VEHICLE SPEED ESTIMATION FROM TWO IMAGES FOR LIDAR SECOND ASSESSMENT

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Abstract: Vehicle speed control has been traditionally carried out by RADAR and more recently by LIDAR systems. We present a solution that derives the speed from two images acquired by a static camera and one real dimension from the vehicle. It was designed to serve the purpose of second assessment in case of legal dispute about a LIDAR speed measure. The approach follows a stereo paradigm, considering the equivalent problem of a stationary vehicle captured by a moving camera. 3D coordinates of vehicle points are obtained as the intersection of 3D lines emanating from corresponding points in both images, using the camera pinhole model. The displacement, approximated by a translation, is derived from the best match of reconstructed 3D points, minimising the residual error of 3D line intersection and the deviation with the known dimensions of the licence plate. A graphical interface lets the user select and refine vehicle points, starting with the 4 corners of the licence plate. The plate dimension is selected from a list or typed in. More than 100 speed estimation results confirmed hypothesis about the translation approximation and showed a maximal deviation with LIDAR speed of less than +/- 10 % as required by the application.

1 INTRODUCTION

Speed control of vehicles on road has been traditionally achieved by RADAR. This estimation by active signals (time of flight for distance and Doppler frequency shift for speed estimation) suffers from possible signal double bounces and from the presence of several vehicles in the quite large field of view. The current technology also proposes LIDAR systems which substitute the diffuse RADAR beam by a sharp LASER spot that sweeps the scene at a given elevation. Beside the reduced influence of neighbouring scene objects the quality of the LIDAR detector enables the identification of the vehicle type thanks to profile analysis.

For law enforcement of vehicle speed, the quality or precision of speed measurement is not the only criterion for acceptance as a practical solution. An alternative speed measurement may be required to assess the estimated speed in case of legal dispute. This second measurement has to be obtained from an independent procedure, possibly less precise, but approved by the national certification institute.

The literature about vehicle speed estimation from camera reports solutions with one or several images in which the vehicle is detected automatically. In the case of a single image, image blur around the moving vehicle is exploited to estimate the vehicle motion in the time elapsed corresponding to the camera shutter speed (Huei-Yung and Kun-Jhih 2005). When a pair or sequence of images is used, the moving vehicle displacement is estimated and converted into real distance thanks to camera and scene parameters. An explicit 3D model is not necessary since information relevant to the problem may be gathered, for instance, from the common direction of motion and the statistics of vehicle sizes (Dailey, Cathey and Pumrin, 2000). But most systems have to identify the homography between the image and the scene in order to convert measured pixel distances into real velocities (Grammatikopoulos, Karras and Petsa, 2005, Tocino Diaz, Houben, Czyz, Debeir and Warzée 2009).

In the specific case of the LIDAR system LMS-06 distributed by secuRoad SA (Belgium), two cameras can capture up to two images each for vehicle identification, with precise shooting time. The idea arose to derive the vehicle speed from its displacement between image pairs.

Compared to the RADAR or LIDAR technology, speed estimation from images is much less

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expensive and reduces installation or maintenance overhead (Kastrinaki, Zervakis and Kalaitzakis, 2003). Hardware requirements consist in a storage and processing unit and in a camera needed anyway for legal proof. Video-based systems, already adopted for general traffic surveillance, will probably emerge for speed enforcement in the near future.

In the following, section 2 introduces the LIDAR speed measurement. Section 3 details our approach for speed estimation from a pair of optical images. Section 4 describes the graphical interface while section 5 presents the results for more than 100 speed tests. Section 6 concludes the paper.

2 LIDAR SPEED MEASUREMENT

For law enforcement, RADAR has been for a long time the common system to control vehicle speed. It is based on the Doppler shift of the frequency of an emitted signal after reflection on the vehicle. The major problem of RADAR systems is their sensitivity to the environment (reflection from nearby objects).

LIDAR is an acronym for *Light Detection And Ranging*. Speed estimation is based on the time of flight of a projected LASER beam converted into distance (range). Early LIDAR solutions for law enforcement used to be guns but nowadays systems project a horizontal plane of LASER light to extract a profile of distances.

The major advantage of the LIDAR is the ability to analyse the 1-dimensional range information of the profile returned by the scan. Vehicle profiles and lane separation can be achieved so that vehicle types and speed may be returned for each lane separately. The analysis of successive range profiles enables the estimation of the (quite instantaneous) speed.

The LMS-06 system allows for the surveillance of vehicles in both directions, thanks to the wide laser scanner and the two cameras pointing in opposite directions. This arrangement, depicted from a top view in Figure 1, offers full flexibility for capturing front or rear licence plates. For instance, a common practice in Belgium is to measure speed with the LIDAR when the vehicle arrives, but to capture one or two images when the vehicle is passed. This is indeed required to get an image of the rear licence plate which is the official one for legal proceedings in Belgium.

Our approach has been designed to offer a speed second assessment from a pair of images captured by the LIDAR system. These images serve the purpose of legal evidence for vehicle identification thanks to the licence plate. They may be used in case of legal dispute as an independent speed measure. To be recognised as such by the Belgian national certification institute, the speed deviation between the two methods should be inferior to +/- 10%.

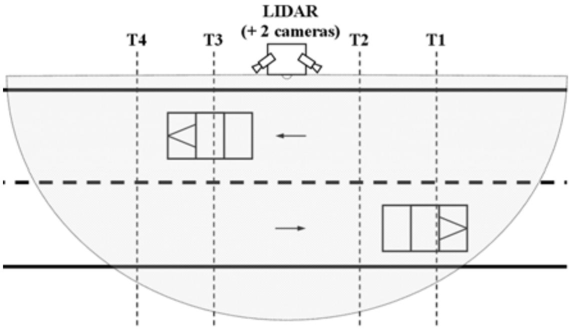


Figure 1: Scheme of the LIDAR systems with two cameras and image acquisition times Ti.

3 CAMERA SPEED ESTIMATION

As previously presented, the LIDAR system LMS-06 disposes of two cameras pointing in opposite directions, each possibly capturing up to two images with a timestamp in millisecond. The challenge of this research is to estimate the speed of a vehicle visible in two images captured by one stationary camera at two known times. To simplify the task, several hypotheses were adopted.

A first reasonable hypothesis is to assume that the camera is not modified between two captures. Its position, orientation and intrinsic parameters are supposed constant. This hypothesis is easily verified by comparing the image position of static objects. As our approach does not require camera calibration, only pair of images with camera modification must be rejected while pairs with the same moving object can be processed for speed estimation.

The second set of hypotheses concerns the vehicles which are supposed to be rigid bodies describing a linear movement. The rigid body constraint ensures that a clear solution exists for motion estimation when considering a few vehicle points. The hypothesis of movement equivalent to a translation was based on observation and is justified from the fact that rotations are negligible (Figure 2).

The roll angle is small as the system is never placed in a turn. The pitch rotation may change if the vehicle accelerates or brakes, breaking the next assumption about constant speed. Mention that brake lights or vehicle leaning can be checked for evidence

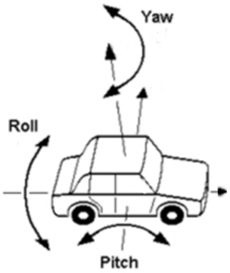


Figure 2: Angle definitions for a vehicle.

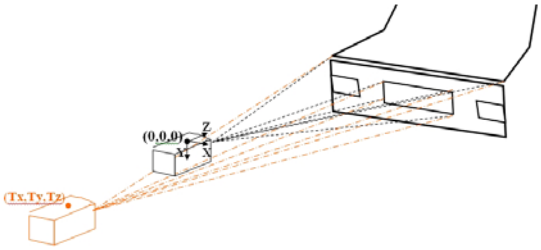


Figure 3: Triangulation from the fictive moving camera and stationary vehicle.

about pitch modification. The yaw angle may be modified when changing lane, but with a limited amplitude, as the majority of the speed remains along the lane. Modelling motion with a translation only requires three parameters, what leads with less computation to a better optimum as dimensionality reduction lowers the likelihood of local minima.

The hypothesis of constant speed is not strictly required for the approach, but is assumed for the evaluation of the camera based speed thanks to the LIDAR measure. This is particularly important in the case of images captured at T3 and T4 (Figure 1), as the time elapsed since the LIDAR measure (before T1) may amount to more than one second. The usual driver’s behaviour which fools the constant speed hypothesis is braking, what effectively modifies speed. This situation is often observed at night, when the camera flash may be seen by the driver.

3.1 Problem Solving by Inversion

Unlike the methods presented in the literature about vehicle speed from images, we estimated vehicle motion from a pure 3D approach. We considered the equivalent problem of a camera in motion capturing a stationary vehicle. We found easier to model the set of 3D points attached to the vehicle with constant coordinates, and to formulate mathematically the artificial camera motion by the 3 coordinates of the optical centre related to the second image capture. Conceptually, we transformed the problem of vehicle displacement into a stereo computation one: the stationary vehicle is captured two times by a moving camera, allowing for triangulation thanks to the different points of view.

Triangulation is solved by 3D line intersection. 3D lines are constructed thanks to the camera pinhole model which exploits the focal length and pixel size. The principal point was supposed to be at the CCD centre and we omitted distortion parameters which appeared negligible with our setup.

More precisely, the optical centre (0,0,0) of the camera for the first image and the camera geometry allows to define 3D lines for each vehicle points localized in the first image. Corresponding 3D lines are evaluated for the corresponding vehicle points localised in the second image, but this time with an optical centre positioned at (Tx,Ty,Tz), to account for the fictive camera translation.

We developed an efficient algorithm for 3D line intersection. In its simplest form, it returns the minimal distance between the lines since two 3D lines do not always intersect. This is computed as the distance of two parallel planes, each one containing one 3D line and parallel to the other 3D line. If a 3D intersection point is desired, the algorithm uses point and vector operations to quickly find the mid point of the shortest segment separating the two 3D lines.

3.2 Localisation of Vehicle Points

Licence plate corners are desirable vehicle point candidates as they must be visible for vehicle identification and are independent of vehicle types. Much more, their known relative distance may serve the purpose of real dimension needed by the approach as explained in subsection 3.3. Other points visible in both images may be added for better stability of the solution.

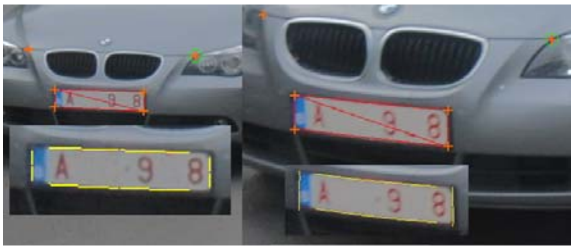


Figure 4: Localised points and plate corners refinement.

Initially, no attempt was made to automate vehicle point localization. The objectives defined by the client did not require full automation as the procedure will involve data input by a user.

Moreover the risk for bad point localisation is high in the licence plate region which is crucial for the success of the approach.

However, in order to reduce the influence of manual point localization, we added the automatic refinement of plate corners. A rectangular region containing the plate defined by the user is processed to derive nearly horizontal and vertical plate edges. For instance, a horizontal low pass filter followed by maximum gradient following in the horizontal direction detects horizontal plate borders. The areas close to corners are excluded as licence plates are rounded rectangles. The intersection of one horizontal and one vertical detected border gives a refined corner if this is not too far from its initial position.

3.3 Search for Translation

To sum up, vehicle speed is estimated from the vehicle displacement, obtained as the artificial camera translation which makes both image captures the valid projections of a stationary vehicle. This problem is ill posed if no object scale is specified. To do so, at least one real object measure has to be given. In our application, we took advantage of the required visibility of the licence plate to impose its (official) dimensions during 3D reconstruction.

Numerically, the solution for (Tx,Ty,Tz) results from minimizing the sum of two error terms: one for the root mean square (RMS) of the 3D line distance of all vehicle points and one for the RMS of the difference between the measured plate sides and their official lengths.

The minimization problem is solved with an exhaustive search on the three parameters, within a coarse to fine approach for speedup. Computational time is also limited thanks to the a priori range of possible translation values in practical situations. Tz, defined along the camera optical axis and mainly along the traffic flow, has a larger value than Tx and Ty and Ty is little as the tilt of the camera relative to the vehicle motion is small.

The validity of the optimization can be checked thanks to the residual mismatch (in mm) of 3D point matching. More precisely, the contribution of each point or plate side to the error can be analysed to identify badly localised points.

4 GRAPHICAL INTERFACE

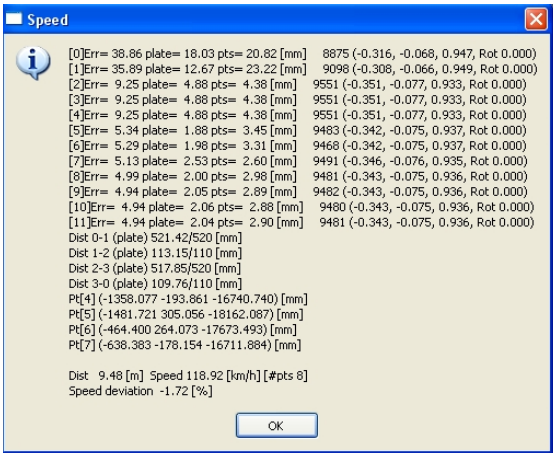
Figure 6 displays the interface composed of a pair of images with superimposed points (orange crosses) whose coordinates are given in the middle area. This area also holds interface for input values like the licence plate size, elapsed time, the camera CCD size and the focal length.

Europe tends to harmonize the licence plate sizes to a standard dimension although many countries are still using their own dimensions and colour. The program was tested with different values for the width (28 to 52cm) and height (8 to 20 cm), as plates originated from a tenth of European countries.

A large number of trials have been undertaken at different geographical locations (in Belgium and Zwitserland) for two cameras with different focal lengths (from 18 to 50mm) to adapt to the field of view and speed. The tested cameras are the Nikon D70S and D90, with a resolution slightly exceeding 3000x2000.

In the current version of the graphical interface, the user first loads a pair of images and specifies the abovementioned parameters. Most of these are incrusted in the images. Then, he clicks to localise vehicle points, starting with a minimum of four points corresponding to the licence plate corners. He may use the ‘Refine Plate Corners’ button to automatically refine the plate corners according to plate edges. A few additional points are welcome to reduce the sensitivity to point localisation. A set of 6 to 8 points were generally specified in the tests.

Once all the parameters are specified, the ‘Get Speed’ button is pressed to launch the optimisation procedure. This will return the convergence history with residuals separated in plate and point values, the estimated speed, and the deviation with the supplied LIDAR speed value (Figure 5). Thanks to the individual point residues (corresponding to 3D line distance) the user can find and adapt badly localised points or remove unreliable ones.



```
[0]Err= 38.86 plate= 18.03 pts= 20.82 [mm]    8875 (-0.316, -0.068, 0.947, Rot 0.000)
[1]Err= 35.89 plate= 12.67 pts= 23.22 [mm]    9098 (-0.308, -0.066, 0.949, Rot 0.000)
[2]Err=  9.25 plate=  4.88 pts=  4.38 [mm]    9551 (-0.351, -0.077, 0.933, Rot 0.000)
[3]Err=  9.25 plate=  4.88 pts=  4.38 [mm]    9551 (-0.351, -0.077, 0.933, Rot 0.000)
[4]Err=  9.25 plate=  4.88 pts=  4.38 [mm]    9551 (-0.351, -0.077, 0.933, Rot 0.000)
[5]Err=  5.34 plate=  1.88 pts=  3.45 [mm]    9483 (-0.342, -0.075, 0.937, Rot 0.000)
[6]Err=  5.29 plate=  1.98 pts=  3.31 [mm]    9468 (-0.342, -0.075, 0.937, Rot 0.000)
[7]Err=  5.13 plate=  2.53 pts=  2.60 [mm]    9491 (-0.346, -0.076, 0.935, Rot 0.000)
[8]Err=  4.99 plate=  2.00 pts=  2.98 [mm]    9481 (-0.343, -0.075, 0.936, Rot 0.000)
[9]Err=  4.94 plate=  2.05 pts=  2.89 [mm]    9482 (-0.343, -0.075, 0.936, Rot 0.000)
[10]Err=  4.94 plate=  2.06 pts=  2.88 [mm]    9480 (-0.343, -0.075, 0.936, Rot 0.000)
[11]Err=  4.94 plate=  2.04 pts=  2.90 [mm]    9481 (-0.343, -0.075, 0.936, Rot 0.000)
Dist 0-1 (plate) 521.42/520 [mm]
Dist 1-2 (plate) 113.15/110 [mm]
Dist 2-3 (plate) 517.85/520 [mm]
Dist 3-0 (plate) 109.76/110 [mm]
Pt[4] (-1358.077 -193.861 -16740.740) [mm]
Pt[5] (-1481.721 305.056 -18162.087) [mm]
Pt[6] (-464.400 264.073 -17673.493) [mm]
Pt[7] (-638.383 -178.154 -16711.884) [mm]

Dist   9.48 [m]  Speed 118.92 [km/h] [#pts 8]
Speed deviation  -1.72 [%]
```

Figure 5: Results of speed estimation with convergence details.

```
1650 1325 261.765 1856.4
1772 1329 509.333 1900.6
1772 1356 515.294 1964.7
1650.38 1351.92 266 1919
1870 1214.29 765.714 159
1728.57 1274.29 418.571 1
```

520x110 mm (EUR-Rear)

113 km/h (LMS speed)

218 ms (Time)

3216x2136 23.6x15.8 mi

18 mm (Focal)

Figure 6: User interface depicting the two images, the set of specified points, the plate dimension, the LIDAR speed, the elapsed time between images and the camera parameters.

5 RESULTS

Figure 7 shows the distribution of the speed deviation between our approach and the LIDAR measure for more than 100 tests.

We directly notice that most deviation values are within the [-10%, +10%] interval, as required by the application. Stronger deviations correspond to particular situations, usually due to serious braking (the driver has seen the flash or the LIDAR pole), as attested by the backlights. These few cases were called ‘Braked’ in the figure and explained speed inferior to more than 7% deceleration.

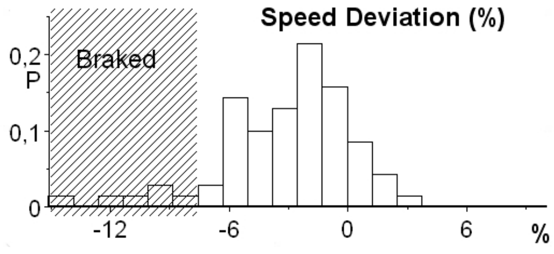


Figure 7: Distribution of speed deviation.

Several error sources explain the deviation for normal cases. First, the constant speed hypothesis may not hold if the driver released gas or if the driving conditions changed (before road crossing or hill climbing). The time interval between the LIDAR measure and the camera captures range from 200 ms to more than 1 s. Secondly, the focal length, given to the closest integer by the camera, may represent a systematic deviation with the real value. Thirdly, the plate size is not measured and is based on official values often only valid for one of the two plates. Finally, the care with which the user localised points has of course a large influence. To have reproducible results, one should optimise points thanks to the automatic ‘Refine Plate Corners’ function and control the global and individual residual errors after convergence.

6 CONCLUSIONS

This paper has presented an application for vehicle speed estimation from two images acquired by a stationary camera. The approach is based on the 3D motion estimation thanks to a set of points localised by the user and possibly refined automatically for the licence plate. The plate dimensions are exploited to obtain real distances and derive a speed.

The particularities of the implementation concern the inversion of the problem, looking for the camera motion of a stationary vehicle; the application of 3D line intersection with a distance measure; and the use of the official plate dimensions to constrain the scale of 3D point reconstruction.

More than 100 tests compared the speed estimated by camera with the LIDAR measurement in different conditions (camera, focal length, plate type, road type, night/day). They showed the adequacy of hypotheses and the implementation correctness. The deviation between both speeds for normal driving cases is in the range [-7%, +3%], below the client requirement of +/- 10%. Mention that the camera and LIDAR speeds were not measured at the same time and that the constant speed hypothesis was probably rarely true where the LIDAR system was tested. Worst cases were observed (speed lower than -7 % deviation) in special conditions (due to the road or driver) but evidence for such cases is usually available from the image.

We intend to further analyse the quality of the approach from pairs of images of a vehicle with known displacement.

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