipeline is: perception, prediction, planning, and control. Perception is responsible for understanding the surroundings, while the rest of the tasks' pipeline use this understanding to produce driving decisions in real time. In addition to using HD maps heavily in prediction, e.g., localization, and planning, e.g., path generation, some researchers investigate using it in improving perception abilities as well. For example, HDNET [42] uses HD maps for improving 3D object detection on roads. HDNET considers the geometric and semantic priors in the HD map and merges them into the bird's-eye view LiDAR representation. When an HD map is not available, it uses a map prediction module, which can estimate two map priors online through one LiDAR scan. Experiments show that the proposed map sensing detector consistently performs better than competitor 3D object detectors. In general, HD maps have added a significant value for perception tasks as presented in [33, 42].

(5) Automated transfer vehicles (ATVs). ATVs is a modern application for HD maps in indoor spaces, e.g., smart factories. Accurate and robust self-localization is an essential task for ATVs. Tas et al. [36] have proposed an ATV-based method for map updates in indoor factory environments, that is highlighted in Section 2.2.2. This method is based on visual SLAM with visual object detection and positioning functions to keep the HD map up to date. The main contribution is to detect new or disappearing safety signs or direction signs in the environment by using relatively effective HD map information and virtual HD map information constructed from visual sensors. In erroneous scenarios, the accuracy and robustness of ATVs are prerequisites for taking real-time corrective decisions [12], which highly depends on the accuracy of indoor HD maps. As highlighted at the very beginning of the section, HD maps in indoor environments have been studied extensively in the robotics literature. These environments are also fundamentally different compared to outdoor navigation environments. So, it is beyond the scope of this paper to discuss in detail HD maps in indoor settings.

4 CONCLUSION AND DISCUSSION

This paper has presented a bird's eye view on the modern literature of high-definition (HD) maps. Modern HD maps are motivated by autonomous driving applications that have introduced machine-based map consumers in outdoor driving environments. This setting is fundamentally different from the indoor environments, for which HD maps have been investigated for robotics applications, e.g., smart factories and smart health facilities. These fundamental differences have triggered a plethora of research activities on the construction and usage of HD maps in outdoor environments. As an excessively rich literature, the paper has provided only a lengthy glimpse on the main categories of existing research work. This gives the interested readers valuable pointers that encourage them to deeply cover one or more of the presented sub-areas.

The paper has categorized the literature into two main categories: (1) *HD maps design and construction* and (2) *HD maps applications*. The first category is further classified into: (1.1) *HD maps modeling and design* that highlights data models and design schemes that are used to represent HD mapping data. (1.2) *HD map creation* that highlights major techniques to build HD maps. (1.3) *HD map maintenance and update* that highlights major techniques to keep HD maps up to date with the significantly higher change rate compared to traditional maps. The second category has discussed five sub-areas that are branched from autonomous navigation, either in outdoor or indoor environments. The five applications sub-areas are: (2.1) *Localization* applications that use HD maps to position objects with high accuracy in real time. (2.2) *Pose estimation* that uses HD maps to understand a detailed view of the surrounding environment. (2.3) *Path planning* techniques and subroutines that generate end-to-end high-precision routes to be consumed by machines for routing. (2.4) *Perception* that uses HD maps to improve real-time accuracy of information perceived about the surrounding elements. (2.5) *Automated transfer vehicles (ATVs)* that use HD maps in indoor environments, e.g., smart factories.

Although HD maps construction is mainly motivated by self-driving cars, there is a potential for endless applications that could make use of such fine-granularity information in other contexts. HD map creation and update techniques use several data sources that are used in other applications. For example, on-going research projects use Google geo images to identify types of trees that suffer from certain problems, building tree atlas in certain areas, and studying the development of urban areas and human migrations through analyzing data from different time snapshots. Combining techniques from the HD maps literature with these contexts has a great potential for breakthroughs in those fields. In general, the on-going efforts to construct high-resolution data about Earth will provide researchers in different fields with a relatively cheap source of data compared to existing methods. From a computer science perspective, one of the major features of the HD maps is the enormous map data size, compared to traditional maps, due to the added details. Currently, there is room for improvement for efficient data management [43] and format compactness and efficiency [26]. Needless to point out that the growing machine learning literature, either in computer vision or in spatial data analysis and GeoAI applications, is already challenged by several HD mapping gaps that need to be filled.

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