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VEHICLE SPEED MEASUREMENT USING STEREO CAMERA PAIR
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PHD THESIS SUMMARY
TEZE DISERTAČNÍ PRÁCE – AUTOREFERÁT

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Abstract

This thesis aims to answer the question whether it is currently possible to autonomously measure the speed of vehicles using a stereoscopic method with the average error within ± 1 km/h, the maximum error within ± 3 km/h, and the standard deviation within ± 1 km/h. The error ranges are based on the requirements of the OIML whose Recommendations serve as templates for metrological legislations of many countries. To answer this question, a hypothesis is formulated and tested. A method that utilizes a stereo camera pair for vehicle speed measurement is proposed and experimentally evaluated. The experiments show that the technique overcomes state-of-the-art results with the mean error of approximately 0.05 km/h, the standard deviation of less than 0.20 km/h, and the maximum absolute error of less than 0.75 km/h. The results are within the required ranges, and therefore the formulated hypothesis holds.

Abstrakt

Tato práce se snaží najít odpověď na otázku, zda je v současnosti možné autonomně měřit rychlost vozidel pomocí stereoskopické měřící metody s průměrnou chybou v rozmezí ± 1 km/h, maximální chybou v rozmezí ± 3 km/h a směrodatnou odchylkou v rozmezí ± 1 km/h. Tyto rozsahy chyb jsou založené na požadavcích organizace OIML, jejichž doporučení jsou základem metrologických legislativ mnoha zemí. Pro zodpovězení této otázky je zformulována hypotéza, která je následně testována. Metoda, která využívá stereo kameru pro měření rychlosti vozidel je představena a experimentálně vyhodnocena. Výsledky pokusů ukazují, že tato metoda překonává výsledky dosavadních metod. Průměrná chyba měření je přibližně 0.05 km/h, směrodatná odchylka chyby je menší než 0.20 km/h a maximální absolutní hodnota chyby je menší než 0.75 km/h. Tyto výsledky jsou v požadovaném rozmezí a potvrzují tedy testovanou hypotézu.

Contents

Chapter 1

Introduction

The speed of a moving vehicle directly influences both the risk of a crash and the severity of its consequences. To minimize this risk and thus to increase the road traffic safety, the law imposes speed limits that should ensure that in the event of a crash, impact energies remain below the threshold likely to produce either death or serious injury.

The threshold value usually depends on the most probable crash scenario which varies with road location. In residential and high pedestrian traffic areas, it is often around 30 km/h. In cities or areas with a higher probability of side impact of vehicles and with a lower amount of pedestrian traffic, it is around 50 km/h. And for highways, where rear-end collisions are prevalent it is around 130 km/h [3, 6, 11].

In order for the speed limits to be effective in increasing road safety, they need to be enforced. The success of the enforcement depends on the ability of empowered authorities to accurately measure the speed of passing vehicles. While various measurement devices exist, only those that comply with metrological legislation implemented in a given country can be used for the enforcement.

The metrological legislation of individual countries defines the requirements in terms of working conditions, measurement range, precision, and accuracy which every speed measurement device has to meet. Before the device is approved and certified, it typically undergoes laboratory and field tests which verify that the device is able to provide reliable measurements within given tolerances. For countries that base their metrological legislation on recommendations of the International Organization of Legal Metrology, the maximum allowable errors for laboratory tests are ±1 km/h for reference speeds up to 100 km/h and ±1 % for greater speeds. For field tests, the maximum allowable errors are ±3 km/h for reference speeds up to 100 km/h and ±3 % for greater speeds. Additionally, the average error during the field test should be within ±1 km/h. If the device is to work autonomously, it has to also meet the field test tolerances with 99.8 % probability. Therefore, if the distribution is Normal, the standard deviation should not exceed 1 km/h.

The main scientific goal of the thesis is the answer to the question of whether it is currently possible to autonomously measure the speed of vehicles using a stereoscopic method with the average error within ± 1 km/h, the maximum error within ± 3 km/h, and the standard deviation within ± 1 km/h. The error ranges are based on the requirements of the OIML whose Recommendations serve as templates for metrological legislations of many countries. The devices that would use the measurement method whose error is within the specified ranges could receive proper certification and be used for speed limits enforcement. This question is answered using the newly proposed stereoscopic vehicle speed measurement method that exploits novel stereo camera pair calibration approach and overcomes the current state-of-the-art techniques.

Chapter 2

Vehicle speed measurement

The speed of a vehicle can be measured by various devices that can be divided into two classes according to the intrusiveness of their installation. The devices that belong to the first class have to be embedded into or placed onto the road, and because of that, they are classified as intrusive. The devices that belong to the second class are placed above or by the side of the road, and because of that, they are labelled as non-intrusive. Only the devices that pass the tests specified by local metrological legislation can be officially used for vehicle speed measurement.

Intrusive technologies

Pneumatic tube detectors, inductive loops, magnetic and weigh-in-motion sensors belong to the intrusive category. Although the devices are accurate, and by themselves low cost, they need to be placed either on the road surface or embedded directly into it. Their installation and maintenance are therefore problematic and expensive because they usually require lane closure, which disrupts the traffic, and a pavement cut with a subsequent repair or resurfacing of the road. The devices detect the presence of the vehicles; therefore, at least two sensor pieces at a known distance apart are needed for the speed measurement. They are also insensitive to the weather as they are located in close proximity to passing vehicles.

Non-Intrusive technologies

Ultrasonic sensors, infrared sensors, laser detectors, radars, and camera-based technologies belong to the non-intrusive category of technologies. The non-intrusive devices represent an emergent field that expands rapidly with rising computational power and continuing advances in signal processing. Their main advantage is that they are placed either above the road or by its side, which makes their installation and maintenance easier and cheaper in comparison with the intrusive technologies. The low costs of their installation and maintenance at least partially offset the higher initial costs. The higher initial costs, weather susceptibility, and lower accuracy are their main disadvantages when compared to the intrusive devices.

Metrological legislation

In order for the device to be recognized as a measurement device, it has to meet the requirements of the metrological legislation and pass the specified tests. The metrological legislations vary by country, and it is not possible to review them all within the scope of this thesis. Fortunately, many countries based their local metrological legislation on the Recommendations published by the International Organization of Legal Metrology[1].

The OIML publish several types of documents. The model regulations for a number of categories of measuring instruments

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[1] `https://www.oiml.org/` (OIML)

are published as the Recommendations documents. The Member States are morally obliged to implement the model regulations as far as possible. The Recommendation that describes the requirements of the vehicle speed measurement devices is focused on the radar measuring equipment [7]. Nonetheless, the general requirements and principles of this Recommendation are usually utilized for other types of vehicle speed measuring equipment as well.

Apart from the construction and protection requirements, the documents describe the process of pattern approval. The pattern approval process consists of several tests that check the ability of the device to provide reliable measurements within an acceptable error range under different conditions. The device under test shall provide the measurement range that includes at least the range from 30 km/h to 150 km/h. The laboratory test is performed in a controlled condition environment. The measurement error for the laboratory test should be less than ± 1 km/h, or ± 1 % at speeds above 100 km/h. The tests of the effects of influence factors and disturbances test the mechanical and climatic resistance and the reliability of electronic and logical components.

The metrological field test is performed in actual traffic. During this test, 500 measurements are made, of which none should give a positive error larger than + 3 km/h, or + 3 % at speeds above 100 km/h. The average error of all results should be within ± 1 km/h. The device does not need to provide measurement for every passing car. If the measurement is recognized as faulty, it can be discarded. For the autonomous devices, the recognition and the discarding of the faulty measurements have to be done automatically by the device itself. For the manually operated devices, the decision can be made by the operators. Additionally, the autonomously operated devices shall provide a high level of confidence that the measurement error is within the permissible limits. That is, the autonomous devices have to meet the field test error tolerances with 99.8 % probability. Therefore, under the assumption of Normal distribution, the standard deviation of errors

Table 2.1: Error requirements on the vehicle speed measuring devices according to the OIML Recommendation [7].

		Lab. test	**Field test**
Max. error range	<= 100 km/h	± 1 km/h	<= 3 km/h
	> 100 km/h	± 1 %	<= 3 %
Mean error range	<= 100 km/h	-	± 1 km/h
	> 100 km/h	-	± 1 %
Stdev (autonomous)	<= 100 km/h	-	< 1 km/h
	> 100 km/h	-	< 1 %

have to be less than 1 km/h. All measured speeds are compared to the ground truth measurements provided by a device that has uncertainty better than one-third of the device under the test; 99.8 % of the reference device results should have errors that are within ± 1 km/h, or ± 1% at speeds above 100 km/h. The laboratory and field test error requirements are summarized in Table 2.1.

The document [14] is a part of the metrological legislation of the Czech Republic. It can serve as an example of how the recommendations of the OIML might be incorporated to metrological legislation of its Member States. Some requirements in this documents are stricter, for example, the required measurement range is extended to at least 200 km/h and the maximum negative error during field test is also specified and should not be larger than -3 km/h, or - 3 % at speeds above 100 km/h. The scope of the document is also not limited to radar equipment only, but it is extended to all speed measuring devices. Although the metrological legislation of individual countries might be a bit stricter, the compliance with the OIML's recommendations is a good starting point for any vehicle speed measuring device.

Chapter 3

Stereoscopic measurement and calibration methods

This chapter presents the most relevant state-of-the-art methods that exploit stereo camera pairs for vehicle speed measurement and long-distance calibration.

Vehicle speed measurement methods

Stereovision-based methods for vehicle speed measurement usually assume synchronized cameras previously calibrated using already established methods. Their most important parts deal with feature point selection and correspondence search. Only three papers that use a stereo camera pair for vehicle speed measurement exist to the extent of my knowledge. All three works are from recent years which signifies a growing interest in this type of vehicle spot speed measurement.

Jalalat et al. [2] use a vertical stereo setup pre-calibrated using a chessboard pattern [13]. After background subtraction in a selected ROI, they detect and track vehicles using a Viola-Jones cascade classifier and Kalman filter. The feature points are selected by uniform sampling in the lower part of a detection bounding box and corresponding points are found with sub-pixel precision by exploiting the single-step DFT technique. The average vehicle speed is expressed in terms of distance travelled, computed from triangulated vehicle positions, per time between two frames. They report the speed measurement error as an arithmetic mean of absolute error percentages compared to reference measurements by Fama Laser III. The worst mean percentage error was 3.3 %. The absolute error was not reported.

El Bouziady et al. [1] use a horizontal stereo laboratory pre-calibrated setup. After background subtraction, vehicles are detected and tracked as convex blobs. The SURF detector and descriptor is used to select the important points on the vehicle and to find the point correspondences. They computed the average speed in the same fashion as Jalalat et al. [2]. They compared the measured speed with ground truth obtained from a GPS. The result was a mean squared error of 1.67 km/h on a dataset with a speed range of 60-90 km/h and 2.33 km/h on a dataset with a speed range of 90-120 km/h. The maximum absolute error was 2 km/h common for both datasets.

Yang et al. [12] use a horizontal stereo setup calibrated using Zhang's method [13]. They detect license plates using a single shot multibox detector. License plate tracking and feature point extraction and matching are done using speed up robust features (SURF). They retain only those feature point pairs that lie near the centre of the detected license plate. These points are then triangulated and their distance to the camera on the left is computed. The triangulated points whose absolute distance z-score is greater than one are filtered. Of the remaining points, the one that is closest to the centre of the license plate is considered as the exact spatial location of the target vehicle in the current stereo frame pair. Using the spatial locations of the vehicle in two frames they compute the average speed in the same fashion as in previous works [2] [1]. They compared the measured speed with the ground truth obtained from a professional satellite speed meter. Their dataset contained 4 vehicle passes with a speed range of between 20 and 50 km/h. The mean error was 0.02 km/h, mean squared error was 0.42 km/h, the maximum absolute error was 1.6 km/h with a maximum percentage error of 3.8 %.

Long-distance calibration methods

In order to provide reliable measurements, the stereo camera pairs need to be calibrated. The calibration process of traffic surveillance cameras has specific challenges and complications. The traditional approaches that involve calibration patterns cannot be easily used after the cameras were installed because cameras are usually focused on a long shot and mounted on hardly accessible locations. The calibration in laboratory conditions prior to installation is also not suitable because the extrinsic parameters and focus are likely to change during the transportation or the installation. This section presents two existing methods for calibration of a stereo camera pair that is focused on a long distance.

Shang et al. [8] presented a method that addresses a task of calibrating the cameras that are focused on a long distance with a large field of view. Their method relies on several control points which lie on approximately the same plane as the cameras' optical centers. They evaluated their method by comparing the computed positions of six control points to the ground truth positions measured by a total station. The points were at a distance between 50 to 70 m from stereo camera pair whose baseline was 30 m. The mean inter-point distance error was 0.008 m with the standard deviation of 0.04 m.

Tian et al. [10] presented a two-step method with a similar approach as Shang et al. In the first step, they manually adjust the cameras in such a way that both their optical centers lie in the same plane with the two calibration points. In the second step, they add another calibration point and estimate the intrinsic parameters. For evaluation, they utilized the task of measuring the position of a UAV (unmanned aerial vehicle). They randomly selected eight positions for which the ground truth data was provided by a total station. The UAV flew at a distance of approximately 90 m from the stereo camera pair whose baseline was 79.88 m. The mean inter-point distance error was 0.0062 m with the standard deviation of 0.0332 m.

Chapter 4

Proposed method for vehicle speed measurement

The current state-of-the-art vehicle speed measurement methods do not achieve the results that are within the ranges required for the autonomous measurement devices by the OIML Recommendation. This chapter presents a novel method for vehicle speed measurement using a stereo camera pair that is used in the following chapter to experimentally test the following hypothesis:

It is possible to measure the speed of vehicles using a stereoscopic method with the average error within ± 1 km/h, the maximum error within ± 3 km/h, and the standard deviation within ± 1 km/h.

The hypothesis assumes Normal error distribution. The error ranges are based on the field test requirements of the OIML Recommendation. Because the proposed measurement method requires a calibrated stereo camera pair and because the calibration of traffic surveillance cameras is a challenging task, this chapter also describes a novel method for stereo camera pair calibration that is suitable for traffic surveillance applications. Both methods were submitted to peer-reviewed journals [5, 4].

Vehicle speed measurement proposal

The equipment setup suitable for the proposed method consists of a synchronized and calibrated pair of two identical cameras with the same focal length. The proposed method exploits a stereo camera pair already calibrated with known calibration features (calibration error) and relies on existing algorithms of license plate detection. The performance of the license plate detection algorithm affects only the fact whether the speed measurement is performed at all, but does not affect its precision. First, the vehicles passing in front of the stereo pair in the series of frames are localized using their license plate co-ordinates. Consequently, the vehicle position is triangulated in the series of stereo images forming a trajectory using the information known about the stereo setup and the calibration information. Finally, once the trajectory and its individual points are known, the speed (and also acceleration along the trajectory) is computed. An overview of the proposed method is shown in Fig. 4.1.

Stereo camera pair calibration proposal

The proposed method is suitable for the calibration of a synchronized stereo camera pair device that will look over a road section with passing vehicles. In order to calibrate the device, both camera matrices need to be estimated. The method splits the sought parameters to two groups. The first group consists of the parameters that can be estimated prior to the device installation. Their values are determined during an off-site calibration. The second group contains parameters that have to be estimated after the installation of the device. These are the external camera parameters and focal lengths. Their values are determined during an on-site

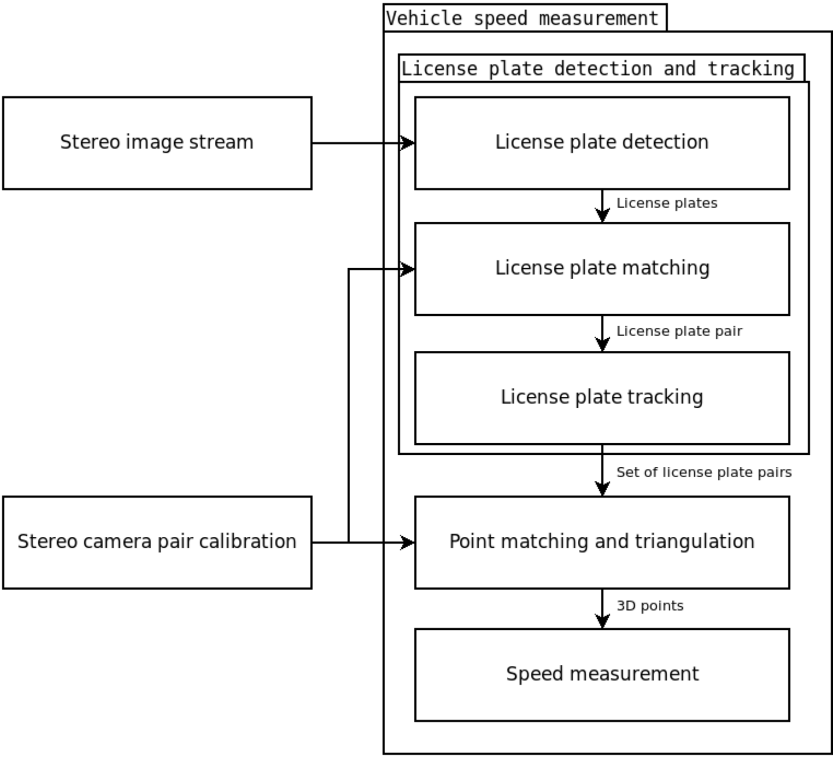

Figure 4.1: Overview of the proposed method. Vehicle trajectory is represented using a set of license plate pairs that are extracted from input stereo images. Several points are triangulated along the trajectory using known calibration parameters. Model of vehicle motion is fitted to the triangulated points in order to measure the vehicle speed.

calibration which utilizes calibration vehicles. An overview of the proposed calibration method is shown in Fig. 4.2.

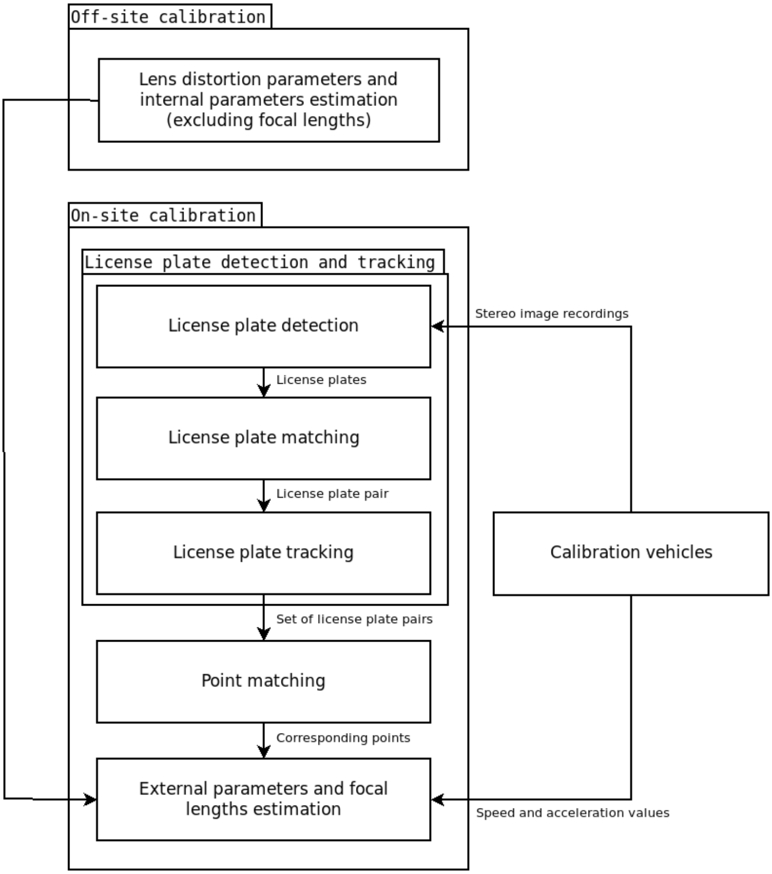

Figure 4.2: Overview of the proposed calibration method. Off-site calibration is performed first. For the on-site calibration, the calibration vehicles with known speed and acceleration are recorded. Their trajectories represented by a set of license plate pairs are extracted from the input stereo image stream. Several corresponding points are identified along the trajectories. The corresponding points, the known speed and acceleration of the calibration vehicles and the off-site calibration results are used to complete the on-site calibration.

Chapter 5

Experimental results of the proposed method

This chapter describes experiments that evaluate the novel measurement method with exploitation of the newly proposed calibration approach. The experiments utilize prototype hardware that is introduced in the first section of this chapter. Using the prototype hardware, a dataset that contains passing vehicles is recorded. The dataset and the reference data for the experiments are described in the second section.

The first experiment tests the presented hypothesis by evaluating the proposed method for vehicle speed measurement. The design of the experiment is similar to the design of the metrological field tests. In this experiment, the speed measurement error is computed from the speeds that are measured by the proposed method and the reference speeds. The results are compared to the existing stereo-based methods. The hypothesis holds if the maximum error, the mean error, and the standard deviation of error are within the ranges it specifies.

The second experiment evaluates the proposed stereo camera pair calibration method. In this test, the stereo camera pair is calibrated by the proposed method and utilized for the measure-

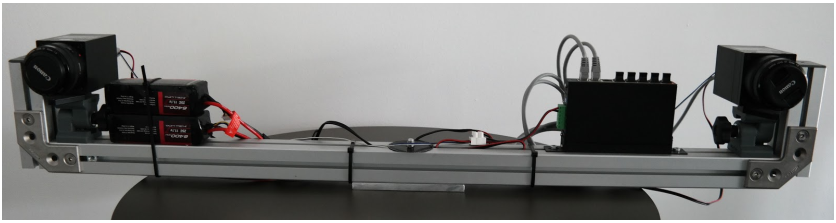

Figure 5.1: The stereo camera pair setup. Two cameras, ethernet switch, and two batteries mounted on an aluminium profile.

ment of distances that vehicles travelled between two consecutive frames. The measured distances are compared to the reference distances from the dataset, and the distance measurement error is reported. The results are compared to the existing stereo camera pair calibration methods.

Prototype hardware

The prototype hardware (see Fig. 5.1) consists of two custom made cameras mounted parallelly on a 1 m long aluminium profile placed on a sturdy tripod. The cameras are fitted with PYTHON 1300 global shutter CMOS image sensors and 35mm fixed focal length lens, which is positioned is a such a way that its principal axis is perpendicular to the sensor plane and intersects it at a sensor centre. The image sensors have 0.0048 mm x 0.0048 mm square pixels and provide monochrome 1280x1024 px images. Raw image data is streamed at a rate of 20 frames per second through a gigabit ethernet switch to a computer where the images are JPEG compressed and stored for further processing. The shutters of the cameras are synchronized using an external trigger with one camera being the master who sends the trigger signal to the second camera. The cameras and the switch are supplied power from two 6400mAh LiPo batteries attached to the profile.

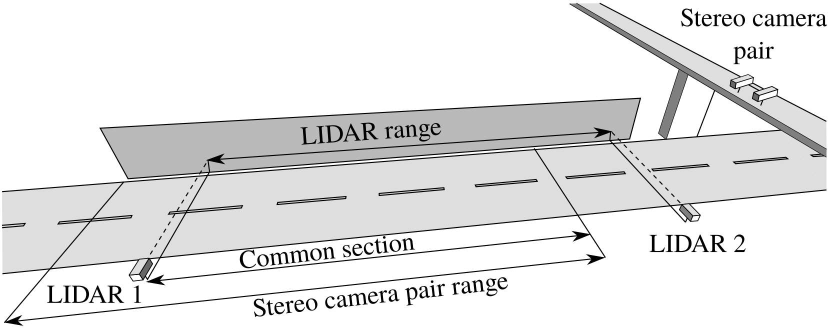

Figure 5.2: Schematic drawing of the relative positions of the sensors, their ranges, and their common area.

Dataset and reference data

For the purpose of evaluation, a dataset was recorded using the above-mentioned hardware. The whole dataset was recorded during a single session lasting approximately 40 minutes. During this session, 698 vehicle passes in two lanes were recorded. The left lane (from the point of view of cameras) is visible in full on both cameras while the right lane is only partially visible. The camera setup was placed on a footbridge across the road looking from above towards the incoming vehicles. Out of the 698 recorded vehicle passes, 44 were used for the on-site calibration of stereo camera pair and the remaining 654 were used for the testing.

To obtain the reference data, the same approach as Sochor et al. [9] was employed. Two LIDARs (LaserAce®IM HR 300) were placed at the same height parallelly to each other and perpendicularly to the street. The distance *D* between the LIDARs was 28.05 metres, and they were synchronized by the GPS time (Leadtek LR9540D). The distance and time data from both LIDARs were logged and processed separately. From the logged data, the processing algorithm calculated for each vehicle its immediate speed

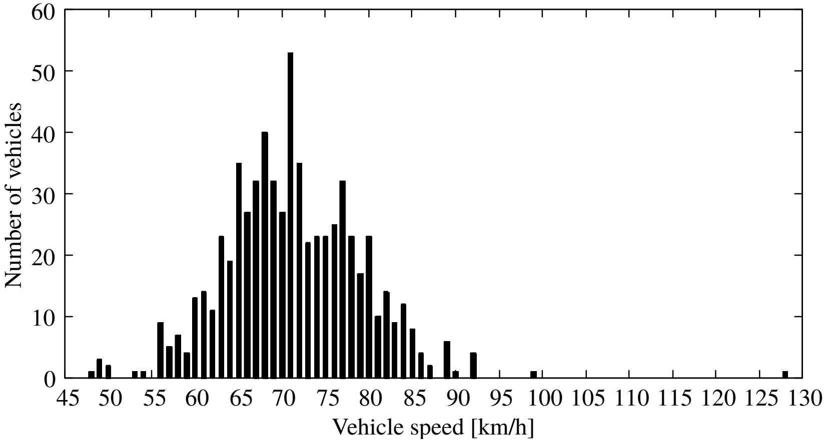

Figure 5.3: Histogram of reference average speeds.

when entering the first and the second laser, its average speed on the distance D, its average acceleration, and its length. For more detail about the measurement process, reference data calculation, and the discussion of measurement error, see Sochor et al. [9].

Vehicle speed measurement

The reference data for the vehicle speed measurement experiment are the average speeds obtained from LIDARs. The reference average speeds are compared to the average speeds measured by the proposed method. However, these values are comparable if and only if they were both measured over the same section of the road. As the section of the road covered by the two LIDARs and the section of the road in the view of the stereo camera pair do not fully overlap, the reference and the measured average speeds are not directly comparable and need to be adjusted so that the road section, where the speed is measured, is common for both setups. The common section starts at the point where the vehicle enters the first LIDAR and ends at the point where the last vehicle

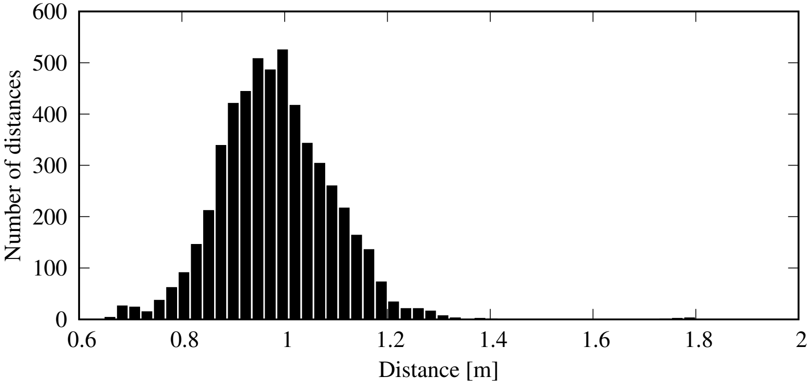

Figure 5.4: Histogram of reference distances measured by the two LIDARs.

license plate is recorded by both cameras (see Fig. 5.2). Because the cameras and LIDARs are time-synchronized, their timestamps can be utilized as a common ground for such an adjustment. The histogram of reference average speeds is shown in Fig. 5.3.

Stereo camera pair calibration

The reference data for the stereo camera pair experiment are the distances that vehicles travelled between two consecutive frames. The histogram of reference distances is shown in Fig. 5.4. The mean distance is 0.982 m and the standard deviation is 0.108 m. The maximum distance is 1.783 m and the minimum is 0.665 m.

Results

This section presents the results of both experiments.

Vehicle speed measurement

The accuracy and precision of the speed measurement were evaluated using the above-mentioned dataset. The speed is measured for 653 of a total of 654 recorded vehicles. One measurement is missing because the license plate detector failed to detect the vehicle license plate. Detailed results for all vehicles in the dataset can be accessed online[1]. From the measured values, the measurement error was computed as:

$$e = v_m - v_d, \tag{5.1}$$

where v_m is average speed measured using the proposed method and v_d is reference average speed from the dataset. For the histogram of the speed measurement errors, see Fig. 5.5. Overall, the measured speed has a maximum negative error of -0.56 km/h and a maximum positive error of 0.72 km/h. The mean error is -0.05 km/h with a standard deviation of 0.20 km/h. The mean absolute percentage error is 0.23 % and maximum percentage error is 1.11 %. As all the error statistics are within the field test ranges recommended by the OIML for the autonomous measurement device, the described method should comply with the metrological legislations that are based on the OIML recommendations or those that have less strict error requirements. The presented hypothesis therefore holds.

The speed measurement errors are compared with three other stereo-based vehicle speed measurement methods, namely, Jalalat et al.'s method [2], El Bouziady et al.'s method [1], and Yang et al.'s method [12]. The error comparison is shown in Table 5.2. For the datasets comparison see Table 5.1.

Stereo camera pair calibration

The accuracy and precision of the presented calibration method were evaluated on a distance measurement task using the above-

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[1] `http://www.stud.fit.vutbr.cz/~xnajma00/results.json`

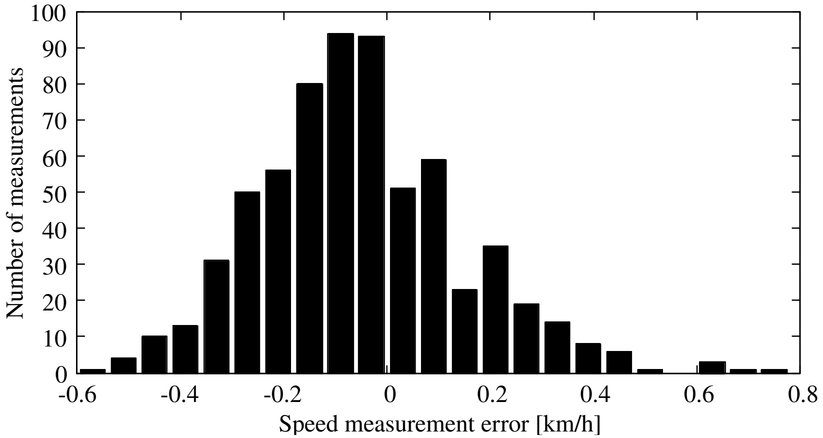

Figure 5.5: Histogram of speed measurement errors.

mentioned dataset. The distances that vehicles travelled between two consecutive frames are computed in several steps.

First, the License plate detection and matching and the License plate tracking steps from the on-site calibration part are applied to a vehicle record in order to extract a set of license plate pairs detected along the vehicle trajectory. Then, the algorithm transforms the set of license plate pairs to a set of license plate pair couples where each license plate pair couple represents a part

Table 5.1: Dataset comparison of stereo-based vehicle speed measurement methods.

	Dataset size	Number of different vehicles
Jalalat et al. [2]	441	441
El Bouziady et al. [1]	12	6
Yang et al. [12]	56	2
Proposed method	**653**	**653**

Table 5.2: Error comparison of stereo-based vehicle speed measurement methods.

	MSE [km/h]	STDEV [km/h]	Max abs. err. [km/h]	Max perc. error [%]
Jalalat et al. [2]	NA	NA	NA	3.3
El Bouziady [1]	2.33	NA	2.00	NA
Yang et al. [12]	0.42	NA	-1.60	3.80
Proposed	**0.04**	**0.19**	**0.72**	**1.11**

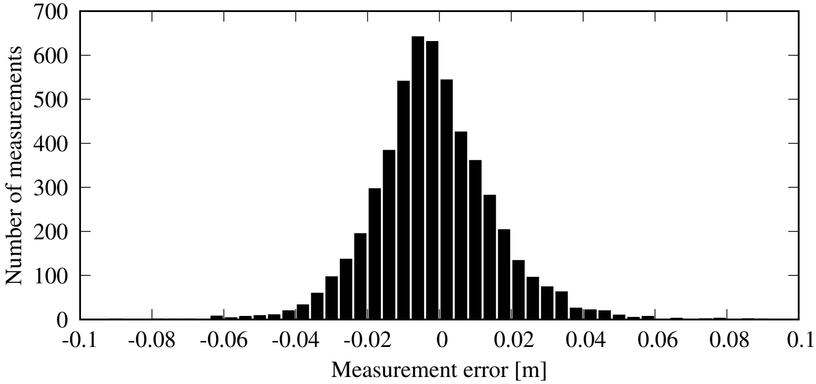

Figure 5.6: Histogram of distance measurement errors.

of a vehicle trajectory whose length we want to compute. This transformation is done by coupling each license plate pair from the set with a license plate pair that was recorded in the consecutive frame, if possible. Next, the Point matching step is applied to each license plate pair couple from the set in order to obtain the nine corresponding point pairs for each license plate pair. Each of the nine point pairs from the first license plate pair of the couple is assigned its corresponding point pair from the second license plate pair of the couple. The point pair couples are then triangulated using the calibration method results, and the distance between the triangulated points of the couple is computed. This results in nine distances for each license plate pair couple, and the method takes their median distance as a distance that vehicle travelled between the two consecutive frames.

The distances are measured for 653 of a total of 654 recorded vehicles. Distances for one vehicle are missing because the license plate detector failed to detect the vehicle license plate. From the measured values, the measurement error is computed as:

$$e = d_m - d_d, \tag{5.2}$$

where d_m is the distance measured using the proposed method and d_d is reference distance speed from the dataset. For the histogram of the distance measurement errors, see Fig. 5.6. Overall, the 99 percentile absolute error is 0.05 m, and the mean error is -0.002 m with the standard deviation of 0.017 m.

The distance measurement errors are compared with two other calibration methods that deal with cameras focused on a long shot, namely, Shang et al.'s [8] method and Tian et al.'s [10] method. The comparison is shown in Table 5.4. Dataset properties and baselines are compared in Table 5.3. The proposed method achieves better results than the other methods in all compared statistics on a much bigger dataset with a much smaller baseline.

The setup that was calibrated using the proposed approach outperformed the existing methods that use the chessboard calibration (Jalalat et al.'s method [2], El Bouziady et al.'s method [1], and Yang et al.'s method [12]) in the precision and the accuracy of the vehicle speed measurement.

Discussion

The newly proposed vehicle speed measurement method achieves better results than the current state-of-the-art methods in all compared statistics on a much bigger and more diverse dataset. The

Table 5.3: Comparison of datasets and baselines of the stereo camera pair calibration methods.

	Distance from cameras [m]	Dataset size	Baseline [m]
Shang et al. [8]	50 - 70	15	30
Tian et al. [10]	49 - 85	28	79.88
Proposed method	**36 - 64**	**5365**	**0.955**

Table 5.4: Comparison of stereo camera pair calibration methods on a distance measurement task.

	MSE [m]	STDEV [m]	99 percentile abs. error [m]
Shang et al. [8]	0.0016	0.04	0.083
Tian et al. [10]	0.0011	0.033	0.063
Proposed method	**0.0003**	**0.017**	**0.05**

speed measurement error of the measurement method is Normally distributed with the mean value of -0.05 km/h and the standard deviation of 0.20 km/h. The maximum absolute error is 0.72 km/h and the maximum percentage error is 1.11 %. These values were measured on a sample of 653 vehicles and are well within the ranges specified by the OIML Recommendation for the field test of the autonomous speed measurement devices, which means that the hypothesis of this work holds. Aditionally, the proposed stereo camera pair calibration method also outperforms the current state-of-the-art long-distance calibration methods.

Chapter 6

Conclusion

This thesis answered the question of whether it is currently possible to measure the speed of vehicles using a stereoscopic method with the average error within ± 1 km/h, the maximum error within ± 3 km/h, and the standard deviation within ± 1 km/h. The error ranges were based on the requirements of the OIML whose Recommendations serve as templates for metrological legislations of many countries. Based on this question, a hypothesis was formulated and tested. A method that utilizes a stereo camera pair for vehicle speed measurement was proposed and experimentally evaluated.

The experimental evaluation was designed according to the design of the field test from the OIML Recommendation. Using the prototype hardware that consists of two synchronized cameras, ethernet switch, and two batteries mounted on one-meter long aluminium profile, a dataset was recorded. The dataset contains recordings of 698 vehicles for which the reference data is provided by a pair of LIDARs. The first 44 vehicles were used for stereo camera pair calibration. The remaining 654 vehicles were used for the evaluation. The reference average speeds and the average speeds measured by the method were used to compute the measurement errors. The results were compared to the existing stereo-based methods and to the OIML requirements.

The newly proposed method measures the speed of the passing vehicles more precisely than the other methods. The mean error, the standard deviation, and the maximum absolute error are -0.05 km/h, 0.2 km/h, and 0.72 km/h, respectively. These values are within the ranges specified in the hypothesis , which means that the presented hypothesis holds. The proposed stereoscopic vehicle speed measurement method should, therefore, comply with metrological legislations that are based on the OIML Recommendation.

Additionally, the stereo camera pair calibration method that is suitable for traffic surveillance applications was proposed and experimentally evaluated. The evaluation of the calibration method was based on a distance measurement task and utilized the same dataset as the vehicle speed measurement method. The results were compared to the results of the existing methods that deal with the calibration of stereo camera pairs that are focused on a long distance. The comparison showed that the newly proposed method is able to calibrate the stereo camera pair more precisely than the other methods.

The intended application of the proposed methods is the autonomous speed limit enforcement. However, due to the rich array of data that is provided by the calibrated stereo camera pair other applications in the field of traffic surveillance are possible. These include, for example, traffic flow monitoring, fine vehicle classification, or air pollution control and improvement. The main focus of the future work should be on maintaining the correct calibration in time. Alternatively, one may also focus on decreasing the execution time, improving the resistance to adverse weather conditions, or experimenting with different detection, re-identification, or correspondence search methods.

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Appendix A

Curriculum Vitae

Education

- 2003 - 2007, Mendelovo gymnázium, Opava
- 2007 - 2010, Bc. FIT VUT Brno, Bachelor thesis on *The Building of Božetěchova 1/2 in Google Earth*
- 2010 - 2012, Ing. FIT VUT Brno, Master thesis on *The Frameless Rendering*

Interests and skills

- Programming in C/C++, Python, JavaScript, and Java.
- Computer Vision and Scene Reconstruction.
- DIY, Home Automation, Electronics.

Publications and contributions

1. NAJMAN P., ZAHRÁDKA J. and ZEMČÍK P. Projector-Leap Motion calibration for gestural interfaces. In: *Interna-*

tional Conference in Central Europe on Computer Graphics, Visualization and Computer Vision (WSCG). Plzeň: Union Agency, 2015,p. 165–172. ISBN 978-80-86943-65-7. Contribution: 40 %.

2. BAŘINA D., NAJMAN P., KLEPÁRNÍK P., KULA M. and ZEMČÍK P.. The Parallel Algorithm for the 2-D Discrete Wavelet Transform. In: *Ninth International Conference on Graphic and Image Processing (ICGIP 2017).* Qingdao: SPIE - the international society for optics and photonics, 2017, pp. 1-6. ISBN 978-1-5106-1741-4. ISSN 0277-786X. Contribution: 20 %.
3. NAJMAN P. and ZEMČÍK P. *Summary Report of Contractual research - Tescan.* Brno: TESCAN Brno, s.r.o., 2018. Contribution: 90 %.
4. NAJMAN P. and ZEMČÍK, P. Vehicle speed measurement using stereo camera pair. *IEEE Transactions on Intelligent Transportation Systems - MINOR REVISION.* 2020. Contribution: 85 %.
5. NAJMAN P. and ZEMČÍK, P. Stereo Camera Pair Calibration for Traffic Surveillance Applications. *IEEE Transactions on Intelligent Transportation Systems - UNDER REVIEW.* 2020. Contribution: 90 %.

Products and contributions

1. NAJMAN P., ZAHRÁDKA J. and ZEMČÍK P. Projector-Leap Motion calibration. 2010. software. Contribution: 50 %.
2. NAJMAN P., KLEPÁRNÍK P. and BAŘINA D. Non-Separable Schemes for Discrete Wavelet Transform for Multi-Core CPUs. 2017. software. Contribution: 40 %.