Automated Traffic Analysis in Aerial Images

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Abstract— **In this work an automated traffic analysis in aerial image sequences recorded by an unmanned aerial vehicle (UAV) has been developed, which provides the trajectories of the vehicles especially during overtaking. Methods of photogrammetry and image processing are used to detect the vehicles and to determine and track their positions. Camera calibration is necessary in order to transform image coordinates into world coordinates.**

Keywords-aerial photography; camera calibration; fisheye lens; image processing; photogrammetry; traffic analysis; unmanned aerial vehicle (UAV)

I. Introduction

Wide range traffic monitoring for the tracking of overtaking manoeuvres is an issue of current research. The collected data will allow the updating of a model which describes overtaking manoeuvres depending on various boundary conditions. The model is used for road planning, e.g. recommendations may be provided to decide where driving on the oncoming traffic lane cannot be allowed due to traffic safety [1].

In this regard, ground based monitoring is very complex and expensive because recorded vehicles may cover or overlap each other [2]. Therefore, the acquisition and analysis of aerial images is beneficial. Innovative measurement systems such as unmanned aerial vehicles (UAV) are capable platforms for this task because they create new opportunities for acquisition of measurement data and photography in areas which are difficult to access. For this reason, the Hovering Remote Controlled Ultra-light Sensor Platform (HORUS) was developed at the Fraunhofer Institute for Transportation and Infrastructure Systems IVI in Dresden. This UAV can be used as technology platform, for measurements and for taking samples because of its compactness with a high payload.

A current application of HORUS is the interdisciplinary research project “Aktualisierung des Überholmodells auf Landstraßen” of the German Federal Highway Research Institute, the Institute of Transport Planning and Road Traffic of the TU Dresden and the Fraunhofer Institute for Transportation and Infrastructure Systems in cooperation with the Airclip GmbH. In this context, HORUS is used to take aerial sequences of overtaking on country roads.

This paper presents the measuring system HORUS and an algorithm for automated analysis of the aerial image sequences, which is already used to determine the trajectories of vehicles. Image processing is used to detect the vehicles shown. The determination of their world coordinates requires camera calibration. Finally, the implemented algorithm is demonstrated with exemplary aerial images.

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II. Measuring System

The measuring system consists of the sensor platform HORUS and a high-resolution camera. It satisfies the following requirements for a successful recording of overtaking on selected routes [1]:

- continuous recording of time and distance travelled by all participants of the overtaking manoeuvres as well as derived velocities and accelerations,
- visibility of large section lengths of at least 600 m and
- imperceptible measurement not affecting the drivers.

HORUS can be operated with 4, 8 or 12 rotors. The 1.0 m × 1.3 m wide copter uses the GPS to fly independently and to keep a defined position during the measurement. The maximum flying height is approximately 250 m due to legal restrictions. The H-shaped geometry of the frame allows any arrangement of the payloads and flight batteries as well as the rapid exchange of different sensor modules.

For the acquisition of aerial image sequences HORUS is equipped with a camera mount which actively balances the pitch and roll motions of the copter. Hence, the camera angle maintains constant. Fig. 1 shows the octocopter HORUS and the mounted camera GoPro Hero3 Black Edition.

Figure 1. Octocopter HORUS with bottom mounted camera

The camera GoPro Hero3 Black Edition is used because it combines a very high optical resolution with low weight and easy usability. Furthermore, its fisheye lens provides a wide angle of view of about 120°, which relates to distances of more than 800 m on the ground for a flying height of 250 m. The ground resolution varies between 14 cm/pixel in the image centre and 50 cm/pixel at the image border. The recorded data are saved with 15 fps and 3840 × 2160 pixels [8].

III. PROJECTION MODEL

An objective is to determine the world coordinates of the recorded vehicles. This requires an appropriate model describing the projection of an object point from the image plane to the world plane.

For this purpose, it is necessary to know the extrinsic and intrinsic camera parameters. The extrinsic camera parameters are the translation vector $(X_0, Y_0, Z_0)^T$ and the three-dimensional rotation matrix $\boldsymbol{R}$ which specify the transformation between the camera coordinate system x, y, z and the superordinate world coordinate system X, Y, Z according to

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \boldsymbol{R}(\varphi, \omega, \kappa)^{-1} \begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{pmatrix}. \tag{1}$$

Within the scope of this project, the origin of the world coordinate system is a point on the ground and the X-axis is in parallel with the captured road.

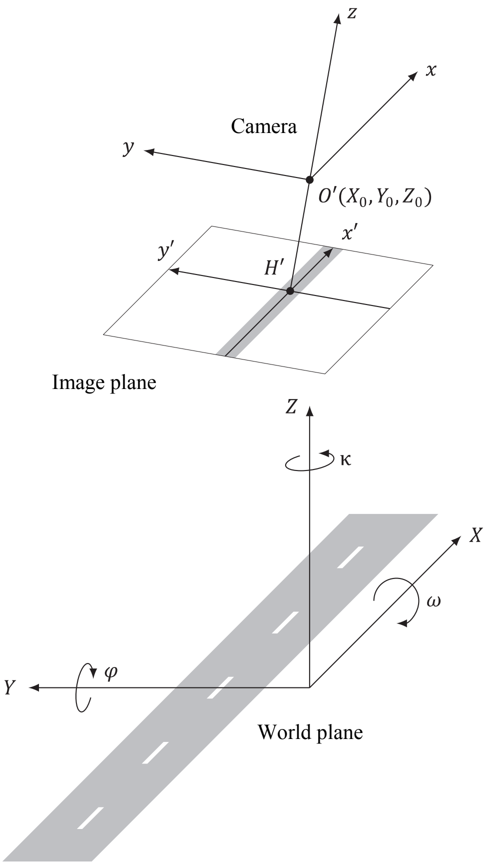

Figure 2. Used Coordinate Systems

The intrinsic camera parameters characterize the geometric and digital characteristics of the viewing camera defining the projection into the image coordinate system x', y' [3]. Its origin is the principal point H' and the x'- and y'-axes are in parallel with the x- and y-axes [4]. The relationship between the coordinate systems is visualized in Fig. 2.

Because of the fisheye lens a ray's incidence angle is different from its accordant reflection angle. In contrast to central projection the rays are refracted in the direction of the optical axis. Thus, the equidistant projection model [5]

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \frac{c \cdot \arctan \frac{\sqrt{x^2 + y^2}}{-z}}{\sqrt{x^2 + y^2}} \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} \Delta x' \\ \Delta y' \end{pmatrix}$$

is applied, where c is the principal distance and the correction terms $\Delta x'$ and $\Delta y'$ contain additional parameters to compensate for systematic effects such as radial symmetric distortion and the decentering distortion [6] as well as affinity and shear [7].

Camera calibration was performed at the Institute of Photogrammetry and Remote Sensing of the TU Dresden where a specially arranged calibration room has been established for the analysis of the geometric models of fisheye lenses. 141 control points are distributed and their coordinates have been determined with an uncertainty between 0.02 mm and 0.23 mm [5].

In order to estimate the intrinsic camera parameters, images were taken in the hemispherical calibration room and the calculation of the spatial resection has been conducted with sub-pixel accuracy. The standard deviation of unit weight can be interpreted as a criterion for the suitability of the geometric model for the camera-lens combination tested. The resulting standard deviation of unit weight of 1/10 pixel is very satisfying because remaining residuals could already partly reflect the influence of the control point accuracy [5].

IV. AUTOMATED IMAGE PROCESSING ALGORITHM FOR VEHICLE DETECTION AND TRACKING

Another central objective of this work is the implementation of an algorithm determining and tracking the positions of vehicles in the world coordinate system of the aerial images. In this context, overtaking manoeuvres are particularly interesting because a model for the car drivers' overtaking behaviour will be created based on the determined vehicle trajectories at the Institute for Transport Planning and Road Traffic of the TU Dresden. The evaluated data set of more than 600 aerial image sequences, about one minute each, until now requires extensive automation.

The automated analysis of the aerial images is performed as schematically shown in Fig. 3. Using methods of image processing, which algorithms can be realized in the integrated development environment for machine vision HALCON, the positions for all vehicles in each frame can be determined. The post-processing tracking combines the single image positions to the required trajectories [8].

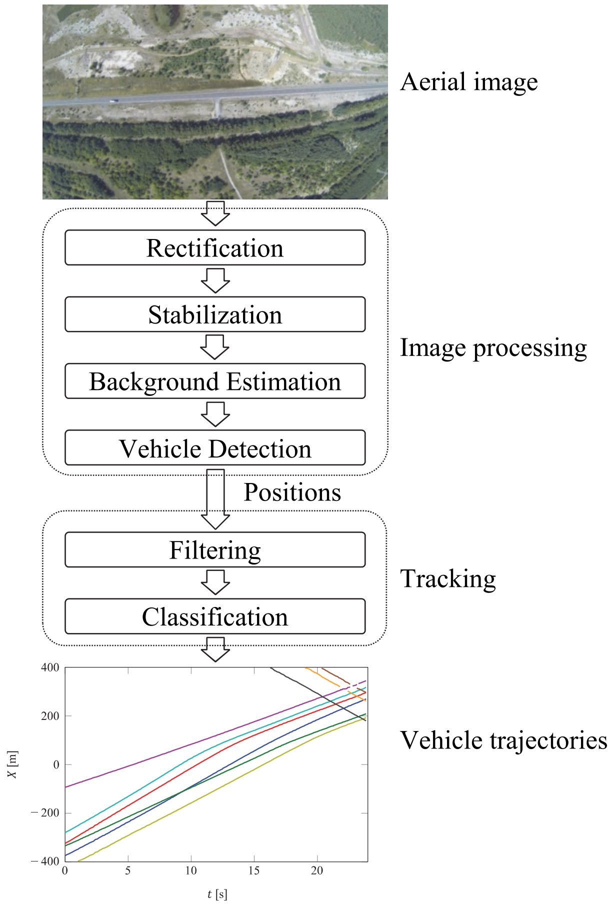

Figure 3. Algorithm for automated analysis of aerial images

After the rectification of each recorded image, stabilization is necessary to compensate for the movements remaining from the camera stabilization of HORUS. The subsequent background estimation enables the automated detection of all vehicles captured. As part of the post-processing, fault detections are removed and the coordinates are assigned to the corresponding vehicles. The resulting trajectories can be further processed, e.g. by calculating the derivatives to gain velocity and acceleration, to formulate a model describing overtaking manoeuvres. The detailed algorithm for automated analysis of aerial images is described below.

A. Rectification

The rectification corrects distortion effects by using the intrinsic camera parameters of the equidistant projection model (2) to convert each image into a central perspective view. This facilitates the further processing because size and shape of the recorded objects are independent of the position in the image. The grey value assignment is performed by bilinear interpolation for each pixel in the output image.

Fig. 4 and Fig. 5 demonstrate an exemplary rectification. The image shown in Fig. 4 contains barrel distortion because of the fisheye lens. The red marked point grid is used to calculate the rectified output image section in Fig. 5. The equally transformed grid points illustrate that the image is stretched at the edge. The rectified image has a width of 6200 pixels which is by a factor of 1.6 larger than the original image.

Figure 4. Input image with barrel distortion

Figure 5. Rectified image

The implemented rectification method is performed without decreasing the image resolution. In addition, interesting areas on the edge remain. Therefore, a loss of image information of the recorded road can be avoided.

In this project the interesting measuring range is the captured street which has a narrow width compared to the total image. This fact facilitates the transformation into world coordinates because the rectified image is connected with the world plane by a scaling factor assuming the camera mount compensates for the pitch and roll of the HORUS.

B. Stabilization

Unlike a stationary camera slight movement of the recorded images cannot be avoided using an UAV despite pitch and roll compensation of the mounted camera. For this reason, image stabilization is necessary to correct the remaining translation and rotation of the HORUS.

One possible approach is the identification and alignment of regions on the roadside, which do not change over the measurement period. To find these manually selected, stationary patterns correlation-based matching is used. The normalized cross-correlation function is used to evaluate the similarity between a pattern and the search area. The point of maximum correlation corresponds to the position of the reference pattern in the image with a high probability. From the results affine transformations equalize the extrinsic camera parameters. Furthermore, the searching areas are generated for the next frame which leads to faster calculation in comparison to constant and larger searching areas.

The correlation-based matching is robust to blur and linear brightness changes. However, the method is sensitive to occlusions and non-linear illumination changes, e.g. due to changing cloudiness. For this reason, it is important to update the reference pattern regularly and automatically. Thus, the images are stabilized even with changing clouds as shown in Fig. 6.

Figure 6. Non-linear illumination changes and stationary patterns

C. Background Estimation

The basis for an automated detection of moving vehicles is a reference image. The background of the captured scene does not contain any moving objects, and therefore presents itself as a reference.

During the determination of the background image, the following problems have to be considered [9]:

- Daytime images without vehicles on average used roads are rare.
- The background image changes due to changing light and visibility conditions.

It follows that a static reference image does not exist. Thus, the background image must be estimated and continuously adapted to the changing environmental conditions such as changes in brightness. An established method of background estimation is the calculation of an arithmetic average image [9]. To reduce the storage requirements, a recursive averaging is possible [10].

The analysis of real traffic sequences has shown that the background estimation with a frame rate 1 fps during a period of 10 s is sufficient for the subsequent vehicle detection.

D. Vehicle Detection

Assuming that vehicles are the only moving objects recorded, their position can be determined. For this purpose, each image to be analysed can be subtracted from the background image. The vehicles can be segmented automatically by thresholding. The following general features of the individual regions need to be considered [9]:

- A vehicle may be composed of a plurality of regions.
- Several vehicles can merge in a region.
- Detected regions may, but need not necessarily belong to vehicles.

For an exemplary rectified aerial image Fig. 7 to 10 show the implemented steps of image processing. The difference between the rectified image in Fig. 7 and the estimated background in Fig. 8 is visualized in Fig. 9. Thresholding leads to the binary image in Fig. 10 containing the detected vehicle regions.

Figure 7. Rectified image

Figure 8. Background image

Figure 9. Difference image

Figure 10. Detected vehicles

E. Tracking

The positions which were stored independently for each image are assigned to the respective vehicles in a post-process. The filtering deletes coordinates that cannot be assigned to any vehicle. Assuming that a vehicle travels a short distance during the time interval between two frames, the most likely positions of a particular vehicle are found. The resulting trajectories characterize the movement of vehicles on the recorded road.

For further analysis of overtaking manoeuvres especially the X-component of the observed movement is interesting. Fig. 11 shows an exemplary time course of the X-coordinate of detected vehicles. The discrete entries are not assigned to the particular vehicles and obviously contain errors.

The result after tracking is shown in Fig. 12. Each curve of one colour documents the movement of a particular vehicle along the captured road. Since the gradient of the curve represents the velocity, an overtaking manoeuvre is characterized by the intersection of two curves of the same signed slope. This can be used for automated overtaking detection. Fig. 12 contains an overtaking manoeuvre at $t = 9.5$ s. Fig. 13 shows the corresponding Y-coordinates of the vehicles involved in the overtaking manoeuvre as well as possible polynomial fitting curves. A lane change manoeuvre is clearly visible.

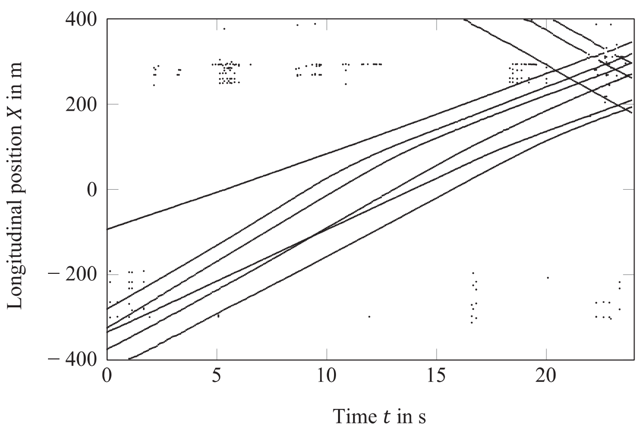

Figure 11. Time series of the longitudinal positions of vehicles detected

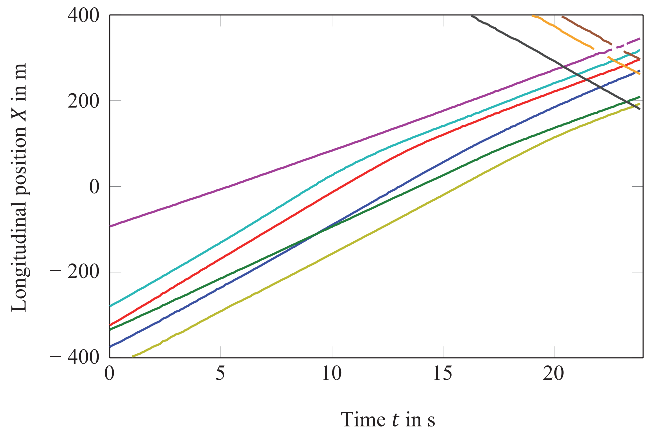

Figure 12. Time series of the longitudinal positions of vehicles tracked

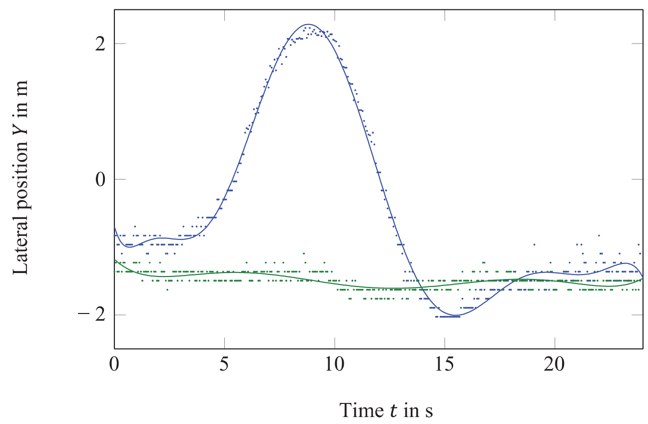

Figure 13. Time series of the lateral positions of vehicles tracked

V. Summary and Outlook

The developed system comprising HORUS measuring platform and the automated image processing provides a novel approach for traffic monitoring. In contrast to state of the art ground based systems a wide area could be monitored in a cost-effective way. A further advantage is the time-synchronized data acquisition with one sensor. The UAV-based measuring process is almost completely automated and therefore easy to operate.

The automated analysis of aerial images presented in this paper in combination with the innovative measurement system HORUS is an efficient tool for the analysis of overtaking manoeuvres. The ability is proven by the successful analysis of more than 600 recorded image sequences.

The automated aerial based vehicle monitoring can be realized for curves or intersection areas as well. In addition the velocities and distances in the range of accident black spots could be investigated. The detection of all vehicles recorded allows the identification of further parameters of transport planning, such as the traffic volume, which provides information about the quality, efficiency and safety of traffic flow and is used in road design.

The modular design of the presented algorithms facilitates further developments: Automation can be further increased e.g. by alternative image stabilization without the manual selection of reference patterns. In this regard, the use of at least three signalized control points with known coordinates is possible. If they are not located on a straight line, a spatial resection provides the extrinsic camera parameters for each frame [4].

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