

MACHINE LEARNING BASED DRIVE-BY ROAD SIDE PARKING DETECTION USING OPTICAL DISTANCE SENSING



Master's Thesis
to confer the academic degree of
Master of Science
in the Master's Program
Computer Science

Author
Markus Hiesmair

Submission
Institute of Telecooperation

Thesis Supervisor
**Ass. Prof. Dr. Karin Anna
Hummel**

March 2018

Affidavit

I hereby declare that the following dissertation "Put your thesis title here" has been written only by the undersigned and without any assistance from third parties.

Furthermore, I confirm that no sources have been used in the preparation of this thesis other than those indicated in the thesis itself.

Linz, on March 4, 2018

Markus Hiesmair

Acknowledgment

Summary

Summary ...

asdf

Abstract

Abstract ...

Contents

1	Introduction	1
1.1	Envisioned Parking Information System	2
1.2	Drive-By Parking Space Sensing	3
1.3	Research Goal and Methodology	5
2	Related Work	7
2.1	Approaches to Park Sensing	7
2.1.1	Stationary Park Sensing with Dedicated Sensors	7
2.1.2	Stationary park sensing using cameras	8
2.1.3	Counting in- and outgoing Vehicles	11
2.1.4	Event Detection based Park Sensing using Smartphones	12
2.1.5	Drive-by Park Sensing using Cameras	14
2.1.6	Drive-by Park Sensing using Distance Sensors	17
2.1.7	Limitations of current drive-by park sensing approaches	19
2.1.8	Comparison of the existing park sensing approaches	20
2.2	Acquiring parking space maps	22
3	Testbed - Prototype Implementation	24
3.1	Used Hardware and Sensor Parts	24
3.2	Collecting Sensor Measurement Data	26
3.3	Raw Data Set	27
4	Data Processing and Machine Learning Approaches	29
4.1	Ground Truth Tagging	29
4.2	Data Preprocessing	31
4.2.1	Sensor Measurement Interpolation	32
4.3	Data Segmentation	32
4.4	Feature Calculation	34
4.4.1	Feature Analysis	35
4.5	Derived Dataset	36
4.6	Machine Learning Experiments	37
4.6.1	Tested Machine Learning Models	37

4.6.2	Used Tools and Frameworks	38
4.6.3	Evaluation Method	38
4.7	Deep Learning	38
4.7.1	Tested Deep Learning Models	39
4.8	Parking Space Maps	40
4.8.1	Parking Space Map of Linz, Austria	41
4.8.2	Approximating Parking Space Maps	41
4.8.3	Using Parking Space Maps to improve Classification Results . . .	44
5	Results and Discussion	45
5.1	Machine Learning Results	45
5.2	Deep Learning Results	45
5.3	Comparison to ParkNet	46
6	Conclusions and Future Work	47
	Bibliography	48

Abbreviations

CNN Convolutional Neural Network

DBSCAN Density-Based Spatial Clustering of Applications with Noise

DL Deep Learning

DWG Design Web Format (file format)

DXF Drawing Interchange Format (file format)

GNSS Global Navigation Satellite System

GPIO General Purpose Input Output

GPS Global Positioning System

I2C Inter Integrated Circuit

kNN k-Nearest Neighbour Classifier

LIDAR Light detection and ranging

NaN Not a Number

List of Figures

1.1	Envisioned system of several vehicles driving through the city and sensing its parking availability situation. The resulting parking availability map can be shown via a Web application or can be used by GPS navigation devices.	2
1.2	The sensing vehicle passes two parked cars and should identify a vacant spot in between using distance and location measurements.	4
3.1	Prototype of the sensing car, which is composed of a LIDAR Lite v3 optical distance sensor, a GPS receiver, a camera for ground truth collection and a Raspberry Pi as processing device.	25
3.2	Acquiring raw sensor data.	27
3.3	GPS trace of all recorded samples in the acquired dataset, while 32 test drives in Linz, Austria. Red dots represent parking cars.	28
4.1	User interface for manual tagging of parking situations. To-Do: crop .	30
4.2	Different types of parking cars.	31
4.3	All sensor measurements are being merged to obtain a dataset where all samples are containing time, distance, location and ground truth information.	32
4.4	Result of the segmentation algorithm. Three parking cars (green dots and orange lines) and two free space segments (yellow dots and black lines) have been detected.	34
4.5	A basic deep learning network having sensor values as input and the probability of all classes as output values. All layers are densely connected with each other.	39
4.6	Approximation of parking zones from the dataset. (a) is showing all GPS points at the selected region while (b) is showing the derived parking zones (clusters of parked cars).	43

List of Tables

2.1	Comparison of all park sensing approaches	21
2.2	All used machine learning models to detect a city's parking space availability.	22
3.1	Comparison of ultrasonic sensors and the used Lidar Lite v3 optical distance sensor.	26
4.1	Feature analysis showing the information gain and learning based score of all calculated features.	36

Chapter 1

Introduction

Traffic congestion in urban areas became a bigger problem every year in the past decades. Increasing traffic causes several issues, for example high monetary and environmental costs due to gasoline consumption and by emitting CO_2 to the environment. There are several strategies to reduce urban traffic to mitigate these problems like for example new investments in public transport infrastructure. However, according to a study by Hao et al. [9], car sales will continue to grow in the upcoming decades and therefore also traffic will continue to become worse in big cities. Thus, it is important to find ways to reduce traffic in urban areas.

With more vehicles driving in urban areas, there also comes the need for a sufficient number of parking spaces. Finding parking spaces in urban areas can be really difficult, frustrating and time consuming. There often exists some information about the availability of parking spaces in parking garages, but in most cities the situation of road side parking is unknown. This not only leads to frustrated drivers, who are searching for parking spaces a long time, but again contributes to urban traffic congestion as many cars have to drive around close to their destination while searching for free parking spaces.

There are many studies, which show that the searching for parking spaces adds a lot of traffic. A study by Nawaz et al. [17] shows that about 30% of traffic congestion is created by drivers looking for free parking spaces. Another study [10] concludes that alone in 2007 searching for parking spaces caused costs of about 78 billion US dollars by using 2.9 billion gallons of wasted gasoline and 4.2 billion lost hours only in the United States. Furthermore, cruising causes a lot of greenhouse emissions which is not only bad for the environment and contributes to climate change, but also lowers the quality of living in big cities through the significant amount of air pollution.



Figure 1.1: Envisioned system of several vehicles driving through the city and sensing its parking availability situation. The resulting parking availability map can be shown via a Web application or can be used by GPS navigation devices.

One of the most important contributors to long search times for parking spaces is not only the lack of vacant parking spaces, but also the lack of information about free parking spaces. Therefore, one way to mitigate many of the above stated problems is to determine the current parking space situation in the city and make it accessible to the public (for instance via a Web application), so that drivers can efficiently navigate to a vacant parking space, or even decide if they want to go by car or use public transportation, depending on the number of parking spaces available close to their destination.

1.1 Envisioned Parking Information System

Detection of road side parking spaces and their states is a challenging task. Of course an obvious approach to the problem would be to put stationary sensors to every parking space in the city, which check, if the corresponding parking space is occupied or vacant. This, however, has the drawback to be very expensive as, for big cities, thousands of sensors would have to be bought, installed, and maintained. Moreover, because the state of parking parking spaces does not often change, the high frequency of sensing with such a system would be rather inefficient.

The envisioned system, which is shown in Figure 1.1, uses a mobile crowd sensing approach to determine the current parking availability situation in urban areas. Several driving vehicles continuously sense their environment using multiple sensors while driving through the streets of the city. These measurements are then used for the analysis of the parking situation, so that parking cars and vacant parking spaces are being detected.

The parking situation analysis can be performed by each sensing vehicle for itself. After obtaining the results, all the derived information may be sent to a central server, which then combines the data of all sensing vehicles and computes a parking availability map. This map of free and occupied parking spaces can then be used for showing users the current parking situation (e.g., through a Web application) so that they can decide if they want to go by car or by public transport. Furthermore, the information of vacant parking spaces could be used effectively by GPS navigation systems which could direct the driver to a vacant parking space close to his end destination and therefore maybe prevent long parking search times.

1.2 Drive-By Parking Space Sensing

The envisioned system is using a promising novel approach, called drive-by park sensing, to sense a city's parking situation. Drive-by park sensing approaches are using mobile sensors instead of static ones to derive a city's current parking availability situation. Several prototypes, including the ParkNet prototype by Mathur et al. [15], which will be discussed later on, show that mobile crowd sensing has the advantage to be usually more cost effective and can provide sufficient accuracy for the purpose of providing parking space availability maps.

The idea of drive-by approaches is that there are sensing vehicles which are driving through the city and collecting data of their environment through mounted sensors. Using the collected data, parking cars and vacant parking spaces can be detected. There already exists a prototype implementation of such a system. In 2010, Mathur et al. [15] presented their system, called ParkNet, which continuously measures the distance to the nearest obstacle on the side of the road, as well as the location of the sensing vehicle through a GPS sensor. Using these data, they used a distance threshold to detect parking cars and vacant parking spaces. A more detailed description of their work can be found in section 2.1.6.



Figure 1.2: The sensing vehicle passes two parked cars and should identify a vacant spot in between using distance and location measurements.

Figure 1.2 shows a standard drive-by scenario of a sensing vehicle that passes two parallel parked cars and a vacant parking space in between them. The distance measurements while passing the parked cars will be much shorter than the measurements taken while passing the vacant parking space. This should allow a basic algorithm to recognize parking cars and vacant parking spaces.

However, the situation shown in Figure 1.2 is an idealistic one. In real life traffic, there will be much more complex situations to face, which are not as easily detectable and which might influence the success of the detection. For instance, the sensing vehicle might not drive in the right-most lane, therefore the measured distances will be much longer. Another possible issue are other driving cars, motorcycles or bicycles which the sensing car overtakes. Many of such distractions have to be filtered out to counteract false detection results.

The high complexity of urban traffic and the many distractions during sensing make it nearly impossible to create a rule set based on the sensor measurements which would be able to detect parking situations at a sufficient accuracy. Therefore, simple thresholding will not work in real life traffic scenarios. Furthermore, such rule sets would have to be created for each city individually because of the different nature of the roads and the parking spaces. For instance, the distance between lanes and parking spaces can vary highly in two different cities. Thus, to be able to detect parking situations, new methods have to be found, that are more flexible to distractions and changes in the environment.

1.3 Research Goal and Methodology

The overall goal of this thesis is to study and increase the accuracy of detecting the parking space situation in urban real world traffic scenarios using drive-by park sensing on multi lane roads. Vacant parking spaces and parking cars are detected and distinguished from other common objects beside the road like trees, houses and other objects. To counteract false detections of parking cars while sensing in real world traffic, several distractions are being identified, detected and filtered out. Common distractions include overtaken cars, bicycles and motorcycles as well as passed cars waiting at traffic lights.

To determine if it is possible to derive parking availability statistics from drive-by sensing in complex road scenarios the following steps of the used research methodology will be taken:

Building a test bed To retrieve the required data, a test bed is being built which is able to access the distance and GPS sensors as well as the camera. It records these data continuously while driving by and saves them for the later analysis. The detailed description of all hardware parts and the data collection process can be found in the sections 3.1 and 3.2.

Acquiring a dataset As soon as the test bed is ready, the sensors are mounted on the prototype car to be able to start recording the dataset. Test drives are being done in some selected streets in Linz, Austria with the focus of variety of the recorded situations. All measured distances, GPS locations and ground truth images are saved to files including the according timestamps to be able to evaluate the results of different approaches later on. Furthermore, using the images taken by the camera, ground truth values are manually labelled in different classes (Parked car, free space, overtaken car, ...). A detailed description about the dataset and the ground truth tagging can be found in the sections 3.3 and 4.1.

Data processing and segmentation As next step the measured sensor values have to be preprocessed and filtered in order for the following algorithms to work. Sensing and overflow errors as well as outliers in the measurements should be identified and removed before further processing. Section ?? is discussing all filter and preprocessing techniques used. After the raw data has been filtered, the sensor data has to be segmented. As parking cars and other objects which should be classified consist of several sensor measurements, the corresponding measurements should be grouped together and merged to segments which can later be classified. A detailed description of the segmentation process can be found in section ??.

Classification using machine learning and deep learning Features on the created segments are calculated (for instance length, average distance and variation of the distance measurements) and are being used to train and evaluate several machine learning algorithms which will be compared on their performance. Furthermore, some deep learning models will also be evaluated on the raw sensor data of the segments and will be compared to common machine learning results. The used features are described in section ??, whereas the tested machine learning and deep learning approaches can be found in the sections ?? and ?. The results of all experiments are evaluated and compared in section **To-Do: ref ??**.

Deriving basic parking space maps To support parking detection accuracy a parking space map using the sensor measurements are being derived. Parking space maps are necessary for the overall system to determine if it is legal to park at a certain location, i.e., if any space is a parking space. As for our test use case there is no parking space map with sufficient quality available at city authorities, a basic parking space map is derived using the acquired dataset. The process of deriving the parking space map can be found in section ?. **To-Do: reference to parking space map to improve accuracy**

Further improvements of the machine learning approaches Several strategies for further improving the accuracy of the machine learning performance are being tested and evaluated. Section ?? describes all of these attempts to improve the detection accuracy.

Chapter 2

Related Work

This chapter will cover work related to park sensing and machine learning. Section 2.1 will discuss different approaches to sensing current parking situations in cities. Furthermore, a comparison of them will be given as well as advantages and disadvantages of the specific approaches. In Section 2.2 the need of parking space maps will be discussed as well as how they can be obtained using several sensing vehicles.

2.1 Approaches to Park Sensing

There already exist numerous approaches for detecting the states of parking spaces as well as the parking situation in a city. In this section parking detection approaches will be categorized in six different categories and in the following subsections several reference papers for all categories will be discussed. The six categories are stationary park sensing with dedicated sensors (Section 2.1.1), park sensing using stationary cameras (Section 2.1.2), counting in- and outgoing vehicles (Section 2.1.3), event detection based park sensing (Section 2.1.4), and drive-by park sensing using either a camera (Section 2.1.5) or a distance sensor (2.1.6). After all detection strategies have been discussed an overall comparison is presented in Section 2.1.8.

2.1.1 Stationary Park Sensing with Dedicated Sensors

The most obvious and technically simple solution to park sensing is to use stationary sensors to determine the state of parking spaces. Usually one sensor per parking space is used which determines its state (occupied or vacant) and sends this state to a central server. Several reference projects already exist implementing this technique[19, 18]. In

this section as a representation of all the similar systems, the SFpark project will be examined.

In San Francisco a first prototype of the SFpark project [19] has been employed from 2008 to 2011. Wireless stationary sensors have been placed at about 8.200 road side parking spaces in specific down town areas in San Francisco with high amounts of traffic. These sensors are able to detect the state of one parking space in real time and send this information to a central server. Furthermore, parking lots also count the in- and outgoing vehicles and share this information, so that the parking situation in the areas with park sensing can be derived. The gained information is being shared as open data, so third party developers and researchers can also use the dataset for all kind of projects and purposes. Furthermore, there exists an App from SFpark itself to help drivers find available parking spaces nearby, navigate to them, and pay as they go with their phones.

A top priority goal of the SFpark project is to increase the availability of parking spaces in every block throughout the city. To achieve this goal, they are using demand responsive pricing. If (almost) all parking spaces in a neighbourhood are occupied for a long time, they raise the price in this specific area and vice versa if no parking spaces are occupied they lower prices. This leads to high overall parking space availabilities (20 - 40%) and also to lower traffic congestion and lower greenhouse gas emissions. However, besides the advantages of high accuracy and being a real-time system, there also are disadvantages. First of all, only metered parking spaces can be tracked, as sensors have to be installed per parking space. Thus, areas where parking is allowed but there are no clearly marked parking spaces cannot be sensed with a reasonable accuracy. Another drawback are the high overall costs. The about 8.200 stationary sensors have to be bought, installed and maintained, which obviously causes high costs while only covering a tiny fraction of the overall San Francisco down town. So if the system should be available in the whole city, costs would increase dramatically.

2.1.2 Stationary park sensing using cameras

Another approach while using stationary sensors is to use fixed deployed cameras which continuously record images of parking areas and analyze them for vacant parking spaces. Cameras can monitor up to one hundred parking spaces simultaneously with an accuracy of up to 96%. Challenges of image detection are of course different lightning and weather conditions as well as occlusions depending on the angle which the camera records the parking scene. Detection algorithms using standard digital image process-

ing will be discussed in this section as well as approaches using deep learning and convolutional neural networks (CNNs).

Parking detection using digital image processing

There exist a few common approaches using digital image processing to detect the state of parking spaces using a captured image of a parking area. First of all, edge detection is often used for parking space classification. Common edge detectors such as the Canny Edge Detector [4] or the Sobel Operator [7] can be used to derive the edge pixels of an image. The edges or edge pixels are counted and if the amount is above a certain threshold, the space will be detected as occupied. The assumption behind this approach is, that usually a vacant parking space has a plain surface and therefore a low amount of edges whereas an image of a parking car should have a lot of edges. Blumer et al. [2] and Liu et al. [13] both used this technique as part of their algorithms.

A slightly different yet related approach object counting [13]. The edges of the image segment of a parking space are analyzed and closed contours (treated as objects) are detected and counted. Then, depending on a threshold which has to be set first, a parking space is classified as either vacant or occupied depending on the object count.

Another common image processing technique is to use foreground/background information of the images. Here, the main background color is identified and compared to the whole image. The background of a parking space can either be defined via extracting a certain part of an image, which should always represent the main background color of a parking space's pavement (done by Blumer et al. [2]), or via an histogram of the image assuming that the background uses the most pixels in a recorded image (done by Liu et al. [13]). After the background color is available it is being subtracted from the original image and using thresholding foreground and background pixels are identified and counted. Depending on the count of the respective pixels, the parking space is then classified as vacant or occupied.

Liu et al. [13] use all of the above mentioned techniques in combination to build a more stable prototype. They only test their prototype indoors which is why weather and lightning conditions do not cause problems. With sensing only a maximum of seven cars, it provides an ensemble technique which should be more reliable. However, the work does not include an evaluation of how well their algorithm performed on a bigger dataset. Another ensemble method is developed by Blumer et al [2]. They use edge counts and background/foreground information as input for different machine learning techniques, which then classify a parking space as vacant or occupied. The

plain algorithm achieves an accuracy of about 77.8%. By improving the algorithm using frames of preceding and following images to identify parking/unparking events, an accuracy of about 88.8% is achieved.

Parking detection using deep learning and CNNs

In recent years deep learning gained a lot of significance in the field of machine learning. Deep learning is a specific variant of neural networks with a high amount of hidden layers. For example in image recognition, convolutional neural networks (CNNs) nowadays perform as well as humans in classifying everyday objects in digital images. A CNN is a neural network with a possibly large amount of hidden layers of which some of them are convolutional layers. In the case of image recognition, CNNs take the spatial relationships between neighbouring pixels into account. This rise in learning power also leads to projects which try to train CNNs in classifying parking situations while using camera images of a parking area.

Amato et al. [1] train two different CNNs on classifying parking space states and compare their performances afterwards. They use the publicly available PKLot dataset as well as a dataset collected by themselves to train and evaluate the neural networks. In total over 700.000 images in different weather conditions and with different levels of quality are processed (in some situations parking lots are almost fully occluded by trees or lamp posts, etc.). The results of the CNN's classifications are promising. Despite the fact that some of the images do not exactly match the parking space and there are a lot of occlusions, the best performing deep neural network achieves an accuracy of above 91% on all subsets of the datasets.

Another work in the field of deep learning is reported by Di Mauro [6]. They also use CNNs and the PKLot dataset as well as a self acquired dataset. However, a slightly different CNN is employed together with pseudo-labelling of the data, which can be seen as semi-supervised approach. When using pseudo-labelling both labelled and unlabelled data are used at the same time to train the network. For unlabelled data the label which was computed by the CNN in the forward pass is used, that is also why it is called pseudo-labelling. Furthermore, a different loss function has to be used as the pseudo labelled data has much less significance than the ground truth labelled data. Di Mauro et al. trained the CNN with about 5% of the data and achieved an accuracy of above 96% with a the fully supervised approach. The pseudo-labelling approach reached about the same level of accuracy, however, the dataset had to be balanced for it to work properly.

Advantages and disadvantages of using stationary cameras

Advantages of cameras are the high level of accuracy they reach while covering a lot of cars at once. However, for all of the above discussed approaches to work, cameras would have to be calibrated manually before their usage to know where parking spaces are located. Furthermore, most of the research focused on the use of cameras for detecting the parking space situation of a single parking lot with many cars rather than for road side parking spaces. For this approach to work at a city wide scope, cameras would have to be mounted at least at every block. Similar to the dedicated sensors per parking space (section 2.1.1) this would cause high costs not only in the form of hardware but also in installation and maintenance costs. Furthermore, mounting cameras throughout the city obviously also brings up privacy issues.

2.1.3 Counting in- and outgoing Vehicles

A rather simple approach of estimating the number of free parking spaces is to count in- and outgoing vehicles at parking zones. Zadeh et al. [22] present a prototype which counts all in- and outgoing vehicles using a Raspberry Pi and two ultrasonic range finders at each gate. Ultrasonic sensors measure the distance from the side of the road to a potentially passing vehicle. Two ultrasonic sensors in sequence are needed to detect if a vehicle is going in or out. According to the order in which the ultrasonic sensors detect a passing vehicle it is decided whether a vehicle is going in or out. Furthermore, the two sensors are also used to differentiate a passing person from a vehicle. Both sensors are as far apart as they can detect a vehicle at the same time but not a person. Misleading detections of passengers are filtered out using this technique.

As described this approach is technically simple to develop and the hardware costs are also very low. However, this system is only designed for parking lots which have a low number of gates where cars go in and out and not for a city wide deployment. For closed parking areas it is easy to detect in- and outgoing vehicles whereas it is hard to do so in open traffic and street scenarios. Furthermore, the counting also will not work with ultrasonic sensors in open street scenarios. For example, there are often several lanes, which would make the sensing impossible as passing cars would possibly occlude each other. Another issue is that with the installation of the required sensors they also have to be calibrated for the specific scene to reach a sufficient performance (e.g. the distance to the road). The calibration effort raises the costs for this approach and also makes it inflexible to context changes.

2.1.4 Event Detection based Park Sensing using Smartphones

Detecting parking and unparking events using a driver's smartphone is another approach to estimate parking space availabilities, which is especially interesting because nowadays almost everybody in the developed world has a personal smartphone. As soon as these parking related information is available for a high enough rate of drivers, a city's parking availability situation can be roughly estimated. There already exist a few research papers which discuss different approaches to this topic. Three of these will be discussed in this section.

In 2013 Nawaz et al. developed ParkSense [17] which is an application for Android phones to detect certain events which relate to the change of parking situations. Using the app a user can log his parking events and furthermore the costs of parking. The app is released to the Google Play Store and recorded 59 parking traces in four different cities at the time their paper was released. However, the app not only records the times when parking and unparking takes place, but also records a detailed profile of Wi-Fi access points while parking as well as Wi-Fi profiles and GPS locations after unparking takes place. Using this dataset, the goal of the prototype was to evaluate how accurately unparking events can be detected using Wi-Fi fingerprints. ParkSense takes several of such fingerprints when parking takes place and then continuously scans the Wi-Fi signal and compares it to the signal while parking. Using this technique ParkSense can detect when users return to their vehicle. However, it cannot be assumed that when a user returns close to his vehicle, that he will leave with his car, therefore Nawaz et al. also implement an activity detection for driving using the change of Wi-Fi signals over a specific timespan. The idea behind this approach is, that while driving, Wi-Fi access points in range will change much more frequently than while walking or while staying at the same place. Out of 41 cases where unparking actually took place ParkSense could detect 38 user returns correctly and 35 times out of the 41 it could detect that the vehicle started driving. Thus, ParkSense reached an overall accuracy of about 85% in detecting unparking events.

A similar approach to the problem of parking related event detection is described in [14]. The overall goal of this research paper is to robustly identify parking and unparking events using different sensors of a typical smartphone. In total, nine indicators are identified which can give hints whether a parking/unparking event occurred. For instance, they use several accelerometer measurements to identify the change of the user from walking to driving and vice versa. Other indicators are the Bluetooth signal strength of the car, sounds of a started motor sensed via a smartphone's microphone, Wi-Fi fingerprints and accessing parking payment apps. To decrease the amount of energy consumed by the application, certain low power sensors (e.g. accelerometer) measure

periodically while other high consumption sensors (e.g. microphone) only confirm or reject events which were already sensed by low power sensors. Using all indicators, Ma et al. build a model based on conditional probabilities which should be able to show the probability of an event at a certain time. To evaluate the approach, an Android application is used to manually collect ground truth events. 40 parking samples are collected to train the model and 60 other samples are used for testing. The best configuration achieves 93% recall and 90% precision on parking events and 81% recall and 93% precision on unparking events.

Estimating events by non-tracked drivers

All of the above mentioned approaches only work if almost all drivers in a specific city have the respective smartphone app installed, so that all parking and unparking events can be detected. That way the states of all parking spaces would be known and parking availability could be derived. However, this is highly unlikely as people would have to know that such an app exists in the first place and furthermore there is no instant positive effect of having such an application installed for a single user. Such an app might also have a negative influence on the battery life of a user's smartphone even if all of the above applications are designed for a low power consumption.

Facing this problem Nandugudi et al. propose PocketParker [16], a smartphone application which not only detects parking and unparking events but also estimates the amount of so called "hidden drivers" - drivers that do not have the application installed. PocketParker uses a simple model to detect parking and unparking events. It uses the Google Play Services activity recognition library to detect changes from driving to walking and vice versa and thus derives parking and unparking events. After this information is available, PocketParker tries to estimate the amount of drivers having the application installed, so that all detected events could be scaled to the right proportion and taken into the overall parking estimation process. The PocketParker app not only identifies the parking space location, but also the user's end target after parking his vehicle. That way they want to identify parking spaces which would be nearer to the end destination of the user, but probably are occupied since the user parked further away and did not take the closest parking space. Using this approach PocketParker derives parking space counts at dedicated parking lots. The overall parking space count of these parking lots is known before. To evaluate its performance Nandugudi et al. performed an experiment at their university's parking lot. 105 users generated 10.827 events over 45 days, therefore an average of 241 events per day. They use cameras to identify the ground truth and then evaluate their results against it. With an esti-

mated driver fraction (drivers which had the app installed) of about 20%, PocketParker achieves a parking space count accuracy of about 94% for the university's parking lot.

Advantages and disadvantages of using an event based approach

There are a number of advantages using smartphones to detect parking availabilities. Nowadays smartphones are wide-spread among people in the developed world. Therefore, smartphones are the optimal sensing devices for detecting a user's activities throughout the day. Also parking and unparking activities can be detected and parking availabilities can be derived. The whole detection process causes no additional costs for hardware installations and maintenance for city authorities. Furthermore, the detection process can all be done without the user even noticing, because the detection process can theoretically run fully as a background process.

However, a big concern of mobile applications is power usage. Activity detection requires certain sensors to run periodically which prevents the phone from being idle and therefore uses more battery. Even if all of the discussed approaches intentionally use high power consuming sensors like GPS sensors or microphones only in rare cases, the immanent sensing of low power consuming sensors will also cause decreased battery hours. Another disadvantage is that a lot of users would have to install the app for accurate parking availability estimations. Even if Nandugudi et al. [16] show that the so called "hidden drivers" can be estimated to a high degree, it will still be challenging to get a user base of even 20% as they propose in their paper. The first obstacle would be to let users even know that there exists such an app, so that they can install it. The following problem would be the cold start problem. After the app is released, usually only a few people will have it installed and they will probably not see an advantage of such an app because the availability estimates will not be accurate if there is only a really small user base.

2.1.5 Drive-by Park Sensing using Cameras

In contrast to approaches with stationary sensors which were discussed in sections 2.1.1 and 2.1.2, drive-by sensing approaches use sensors which are mounted on vehicles driving through the city to sense vacant and occupied parking spaces. Using such mobile sensors has the goal of achieving a high enough accuracy at a fraction of the costs of stationary solutions. In this section the usage of cameras mounted on driving vehicles to detect parking spaces is discussed.

There exist a lot of different approaches in detecting parking spaces from a picture captured by a camera which is mounted on a vehicle. Most of them were designed for the purpose of park assistance, so that parking is being made easier for drivers or that the vehicle can even park itself. However, almost all of such approaches could also be applied for camera-based drive by sensing.

The first discussed approach is to use parking markings. Xu et al. [21] introduce a color vision based parking space detection algorithm which tries to identify parking markings on the street. They use neural networks to learn to distinguish parking marking pixels from others and they use stereo vision to identify obstacles on parking spaces. A similar approach is followed by Jung et al. [11] who applies a hough transform on the captured images to detect lines (parking markings) on the images. However, the accuracy of color vision based approaches, as just discussed can vary highly due to different lightning conditions, conclusions or shadows. Furthermore, this approach obviously only works with parking spaces where markings are present.

Another approach is to use two or more images to create depth maps to estimate vacant parking spaces. Kaempchen et al. [12] developed a stereo camera based approach which estimates depth maps based on two images of calibrated cameras placed on the vehicle next to each other. By finding features in both images and correlating them, the disparity and thus the depth of points can be estimated and vehicles as well as free spaces can be detected using the 3D information. However, a stereo camera solution has the drawbacks of relying on sensitively calibrated cameras which should have a reasonable resolution to be able to match the features in both images.

Depth maps can also be generated using a single camera with motion stereo-based 3D reconstruction. In 2010 Suhr et al. [20] developed an approach using a fish eye camera mounted on a vehicle, which is facing backwards. It takes multiple images in a sequence and searches for point correspondences in adjacent images to reconstruct 3D structures and to estimate depth maps. This eliminates the need of a second camera while still providing similar results. Suhr et al. reported a 90% success rate of their approach in detecting vacant spaces.

All of the above discussed camera based drive-by approaches are not designed to detect parking spaces while driving through the city and would have to get evaluated to know if they are suited for the task. However, there exists a recent work of Grassi et al. [8] about drive-by sensing to detect parking space availability at a road segment accuracy level. They introduce a smartphone application, called "ParkMaster". The user has to mount his smartphone behind the wind shield of his vehicle so that the smartphone camera is able to capture images of the area in front of the vehicle. ParkMaster tries to detect

parking cars using the camera's video stream and counts them. In combination with parking space counts at a road segments level the number of vacant parking spaces then gets estimated. For the detection of the parking cars ParkMaster uses the video stream of the smartphone camera as input for a Viola-Jones feature-based cascade classifier, which is a machine learning technique to detect complex objects within images. Several positive and negative examples in different lightning conditions were used to train the classifier in an offline process. While driving, the smartphone searches for the learned features in the captured images and the classifier reports the bounding boxes of detected vehicles. However, as the vehicle is driving, it might detect the same vehicle in multiple subsequent frames of the captured video sequence. ParkMaster handles this problem by estimating the GPS coordinates of detected parked vehicles and then compares their position to identify multiple detections of the same vehicle. For the calculation of the sensed vehicle's GPS coordinates, ParkMaster uses the coordinates of the bounding box in the image in combination with self calibrated parameters of the smartphone camera.

Grassi et al. evaluated their prototype with real world experiments in Paris, Los Angeles and a small village in Italy¹. During their test drives, they recorded a dataset containing 5.896 parking cars and 2.280 vacant parking spaces. They manually assigned ground truth values, optimized the variables of their algorithm and tested their approach on the dataset which produced an overall accuracy of close to 90%.

Advantages and disadvantages of camera based drive-by park sensing

As only the last approach discussed in this section, is designed for parking space availability estimation, this paragraph will be focused only on ParkMaster's advantages and disadvantages. The main arguments, Grassi et al. give to promote their approach is the high enough accuracy and that high hardware costs can be avoided, because of the use of smartphones of end users as processing devices. If smartphones are used, costs would be lower, however, as already discussed in section 2.1.4, smartphone apps would need to have a high enough distribution for enough drivers to sense available parking space. Furthermore, drivers would have to mount their phone each time they drive through the city and this obviously also costs a lot of battery hours. Therefore, it is not sure if a smartphone based system would give a good enough coverage. Of course dedicated cameras could be used as part of a hardware installation in a car, but this would of course introduce new costs, while still keeping costs lower than with stationary sensor deployments. Further limitations of drive-by park sensing in general will be discussed section 2.1.7.

¹Sant' Angelo in Vado

2.1.6 Drive-by Park Sensing using Distance Sensors

Another approach of drive-by sensing is to use a distance sensor instead of a camera as discussed in the previous section. The approaches discussed in this section are closely related to the work presented in this thesis. Two different approaches will be discussed in this section. First an approach using a 1D ultrasonic sensor will be described and furthermore another prototype using two 2D LiDAR scanners will also be examined.

Drive-by park sensing using a 1D ultrasonic distance sensor

Mathur et al. [15] developed a drive-by prototype, called ParkNet, in 2010. It consists of an ultrasonic range finder which continuously measures the distance to the nearest obstacle on the right side of the road (at an interval of about 50 ms - 20 measurements per second) and a GPS receiver which records the corresponding locations. Furthermore, a camera is used for obtaining ground truth information through manual tagging of the captured images. Mathur et al. deployed their system on a standard car, which collected test data in drives during daily commuting throughout 2 months in selected areas in Highland Park, New Jersey. Altogether, about 500 miles of street parking scenes were collected during their test period.

ParkNet's detection algorithm is based on thresholding. It tries to detect so called "dips", which are parts of the sensor signal caused by parking cars or other objects. Sensor readings are separated from each other by overflow measures which show that at that point the distance is higher than the range of the ultrasonic sensor. In a second step, these dips are compared to two thresholds for the distance and the length of the dip. Both thresholds have been derived by a subset of the data and produce an overall error rate of 12.4% on this training set. ParkNet assumes that detailed parking space maps are available. They distinguish between a slotted and unslotted model for their parking space detection. In the slotted model, they assign detected parking cars to single parking spaces using the GPS position. However, GPS positions are not always as accurate as they need to be to correctly identify a parking space. Therefore, ParkNet uses an environmental fingerprinting algorithm which corrects GPS positions using multiple test runs on the same street. They identify static objects which are there on all sensor traces and then cluster their positions. Mathur et al. use the first cluster center as true position and correct the surrounding GPS measurements. In the unslotted model, ParkNet estimates the number of free parking spaces by checking for all free spaces if the length is high enough for a car to park in between the two enclosing objects.

Mathur et al. used their self acquired dataset to evaluate their algorithm. On the unslotted model, they tried to estimate the number of vacant parking spaces in a specific street. Their algorithm turned out to have an overall accuracy of about 95%. For the slotted model they reach an accuracy of 91% using their environmental fingerprinting approach to correctly assign detected parked cars to parking spaces.

To show that their system is more cost effective than stationary sensor deployments, Mathur et al. also present a mobility study which has been done in the city of San Francisco, California. They try to estimate the interval in which a sensing vehicle would visit a street. The GPS locations of 536 taxi cabs which were collected during one month are used and the analysis of these data shows that while in the outer San Francisco areas visiting intervals can be as high as hundreds of minutes, in the down town areas 80% of the streets are visited every 10 minutes. Furthermore, they estimate the costs of running their system to be more than 12 times cheaper than with the use of stationary sensors at each parking space.

Drive-by park sensing using two 2D LiDAR distance sensors

Bock et al. [3] use two 2D LiDAR distance scanners to approach the problem of drive-by park sensing. They are both deployed on a regular car facing to the right side of the road with an angle of 60 degrees in between them. The position of the vehicle is measured via a GNSS sensor. The LiDAR scanners measure at a frequency of up to 300.000 measurements per second and produce 3D point clouds of the sensed scenes. These point clouds are used to detect parking cars. In a first step the data is preprocessed and segmented. For the segmentation Bock et al. use a "similar region growing approach" to differentiate between multiple objects in a single scan. They use a random forest classifier to classify sensed objects into two distinct classes: non-moving objects and other objects. The random forest classifier is being used because it is less prone to overfitting, fast and easy to interpret. As input for the classifier, several calculated features based on the geometry of the sensed objects are used. To distinguish moving cars from non-moving ones, Bock et al. use two LiDAR scanners instead of one. Because of the angle of 60 degrees in between the two sensors, moving vehicles can be identified as they appear at different times in both sensors and therefore at different positions.

For the evaluation of the performance of their prototype, Bock et al. obtained a dataset in Hannover, Germany. They gathered data of 1.313 parallel and perpendicular parking cars as well as 1.360 other objects. Altogether, their approach reaches a high accuracy of 95.8% recall and 98.4% precision for parallel parking cars and 93.7% recall and

97.4% precision for perpendicular parking cars. However, despite the good results for the detection, 2D LiDAR systems are very expensive in comparison to one dimensional sensors as used by ParkNet (described in the previous paragraph).

Advantages and disadvantages using distance sensor based drive-by park sensing

As already discussed the use of 1D distance sensors for a drive-by approach can be much cheaper than stationary sensor deployments while providing a sufficient accuracy with enough sensing vehicles. In contrast to camera based drive-by sensing a higher accuracy can be achieved, due to the fact that detailed distance information is instantly available and does not have to be derived from camera images. The presented camera based drive-by sensing approach can only detect cars and then estimate the vacant parking spaces using an overall count of parking spaces per road segment. Using distance information distance sensor based drive-by approaches are also able to detect free spaces which improves the overall result. The use of 2D LiDAR distance scanners brings another gain in accuracy, however, such systems are still very expensive and therefore, not suited for the use of a lot of vehicles sensing the parking situation in a city. Further limitations of drive-by park sensing in general will be discussed in the next section.

2.1.7 Limitations of current drive-by park sensing approaches

In this section limitations which apply to both camera based- and distance sensor based drive-by park sensing will be discussed. The first limitation is based on the cars which are detectable. Most drive-by sensing approaches currently only try to detect limited types of parking cars. Even if in most cities parallel parking spaces are the most prominent type of parking spaces, obviously there exist a lot of other parking spaces (e.g. perpendicular parking cars and angular parking cars). Camera-based drive-by sensing would have to also learn to detect images of such parking cars and distance sensor based drive-by sensing would have to be much more variable in terms of the length of detected cars as well as the patterns of the detected distance to the obstacle. For instance, in the case of angular parking spaces, the discussed approach of the ParkNet prototype would not work as they only apply thresholding and therefore it is likely that such parking spaces would not be segmented and detected correctly.

Another limitation of drive-by sensing are multi-lane roads. Most of the discussed drive-by sensing approaches only work when the sensing vehicle drives in the right-most lane. In modern cities, there are often multiple lanes and GPS is too inaccurate to estimate

the lane, where a vehicle is going. Therefore, to work properly, lane detection would have to be performed for the systems to work on multi lane roads. However, it would be preferable to have an algorithm which also works in other lanes than the right most one as then the coverage of detections would be greater. For algorithms to work on non-right lanes, they also have to face several distractions. Of course, the distances to parking cars will be greater if the sensing vehicle is going on a left lane. Additionally, when a sensing vehicle overtakes another car which is going slower, it will record the distances to this vehicle instead of the distance to parked cars. Furthermore, also distractions such as traffic lights or traffic jams have to be taken into account for a real life installation of such prototypes.

2.1.8 Comparison of the existing park sensing approaches

Table 2.1 shows a comparison of the park sensing approaches which were discussed in this section. All of the above discussed approaches show high accuracy ($\geq 90\%$) but not all of them are suited for all kinds of park sensing. For instance, the drive-by approaches are not able to detect parking availabilities in dedicated parking lots or parking garages whereas vehicle counting cannot detect the parking situation of road side parking spaces and thus a city's overall parking situation.

The costs of the different approaches also vary highly. Approaches with stationary sensors usually have the highest accuracy, but also bring the highest costs. Event-based sensing operates on very low costs because it usually uses smartphones as sensing and processing devices. However, to reach a high accuracy a lot of people have to sense parking events. Furthermore, such apps will also drain the user's battery faster than usual.

Drive-by park sensing approaches are in the medium cost range because the vehicles which are sensing have to be equipped with the required sensors, but in contrast to stationary sensing, much fewer sensors can reach a sufficient degree of accuracy. However, there are certain limitations of the current approaches as described in the previous section. In this thesis, a prototype using distance sensor based drive-by park sensing will be developed and evaluated, as the ratio from cost to accuracy seems to be the best of the investigated approaches. To improve accuracy in real life scenarios, machine learning will be used to identify all types of parking cars as well as different distractions such as overtaking while driving on multi lane roads.

	Accuracy	Costs per sensor setup	Limitations / Drawbacks
Stationary Sensors	[19] 100%	\$250 - \$800	- High amount of sensors needed - Therefore high overall costs
Stationary Cameras	[2] 88.8% [1] 91% [6] 96%	about \$85	- Cameras can only cover limited area - A lot of cameras needed for city-wide deployments - affected by lightning and occlusions
Counting Vehicles	[22] 100%	about \$45	- hardly applicable in open street scenarios - gates needed for in- and outgoing vehicles
Event-based Sensing	[17] 85% [14] 89% [16] 94%	\$0	- high user base required (crowd sensing) - drains battery of the user's smartphones
Drive-by Sensing (Camera)	[8] 90%	\$0	- high user base required (crowd sensing) - detection of different types of parking cars - multi lane and overtaking situations - detecting standing cars (e.g. at traffic light) - avoiding multiple detections of the same car
Drive-by Sensing (1D-Distance sensor)	[15] 93%	about \$400	- detection of different types of parking cars - multi lane and overtaking situations - detecting standing cars (e.g. at traffic light)
Drive-by Sensing (2D-Distance sensor)	[3] 96%	\$1000 - \$5000	- high costs per sensor setup - detecting standing cars (e.g. at traffic light)

Table 2.1: Comparison of all park sensing approaches

	Accuracy	Dataset
Convolutional Neural Networks (Stationary cameras)	[1] 91%	[1] about 700.000 images
	[6] 96%	[6] about 970.000 images
Viola-Jones feature-based cascade classifier (camera-based drive-by sensing)	[8] 90%	5.896 parked cars and 2.280 available parking spaces
Random Forest Classifier (2D distance sensor based drive-by sensing)	[3] 96%	1.313 parking cars and 1.306 other objects

Table 2.2: All used machine learning models to detect a city’s parking space availability.

Used Machine Learning Approaches

Table 2.2 shows an overview of all machine learning algorithms which were used for the classification of parking situations in cities in the related work. Convolutional neural networks are used to classify images of parking lots obtained by stationary cameras (Section 2.1.2), whereas a Viola-Jones feature-based classifier is used in camera-based drive-by sensing (Section 2.1.5) and a random forest classifier is used in the 2-dimensional distance-sensor based drive-by sensing (Section 2.1.1). **To-Do: passt diese Tabelle bzw Absatz wirklich so???**

2.2 Acquiring parking space maps

Parking space maps are of great importance when sensing a city’s parking availability. Knowing where parking is allowed and how parking is possible is crucial information for park sensing approaches. Several of the in section 2.1 discussed approaches use some kind of parking space map. Coarsely grained parking maps in the form of parking space counts for road segments/parking lots are necessary for several approaches, like the counting all in- and outing vehicles approach discussed in section 2.1.3. Furthermore, such information is also necessary for event-based park sensing (section 2.1.4) as well as drive-by sensing (2.1.5 and 2.1.6). Of course parking space maps with a higher granularity can be beneficial in most cases and are sometimes even necessary. For instance, the exact position and orientation of parking spaces can increase the performance of drive-by sensing.

Most previously discussed papers assume that parking space maps are already available, for example at city authorities. However, even if a city authority has a parking space map of their road side parking spaces, that does not mean that it is ready for processing and may not contain the necessary information. That is why Coric et al. [5] developed

an algorithm to derive parking space maps from the data stream of an ultrasonic range finder. They used the same equipment as ParkNet [15] to record GPS and distance information to the right side of the road while driving through streets in their test zones. Using their testbed, they acquired two datasets in Highland Park, New Jersey and in Brooklyn, New York City. After obtaining the data, they try to predict areas where parking is legal and such where it is not. Their hypothesis is that spaces which are almost never filled will be most likely illegal spots, whereas spaces which are often occupied will be likely legal parking spaces.

Using sensor readings from several runs they try to aggregate this data to derive their results. They first assign the sensor readings to one meter cells and then try to classify these cells as legal or illegal parking spots. Using their algorithm, called "Weighted occupancy rate thresholding approach", they not only use occupancy rates per cell, but also take into account, that runs with almost only occupied cells provide better information than runs with a lot of vacant spaces, as usually only the illegal spaces stay vacant, when the parking availability is low in a certain street. They compute a occupancy rate per cell and weight it using the overall occupancy of the street. Then they apply thresholding to the occupancy rates to classify whether parking in the range of a cell is legal or not. Coric et al. evaluated their approach using the obtained dataset and found that their acquired parking space maps have a false negative rate of 5.21% and a false positive rate of 5.89%. Thus, using the specified setup, parking space maps can be derived at a good accuracy and may be used for the approaches stated in section 2.1.

To-Do: short paragraph about deriving parking space map in this thesis?

Chapter 3

Testbed - Prototype Implementation

As already discussed in Chapter 1, sensing a city's parking availability and thus making the parking situation more transparent would be highly beneficial for reducing traffic congestion and greenhouse gas emissions as driver's looking for parking spaces in urban areas could navigate directly to vacant parking spaces close to their destinations. To support this goal, a prototype of drive-by sensing using an optical distance sensor has been designed, implemented, and evaluated. This chapter introduces the prototype and testbed which have been developed to acquire the necessary dataset to run the machine learning experiments.

3.1 Used Hardware and Sensor Parts

Figure 3.1 shows the sensing car and its mounted sensors. For collecting, processing, and saving the sensed data a Raspberry Pi 2 Model B¹ is used. A Raspberry Pi was chosen because of its simplicity to connect and access sensors and moreover because it is really easy to program as it is just a regular Linux-based computer. Furthermore, the price of a Raspberry Pi is also quite low (about €35), therefore the overall cost of the system will remain low.

To determine the location of the sensing vehicles while driving through the city, a Navilock USB GPS receiver² is used. The receiver is connected to the Raspberry Pi using a USB port and measures the GPS location (latitude and longitude) at a rate of about 1 Hz. According to the manufacturer the acquired positions are correct in the

¹<https://www.raspberrypi.org/products/raspberry-pi-2-model-b/>

²http://www.navilock.de/produkte/G_61840/merkmale.html?setLanguage=en



Figure 3.1: Prototype of the sensing car, which is composed of a LIDAR Lite v3 optical distance sensor, a GPS receiver, a camera for ground truth collection and a Raspberry Pi as processing device.

range of 2.5 meters. The GPS receiver is mounted on the top of the sensing car using a magnet in order to receive more accurate sensor readings. The Navilock USB GPS sensor costs about €50.

Two major distance sensor technologies can be differentiated: an ultrasonic range sensor and an optical laser distance sensor. While ultrasonic sensors are cheap and widely used in commercial parking assistance systems, they also have limitations in terms of sensing frequency (about 20 Hz) and range (a few meters). These specifications limit the use of ultrasonic sensors for drive-by sensing on multi-lane roads or high speed. Due to these limitations an optical distance sensor, the "Lidar Lite v3"³ is used in our testbed. It measures the time of flight of an emitted laser signal which is reflected by an object in its way. The Lidar Lite v3 can measure distances from a few centimeters up to 40 meters at a frequency of 1 to 500 Hz. Furthermore, it is able to measure distances with an accuracy of about 2.5 centimeters. However, in comparison to ultrasonic sensors, optical sensors are more expensive. While the costs of ultrasonic sensors are often below €10, the Lidar Lite v3 and other comparable sensors cost about €150.

The distance sensor is mounted on the co-driver's door using a sucker handle in order to face the right side of the road and to take measures at about 62 cm above the ground. It is connected to the Raspberry Pi via GPIO (General Purpose Input Output) pins, communicating using an I2C (Inter Integrated Circuit) interface, according to the manufacturer's specifications.

³<https://www.sparkfun.com/products/14032>

	Ultrasonic Range Finder	Lidar Lite v3
Costs	from about €5,00 to €100,00	about €150,00
Sampling Frequency	up to 20 Hz (at 10 m distance)	up to 500 Hz
Range	2 cm - 10 m	30 cm - 40 m
Distance between Measurements at 50 km/h	about 70 cm	about 3 cm

Table 3.1: Comparison of ultrasonic sensors and the used Lidar Lite v3 optical distance sensor.

Table 3.1 shows a comparison of the characteristics of ultrasonic sensors and the Lidar Lite v3 sensor. The most significant limitation is the sampling frequency. While optical laser sensors are based on the speed of light, ultrasonic sensors are based on the speed of sound, which is much lower. Therefore, also the distance between consecutive measurements varies highly from an ultrasonic to an optical laser sensor. At a speed of 50 km/h, the distance between two consecutive measurements is up to 70 cm using an ultrasonic sensor while it is only about 3 cm when using an optical distance sensor.

A camera is leveraged to capture images of the ground truth, here, a Logitech C922 Pro Stream⁴ is used. Images with a resolution of 352 x 288 pixels are captured at a frequency of about 30 Hz while the car is sensing parking spaces. The camera is mounted on the co-driver's door on the same horizontal position as the sensor. This way the center of the image will be the position where the distance measurement is taken. The Logitech camera is connected to the Raspberry Pi using an USB port and is available at about €90.

3.2 Collecting Sensor Measurement Data

A Python script has been developed which saves all sensor readings during the test runs into a text file for later analysis and evaluation. Furthermore, all images captured by the camera are saved into a specific folder on the Raspberry Pi to be able to derive the ground truth information later on (see Section 4.1). The sensing of all three devices (GPS, Lidar Lite v3, Logitech camera) is performed asynchronously in separate threads so that none of them influence the other sensor's readings. For accessing the GPS

⁴<https://www.logitech.com/en-us/product/c922-pro-stream-webcam>



Figure 3.2: Acquiring raw sensor data.

receiver the Python GPS library is used whereas for measuring the distance using the Lidar Lite v3 sensor, an open source library available on [github.com](https://github.com/Sanderi44/Lidar-Lite) is used ⁵.

Figure 3.2 shows how the sensor data gets collected and furthermore presents a sample of raw sensor data derived during a test drive. The sensor data text file contains GPS and distance measurements. The first column contains the sensor type. The second column gives the time stamp of the Raspberry Pi's system time in seconds. GPS measurements also result in latitude, longitude and speed values while the Lidar Lite measurements result in the measured distance in centimeters.

3.3 Raw Data Set

To obtain a dataset, in total 32 test drives were completed in the city of Linz, Austria. The street scenarios have been selected aiming at a high variability of road scenarios. The test scenes include single lane as well as multi lane streets. While collecting the test measurements the sensing car was driving as it would in regular traffic (not only in the right most lane, etc.) and the scenes also include high and low traffic scenarios. For all street scenarios, measurements have been repeated multiple times. Figure 3.3 shows an aggregated GPS trace of all test drives on a map of Linz. Red dots represent parking cars while black dots represent other objects. In total **444.427 distance measurements** and **14.997 GPS measurements** were taken, which makes up about 15,9

⁵<https://github.com/Sanderi44/Lidar-Lite>



Figure 3.3: GPS trace of all recorded samples in the acquired dataset, while 32 test drives in Linz, Austria. Red dots represent parking cars.

megabytes of distance and GPS data. Additionally, **266.309 images** were captured to record the ground truth of the sensed scenes. The images, which make up about **5.072 megabytes**, are used to determine the ground truth of the recorded scenes. Sensed data and ground truth data are applied to supervised machine learning algorithms later on. Ground truth tagging is described in the following section.

Chapter 4

Data Processing and Machine Learning Approaches

This chapter describes all the steps which are necessary to prepare the raw dataset for the use in machine learning. The required steps include manual ground truth tagging (Section 4.1), data preprocessing (Section 4.2), and data segmentation (Section 4.3). Furthermore, the creation of the features for the dataset used in the machine learning experiments is described (Section 4.4) as well as the machine learning experiments including the experiment methods (Section 4.6). Finally, the use of parking space maps to improve classification results and acquiring these parking space maps is described in Section 4.8.

4.1 Ground Truth Tagging

The recorded raw dataset contains distance and position measurements as well as images showing the ground truth at a specific point in time. To be able to process the ground truth information included in the images, a manual ground truth tagging task has to be performed. Figure 4.1 shows the user interface of the program which has been implemented to manually tag an image with one of nine pre selected class labels. The file name of each image is the time stamp of the recording. After the images are loaded, the user has to tag the situation which is present at the center of the image (red line). For instance, Figure 4.1 shows a parking car at the center of the image. In addition, on the right side of the image, a car which has been overtaken by the sensing vehicle is also visible, but as it is not in the center, the image is labelled as "parking car". Possible class labels are:



Figure 4.1: User interface for manual tagging of parking situations. **To-Do:** crop

Parking car: A parking car is a non-moving vehicle which is parking at the right side of the road. There are three kinds of parking vehicles: *Parallel parking cars*, *perpendicular parking cars*, and *angular parking cars*. Figure 4.2 shows the different types of parking spaces.

Overtaking situation: This class label means that the sensing vehicle is overtaking another road vehicle. The user can choose between *overtaken cars*, *overtaken motorcycles* and *overtaken bicycles*.

Other parking vehicle: The user can also tag *parking motorcycles* and *parking bicycles*. This class represents obstacles which can be located on parking spaces and therefore make it unavailable for parking.

Free space: This class label should be used, when none of the above listed class labels are applicable. It represents a free space where it is maybe possible to park a vehicle. Yet only with the help of a parking space map, a free space can be marked as vacant parking space as a random free space may be an illegal parking space (e.g. a driveway).



Figure 4.2: Different types of parking cars.

The output of the ground truth tagging process is persistently saved as a text file where each line contains an entry with a time stamp and its corresponding tagged ground truth class label. This ground truth file will be further processed during the machine learning process as described in **To-Do: ref.**

4.2 Data Preprocessing

Before the raw dataset can be used to create the input features for machine learning models, a few preprocessing steps have to be taken. First of all, error values of the GPS sensor and the LiDAR Lite v3 sensor are deleted. The GPS sensor usually shows erroneous output (NaN values) when it starts sensing due to the fact that it is not yet connected to enough satellites. The distance sensor can provide overflow measurements when the target object is too far away or too close to the sensor. In both cases it will give an output of less than 10 centimeters. Furthermore, outliers where a single measurement differs greatly (more than 1 meter) from the enclosing measurements are also detected so that they won't cause over-segmentation in the data segmentation process (discussed in Section 4.3). All of the detected error/overflow/outlier measures will be simply deleted from the raw dataset before further processing to ensure the quality of the sensor measurements.

Another necessary preprocessing step is the filtering of standing situations of the car. For instance, when the sensing vehicle is waiting at a traffic light or in a traffic jam, such situations would not lead to meaningful samples for the machine learning process and would decrease the accuracy of the classification results. As the sensing vehicle stands still it measures the distance always to the same object on the right side for a long time and this way the features which are calculated as input for the machine learning process (described in Section 4.4) would may be misleading. Therefore, all



Figure 4.3: All sensor measurements are being merged to obtain a dataset where all samples are containing time, distance, location and ground truth information.

situations where the car is driving at a speed lower than 1 m/s are deleted from the dataset.

4.2.1 Sensor Measurement Interpolation

Due to the fact that all used sensors measure at different frequencies, the sensor data of all sensors has to be unified before the next steps can be taken. The distance sensor measures at a much higher frequency (about 100 Hz) than both the GPS sensor (about 1 Hz) and the camera (about 30 Hz). Therefore, the GPS location as well as the ground truth at each distance measurement have to be approximated. Linear interpolation using the timestamp of the measurements is being used to calculate the approximate location and ground truth at the times of all distance measurements. Figure 4.3 shows how the raw sensor data and the ground truth data get unified so that a list of data points containing distance, GPS position and ground truth can be derived.

4.3 Data Segmentation

As the used distance sensor measures at a high frequency, it usually collects several distance measurements belonging to the same object. For example, if the sensing vehicle passes a parallel parked car (having a length of 4 meters) at a speed of 30 km/h

it will collect approximately 24 measurements belonging to the passed car. To be able to automatically evaluate the performance of different approaches to sense parking cars and other objects the sensor measurements belonging to the same objects have to be grouped together. After the raw data points, which contain all information, are being derived by the preprocessing step, the segmentation process has to be performed, which groups similar consecutive data points together.

There are several strategies how sensor data can be segmented, for example using sliding windows. However, such approaches will not work accurate enough in the case of street side parking detection, as the objects which should be segmented range from a few centimeters to a length of tens of meters. Therefore, a new strategy to segment the sensor data points is proposed. The used segmentation algorithm searches for high frequent changes in the distance signal and starts a new segment everywhere where the distance difference between two consecutive measurements is above a certain segmentation threshold. Furthermore, if the timestamp of two measurements differ more than one second the start of a new segment will also be detected (this can be the case if the sensing vehicle was standing or driving at a very low speed and many measurements have been deleted in the preprocessing steps).

The best threshold to detect the segmentation points in the distance sensor signal has been identified by running several experiments with different thresholds and by manually reviewing the resulting segments for under- and over-segmentation. The resulting segmentation threshold turned out to be 1,05 meters. This means that if two consecutive measures differ more than 1,05 meters, the algorithm will assume that the sensor measurement belongs to a new object (e.g. a parking car or an overtaken car) and will detect a new segment.

Figure 4.4 shows an example of the segmentation process. All points represent distance measurements. The green points represent measurements belonging to a parking car whereas the yellow points show free space measurements. The lines represent detected segments which belong to the same object classes. Black lines represent free space and orange lines represent a parking car. Thus, the segmentation shown in Figure 4.4 has successfully detected three parking car- and two free space segments.

Another challenge of the segmentation task is to estimate the ground truth classes of the segments. So far, only each sensor reading got a ground truth class assigned. However, as described earlier, each segments consists of multiple sensor measurements and therefore it is possible that it also consists of multiple different ground truth classes. You can see this phenomenon in Figure 4.4 where both "Free space"-segments also have some measurements assigned which are marked as "Parking Car". To overcome this



Figure 4.4: Result of the segmentation algorithm. Three parking cars (green dots and orange lines) and two free space segments (yellow dots and black lines) have been detected.

problem, the segments are tagged with the label which is tagged in a majority of the sensor readings. This approach turned out to work well as in most cases only the first and last ground truth values are assigned wrong.

4.4 Feature Calculation

To conduct machine learning experiments with common machine learning models, feature values for each segment have to be computed using the sensor measurements. These feature values serve as input values of the machine learning model to help classifying the corresponding segment to one of the available class labels. All computed features which were used as input are:

Average distance to the sensing vehicle: The average of the segment's distance sensor measurements to the closest object on the right side of the road in meters.

Length: The distance the sensing vehicle drove during sensing the segment in meters (the distance between the first and last GPS location).

Duration: The duration in seconds the sensing vehicle needed to sense the segment (the last time stamp - the first time stamp).

Number of distance measurements: The number of distance measurements assigned to the segment.

Variance of the distance measurements: The variance of all distance measurements belonging to the segment.

Speed: The speed of the sensing vehicle while sensing the segment in m/s.

Acceleration: The acceleration of the sensing vehicle while sensing the segment in m/s^2 .

Distance difference to the next/previous segment: Difference of the average distance measurements to the next/previous segment in meters.

4.4.1 Feature Analysis

The goal of each feature is to help identify the true class of a sample which should be classified. The feature analysis presented in this section should determine if all features are necessary and beneficial to this goal. Too many features maybe do not produce better results and also increase the learning time of all models. Using the tool Weka¹ two analytic approaches have been used, which show for each feature how useful it is for the classification tasks:

Information Gain Analysis: Weka provides a tool called "InfoGainAttributeEval" which calculates the information gain (also known as entropy) of all the features for the classification task. The features which will contribute more to an accurate classification result will have a higher information gain than others. The resulting values are in the range of 0 to 1.

Learner based Feature Analysis: This approach tests several feature subsets on a real machine learning algorithm (a J48 decision tree is used) and identifies the best feature subset. The process is repeated with different training sets and counts how often the features are used in the different runs. If a feature is used in all runs it gets a value of 1 whereas if it is never used its value will be 0. So the higher the value is, the more the feature helps in the classification task.

Table 4.1 shows the results of the feature analysis process. Both results are showing that there are five important features, which provide the most value to classification

¹<https://www.cs.waikato.ac.nz/ml/weka/>

	Information Gain	Learning based Score
Average distance	0.361	1.0
Diff to next	0.232	1.0
Diff to prev.	0.233	1.0
Length	0.223	1.0
Nr of measures	0.178	1.0
Duration	0.175	0.2
Distance variance	0.055	0.0
Avg speed	0.019	0.3
Avg acceleration	0.011	0.1

Table 4.1: Feature analysis showing the information gain and learning based score of all calculated features.

(average distance, distance difference to next and previous segment, length and number of measurements). All of them have a high information gain and are used in all feature subsets which lead to the best results in the learning based analysis. The other four features (duration, distance variance, average speed and average acceleration) are only used in a minority of the feature subsets and also have lower information gain. This means that they won't contribute so much to a good classification result. However, these findings have to be confirmed by machine learning experiments later on.

4.5 Derived Dataset

After data preprocessing, data segmentation and feature calculation have been performed, the final dataset which is being used for the further machine learning is available. The dataset is made up of samples with all feature values described in the previous section and the corresponding class label. The dataset consists in total of **14.303 samples** which are composed of **11.811 free spaces**, **2.216 parking cars**, **207 overtaking situations** and **69 other parking vehicles**. Obviously, the dataset is highly imbalanced. About 82.6% of all samples are tagged as "free spaces" while only about 1.4% are tagged as "overtaking situations" and 0.5% as "other parking vehicles".

4.6 Machine Learning Experiments

There are a lot of different machine learning approaches, which can be chosen from. All of them have their strengths and weaknesses and are applied in different scenarios. To find out which machine learning model works best, experiments are being performed and the results are compared so that the best model can be identified. The overall goal of the experiments is to find the feature subset and the machine learning model which in combination produce the highest accuracy in classifying all segments.

4.6.1 Tested Machine Learning Models

This section will discuss all machine learning models which were investigated on their performance. Furthermore, also all parameters which could be set for the different machine learning models will be presented. The tested machine learning models are:

To-Do: passt hier eine kurze Beschreibung von den jeweiligen getesteten Algorithmen?
Soll ich da auch immer grundlegende Papers dazu zitieren?

Naive Bayes Classifier

Decision Trees

Random Forest Classifier

Neural Networks

kNN Classifier

Support Vector Machines

Ensemble Methods

4.6.2 Used Tools and Frameworks

4.6.3 Evaluation Method

Cross-Validation...

4.7 Deep Learning

Deep learning gained a lot of attention in the last few years because of its raising classification accuracy results. For example, deep learning models became the first classifiers which could compete with humans on simple classification tasks. A deep learning network is a special form of a neural network with a possibly large amount of hidden layers between the input layer and the output layer. Furthermore, in most applications raw sensor measurements are used as input instead of pre-computed feature values (which are derived from the raw sensor values). In theory, a simple neural network containing only one hidden layer can derive any function given enough hidden elements and long enough training time. However, that does not mean that such a simple neural network will find a optimal solution and that it will find it in a finite amount of time. Adding more hidden layers (to get a deep neural network) can help to find a solution more easily and with less training time. Figure 4.5 shows an example of a deep learning network with several hidden layers which are densely-connected.

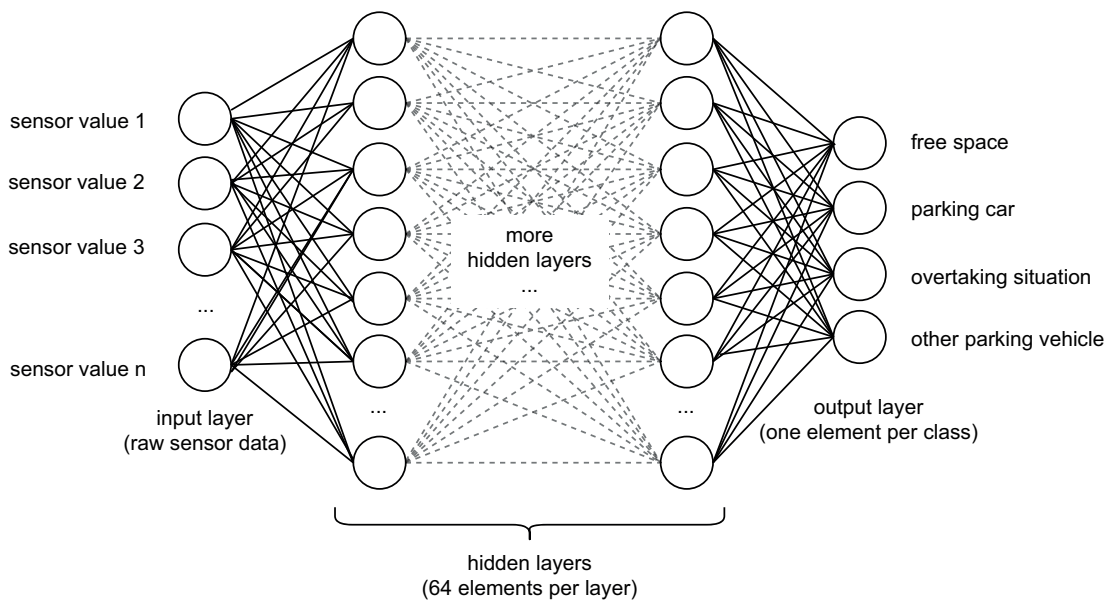


Figure 4.5: A basic deep learning network having sensor values as input and the probability of all classes as output values. All layers are densely connected with each other.

Due to the classification power, deep learning should also be tested for the use in classifying parking situations using our dataset. It should be investigated if deep learning can be used to do this kind of classification on raw sensor data and the results should be compared to classical machine learning algorithms (described in Section 4.6.1) using pre-computed feature values.

As input for the deep learning experiments a dataset containing all sensor measurements for each segment is needed. In a pre-processing step a dataset for the deep learning experiments is created which is made of a vector of sensor measurements for each segment. Each vector has a fixed size of 1024 sensor measurements (that will be enough for most segments). In most cases the segments have a much lower number of measurements. In these cases the measurements will be zero padded to the required size. If a segment has more than 1024 measurements, only the first 1024 will be used. This step is necessary to have a fixed length input for the experiments as the input size for all segments has to be equal. A vector represents the input layer of the neural network.

4.7.1 Tested Deep Learning Models

As baseline deep learning network a dense neural network with 5 hidden layers and 64 hidden elements per layer is used. This basic deep learning network should show how a

densely-connected deep learning model performs on the raw sensor dataset. Figure 4.5 shows the illustration of the created deep learning network containing of an input layer with 1024 elements (one for each sensor value), 5 hidden layers containing 64 hidden elements per layer and four output elements which calculate the probability of each class for the given input. The class which gets predicted is the one with the greatest probability out of the four classes.

In addition to the basic deep neural network, several known strategies should be tested to improve the performance of the deep learning approach. First of all, dropout between the layers should be tested. Dropout is a technique in deep learning to handle overfitting of the neural network. If dropout with a probability p is introduced between two layers, a connection between two elements is maintained only at a probability of $1 - p$. The result is a more sparsely connected deep neural network which should be less prone to overfitting. Dropout should be tested between several layers and with different values for the deletion-probability p .

Another popular technique to improve deep learning models is the use of convolution. Convolutional neural networks are especially popular for image classification. However, convolution can also be applied on the one-dimensional distance sensor data available in our dataset. Different configurations for the configuration of such a convolutional neural network should be tested and the performance should be compared to the other approaches.

To-Do: todo

To implement the deep learning models, the programming language Python² (version 3.6.4) is used as well as the TensorFlow framework³. TensorFlow is built for creating neural network models and especially for building deep learning models using a lot of pre-built components and easy readable syntax.

4.8 Parking Space Maps

When sensing a city's parking availability situation parking space maps are of great importance. As already discussed the machine learning models only classify road segments to "free spaces" (rather than "vacant parking spaces") which means that there are no parking cars and a car can possibly park there. However, parking space maps are necessary as it cannot be sensed if it is legal to park at a certain free space. For

²<https://www.python.org/>

³<https://www.tensorflow.org/>

example, a free space might just be a driveway or a bus station. Vacant parking spaces can be identified when their location is compared to a parking space map matching parking spaces there.

Furthermore, the use of parking space maps will also possibly improve the performance of the classification task. If only segments in areas where parking spaces are located are used as training set, the overall data will be much more balanced (there will be less "free space" segments, but still the same amount of parking cars) and moreover the machine learning model will only be trained with relevant samples as all samples which are not close to parking spaces won't be classified later on anyway.

4.8.1 Parking Space Map of Linz, Austria

As it is crucial to have accurate parking space maps, the goal was to obtain such maps for the area of the experiment. As a first try, the APIs of OpenStreetMap⁴ have been used to obtain map data of the city of Linz, Austria. The maps of OpenStreetMap are created and maintained by independent communities which operate in their free time. Parking spaces are available in the downloaded map data but unfortunately, only parking spaces of big parking lots (of shopping malls, etc.) are available but most of the city's road side parking spaces, which are being sensed in this work are not present. Therefore, the parking space maps of OpenStreetMap cannot be used due to insufficient data.

Another possibility to obtain a parking space map is to use data from city authorities in Linz. City authorities keep detailed digital maps of the streets as well as the road side parking spaces. However, the only format available are several DXF- or DWG-files, created using the program AutoCAD⁵, which is commonly used for designing and drawing as well as for geographical applications. There exist libraries which can read all components of DXF-files and their attributes but unfortunately there are no geographical position data attached to the components and therefore the GPS location of all parking spaces is unknown. Only an absolute coordinate from the drawing is available, but cannot be converted to a GPS location. This fact makes it impossible to use the parking space map in the park sensing prototype as the parking spaces of the map cannot be matched with the sensed segments obtained during the experiments.

⁴<https://www.openstreetmap.org>

⁵<https://www.autodesk.eu/products/autocad/overview>

4.8.2 Approximating Parking Space Maps

As parking space maps are unavailable in a sufficient quality from outside sources, an algorithm is introduced to derive a coarse parking space map from the dataset which was acquired during the test drives. The dataset contains the GPS positions of over 2.000 parking cars and most streets have been sensed several times. As of the limited amount of data, the goal is to create a coarse parking space map which contains areas where it is likely that vehicles park (parking zones).

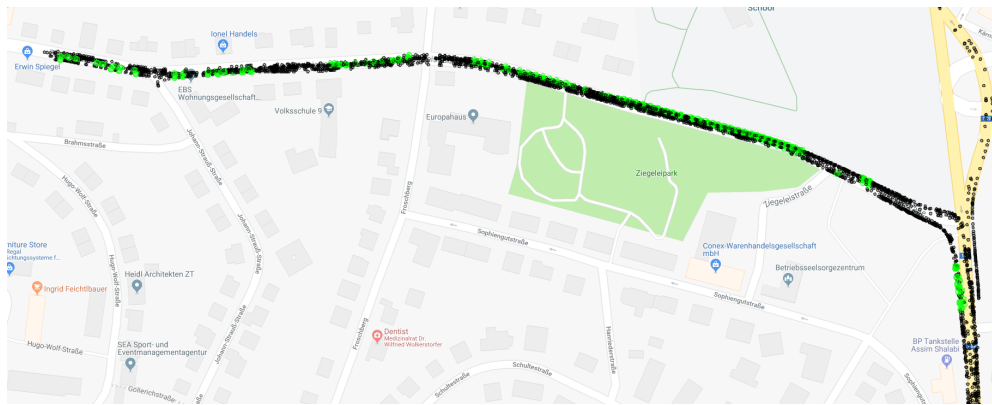
The proposed algorithm uses clustering to group parked cars to parking zones. The idea is that if there are several cars parking at the same location in several test drives then it is likely that there are parking spaces at that position. A DBSCAN⁶ clustering algorithm (part of the scikit learn⁷ python framework for machine learning) is being used to cluster the position of the parked cars. The DBSCAN algorithm searches for high density core samples and expands clusters from them. It takes the a similarity function which compares two data points and a minimum similarity as input parameters.

As similarity measure for the clustering algorithm a custom function has been implemented. Two parked cars are considered to be similar if the sensing car is driving in the same direction while sensing and if both cars are close to each other in terms of their GPS position. The check of the direction the sensing car is going while sensing is performed ensure that both compared parking cars are on the same side of the street. If the sensing vehicle is going in the opposite direction while sensing another parked car both cars will be at the same position but at the opposite side of the street. If the first check is passed, the similarity function will compute the distance in meters between the GPS positions of both parked cars which are compared. The described similarity function is used by the DBSCAN clustering algorithm to identify core samples and to cluster multiple parking cars to parking zones. The maximum distance between two cars to be considered to be similar is set to eight meters. If two parking cars are further apart they are not considered to be able to be in the same parking zone.

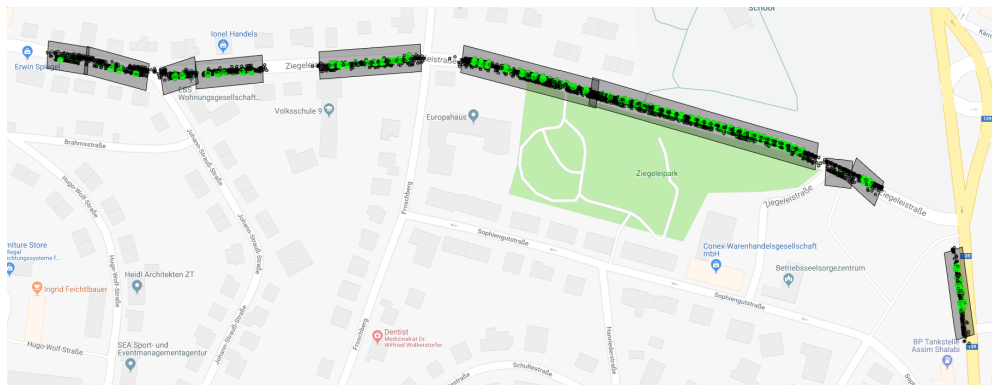
Figure 4.6 shows two images of the same test region in Linz, Austria. In (a) there are shown the GPS positions of all sensed segments which are part of the dataset, while in (b) only the GPS positions of segments which are in parking zones are shown. In both pictures green dots represent parking cars, while black dots show other segments. The semitransparent boxes which are shown in (b) show the clusters (parking zones) which were derived by the proposed algorithm. Only areas where there are lots of parking

⁶Density-Based Spatial Clustering of Applications with Noise - <http://scikit-learn.org/stable/modules/generated/sklearn.cluster.DBSCAN.html>

⁷<http://scikit-learn.org/>



(a) All GPS points



(b) Detected parking zones

Figure 4.6: Approximation of parking zones from the dataset. (a) is showing all GPS points at the selected region while (b) is showing the derived parking zones (clusters of parked cars).

cars are extracted to be parking zones. In total 131 parking zones are derived from the whole dataset containing 97.2% of all parking cars in the dataset. The remaining 62 parking cars are classified as noise by the clustering algorithm because there are no other parking cars in the dataset nearby. A bigger dataset with more test drives during different times would be needed to get a more accurate parking space map and to reduce the parking cars which are classified as noise.

4.8.3 Using Parking Space Maps to improve Classification Results

As already mentioned, it does not make sense to classify segments which are not close to parking zones. Such segments will not make a difference to the end result as it is known that at these positions parking is not possible (or legal) and thus the classification result will not make any difference. To improve the classification results, only segments which are close to parking zones will be used for training and for evaluating the machine learning models. The dataset, which is described in Section 4.5, is filtered by matching the GPS positions of the segments with the bounding boxes of the parking zones. All segments which are contained in at least one bounding box of a parking zone will remain in the dataset while all others are deleted.

The remaining filtered dataset is much smaller than the original one. In total it consists of 8.591 segments, which are composed of 6.345 free spaces, 2.131 parking cars, 55 overtaking situations and 60 other parking vehicles. This filtered dataset is much more balanced than the original one, because almost all of the parking cars are still included while approximately half of the free spaces, which has been the dominating class, is deleted. Usually the more balanced dataset will lead to better values of precision and recall of the parking car class, but this has to be confirmed in the machine learning experiments. The results of the classification task using the parking space map filtered dataset can be found in Section **To-Do: ref.**

Chapter 5

Results and Discussion

Description of chapter...

5.1 Machine Learning Results

This section discusses the results of the machine learning experiments with common machine learning models using computed feature values as input. As evaluation-method 10-fold cross validation has been chosen. Figure ... shows the comparison of several machine learning models with different parameters in terms of accuracy, precision and recall of the "parking car"-class and the necessary runtime to learn the model.

Comparison of all tested algorithms -> accuracy -> different feature sets -> Graphics

Description of Graphic

Maybe binary classification

Filtered Dataset -> Parking Space Maps

Stacked Classifier

5.2 Deep Learning Results

Same as Machine Learning REsults

5.3 Comparison to ParkNet

Using only the two features used in ParkNet - Which accuracy can be reached on our dataset.

ca 75% recall and precision using ParkNet-approach

Chapter 6

Conclusions and Future Work

Bibliography

- [1] G. Amato, F. Carrara, F. Falchi, C. Gennaro, and C. Vairo. Car parking occupancy detection using smart camera networks and deep learning. In *2016 IEEE Symposium on Computers and Communication (ISCC)*, pages 1212–1217, June 2016.
- [2] Katy Blumer, Hala R. Halaseh, Mian Umair Ahsan, Haiwei Dong, and Nikolaos Mavridis. *Cost-Effective Single-Camera Multi-Car Parking Monitoring and Vacancy Detection towards Real-World Parking Statistics and Real-Time Reporting*, pages 506–515. Springer Berlin Heidelberg, Berlin, Heidelberg, 2012.
- [3] F. Bock, D. Eggert, and M. Sester. On-street parking statistics using lidar mobile mapping. In *2015 IEEE 18th International Conference on Intelligent Transportation Systems*, pages 2812–2818, Sept 2015.
- [4] J. Canny. A computational approach to edge detection. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, PAMI-8(6):679–698, Nov 1986.
- [5] V. Coric and M. Gruteser. Crowdsensing maps of on-street parking spaces. In *2013 IEEE International Conference on Distributed Computing in Sensor Systems*, pages 115–122, May 2013.
- [6] Daniele Di Mauro, Sebastiano Battiato, Giuseppe Patanè, Marco Leotta, Daniele Maio, and Giovanni M. Farinella. *Learning Approaches for Parking Lots Classification*, pages 410–418. Springer International Publishing, Cham, 2016.
- [7] R. C. Gonzales and R. E. Woods. *Digital Image Processing*. 2002.
- [8] Giulio Grassi, Kyle Jamieson, Paramvir Bahl, and Giovanni Pau. Parkmaster: An in-vehicle, edge-based video analytics service for detecting open parking spaces in urban environments. In *Proceedings of the Second ACM/IEEE Symposium on Edge Computing, SEC '17*, pages 16:1–16:14, New York, NY, USA, 2017. ACM.

- [9] Han Hao, Yong Geng, and Joseph Sarkis. Carbon footprint of global passenger cars: Scenarios through 2050. *Energy*, 101(Supplement C):121 – 131, 2016.
- [10] Texas Transportation Institute. Urban mobility report. 2007.
- [11] Ho Gi Jung, Dong Suk Kim, Pal Joo Yoon, and Jaihie Kim. Parking slot markings recognition for automatic parking assist system. In *2006 IEEE Intelligent Vehicles Symposium*, pages 106–113, 2006.
- [12] N. Kaempchen, U. Franke, and R. Ott. Stereo vision based pose estimation of parking lots using 3d vehicle models. In *Intelligent Vehicle Symposium, 2002. IEEE*, volume 2, pages 459–464 vol.2, June 2002.
- [13] J. Liu, M. Mohandes, and M. Deriche. A multi-classifier image based vacant parking detection system. In *2013 IEEE 20th International Conference on Electronics, Circuits, and Systems (ICECS)*, pages 933–936, Dec 2013.
- [14] Shuo Ma, Ouri Wolfson, and Bo Xu. Updetector: Sensing parking/unparking activities using smartphones. In *Proceedings of the 7th ACM SIGSPATIAL International Workshop on Computational Transportation Science, IWCTS '14*, pages 76–85, New York, NY, USA, 2014. ACM.
- [15] Suhas Mathur, Tong Jin, Nikhil Kasturirangan, Janani Chandrasekaran, Wenzhi Xue, Marco Gruteser, and Wade Trappe. Parknet: Drive-by sensing of road-side parking statistics. In *Proceedings of the 8th International Conference on Mobile Systems, Applications, and Services, MobiSys '10*, pages 123–136, New York, NY, USA, 2010. ACM.
- [16] Anandatirtha Nandugudi, Taeyeon Ki, Carl Nuessle, and Geoffrey Challen. Pock-
etparker: Pocketsourcing parking lot availability. In *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing, UbiComp '14*, pages 963–973, New York, NY, USA, 2014. ACM.
- [17] Sarfraz Nawaz, Christos Efstratiou, and Cecilia Mascolo. Parksense: A smartphone based sensing system for on-street parking. In *Proceedings of the 19th Annual International Conference on Mobile Computing & Networking, MobiCom '13*, pages 75–86, New York, NY, USA, 2013. ACM.
- [18] Vehicle Sense. <http://www.vehiclesense.com> (accessed on november 9th). 2017.

-
- [19] SFMTA. <http://sfpark.org> (accessed on november 9th). 2017.
 - [20] Jae Kyu Suhr, Ho Gi Jung, Kwanghyuk Bae, and Jaihie Kim. Automatic free parking space detection by using motion stereo-based 3d reconstruction. *Machine Vision and Applications*, 21(2):163–176, Feb 2010.
 - [21] Jin Xu, Guang Chen, and Ming Xie. Vision-guided automatic parking for smart car. In *Proceedings of the IEEE Intelligent Vehicles Symposium 2000 (Cat. No.00TH8511)*, pages 725–730, 2000.
 - [22] N. R. N. Zadeh and J. C. D. Cruz. Smart urban parking detection system. In *2016 6th IEEE International Conference on Control System, Computing and Engineering (ICCSCE)*, pages 370–373, Nov 2016.