MOVING CAMERA ROTATION ESTIMATION USING HORIZON LINE FEATURES' MOTION FIELD

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Abstract: In this paper we propose a method for estimating the instantaneous rotation angles of a camera placed on a mobile robot/vehicle using the motion field of horizon line features'. A fast matching technique of some relevant horizon line points in consecutive frames was implemented. Such far distance features are characterized only by rotational flow. Therefore the rigid body motion equation were simplified by neglecting the translation component of the image flow, ensuring an overall processing time of about 1 ms. The computed rotation angles of the camera can be used as measurements in image stabilization of video sequences or more complex applications as obstacle and lane detection for real-time autonomous robot/vehicle guidance systems.

Key words: robot vision, on-line camera calibration, motion field, feature matching

1 Introduction

Knowing the camera position and orientation is essential in almost any vision based measurement application. There are two cases which must be outlined: the camera is static relative to the measurement coordinate system or the camera is moving.

The first one is the case of the applications for visual inspection or measurement, traffic surveillance applications etc. General purpose calibration methods which are estimating the camera's position and orientation relative to a world reference system in for the measurements are widely covered in literature. The main idea of all methods is the usage of a static scene or calibration object with a known 3D structure.

The second case deals with the vision based guidance of mobile robots or vehicles. Here, if the measurements are made in the robot's/vehicle's coordinate system (e.g. we want only to measure the distance to an obstacle), static calibration can be applied [1, 2, 3]. But some applications are requiring the description of the surrounding environment in which the robot is moving and we have to know the instantaneous position and orientation of the camera in an environment related coordinate system. The difficulty which arises in this case is that we don't have any more a scene with known structure/geometry.

Nevertheless in any environment we can infer some prior knowledge. This could be the case of a vehicle driven on the road/highway, which is usually a flat surface having parallel lane marking delimiters. In [4] and [5] methods for estimating the camera height, pitch and yaw angles by detecting the vanishing point of straight or curved lane/road borders from monocular images are presented. In [6] methods for estimating the same parameters using the stereo correspondence of road points or lane markers are outlined, but these methods work only on canonic stereo images.

If such prior knowledge as the road geometry is not available, techniques based on image flow estimation can be implied. In [7] and [8] such methods which are estimating the camera motion in consecutive video-frames by extracting and tracking some clearly distinguishable feature points are exposed. In [9] an image stabilization technique that estimates the camera rotation angles between successive images using the optical flow of horizon line points is presented. The advantage of taking in account distant features is that their rotational flow is dominant and the translational flow can be neglected, simplifying the computational effort.

In this paper we propose a method for estimating the instantaneous rotation angles of a camera placed on a mobile robot/vehicle using the motion field of the horizon line. But instead of estimating the image flow using differential techniques (actually this is known as the optical flow) as in [9], we use matching techniques. That means that we will estimate the disparities of the horizon line features between frames. First the horizon line is detected, then segments of the horizon line are matched in consecutive frames. From the matched segments, some relevant features are selected which are further matched individually with sub-pixel accuracy obtaining their motion field. From the motion field vectors, the relative rotation angles between frames are computed in a least squares fashion. The proposed technique can be used further in autonomous vehicle guidance applications for the estimation of the instantaneous rotation angles of the robot /vehicle and proper mapping of the measurements from the robot/car coordinate system into the environment related world coordinate system.

2 Estimation of the horizon line features motion field

2.1 The theory of the motion field

The *motion field* is defined as 2D vector field of velocities of the image points, induced by the relative motion between the viewing camera and the observed 3D scene [10].

Suppose that such a 2D image projection point of a 3D feature had changed its positions from coordinates (x_O, y_O) in the previous frame to the coordinates (x_C, y_C) in the current frame. Thus the motion vector of the 2D image point in the image plane can be written as:

$$\partial \vec{r} = \partial x \cdot \vec{i} + \partial y \cdot \vec{j} \tag{1}$$

Differentiating equation (1) with respect to time we will obtain the velocity for the considered 2D point in equation (2). The set of the velocity vectors for the considered feature points will form the motion field.

$$\vec{v} = \frac{\partial \vec{r}}{\partial t} = \frac{\partial x}{\partial t} \cdot \vec{i} + \frac{\partial y}{\partial t} \cdot \vec{j} = v_X \cdot \vec{i} + v_Y \cdot \vec{j} \tag{2}$$

2.2 Detection of the horizon line contour

The proposed detection method consists in two steps:

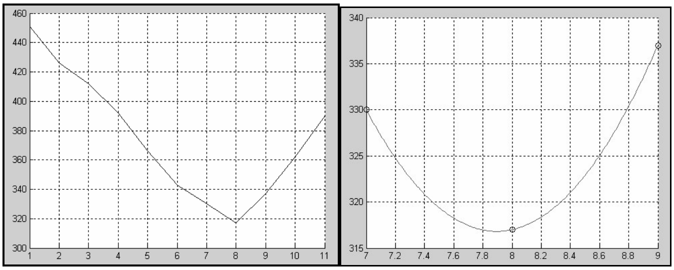
- Initialization step: tests if exist or not sky regions in the image and which are their global features (mean/variance).
- Detection of the horizon line: the horizon line is defined as the border between sky regions and earth regions (with mean values bellow a specified threshold).

In the initialization step the existence of any sky regions/samples is checked (average brightness above a threshold). If there a minimum number of 3 sky samples are found, their global mean and variance are computed.

We define the horizon line/contour as the border between sky regions and earth features. It is assumed that sky is always placed above any earth feature. The image columns are scanned from top to bottom beginning from the image center to left and right in a specified range When the first pixel having the intensity value smaller than the previously computed global sky mean value (in the initialization step) is found, it is marked as horizon contour point.

2.3 Horizon features detection and matching

Having the horizon line detected in the current and previous images, a horizon segment of predefined length from the current image is matched against possible candidate segments of the same length from the previous frame by computing the SAD (Sum of Absolute Differences) metric on the vertical coordinates of the corresponding horizon segment points. The minimum value of the correlation function (fig. 1.a.) is computed with sub-pixel accuracy using a 2-nd order polynomial interpolation function (fig. 1.b), and represents the horizontal offset *dxm* [pixels] between the matched horizon line segments. Their vertical offset *dym* is estimated by averaging the vertical offsets of the corresponding horizon segment points. The results of the correlation are illustrated in figure 2.



a. b.

Fig. 1. a. SAD correlation of the vertical coordinates of the matched segments; b. The horizontal offset *dxm* is the minima of the 2-nd order polynomial interpolation function

The previous correlation offsets (*dxm* and *dym*) are global ones, characterizing the average motion of the horizon line in consecutive frames. Further, individual feature points must be correlated, because we are interested in the refinement of the vertical correlation of these features (which could differ from one point to another in the same horizon line segment due to camera role angle variations). Therefore, the features of interest for this step will be the mid points of small horizontal segments (few pixels in length) in order to improve their vertical correlation. Such corresponding feature points from the current and previous horizon line segments are correlated using the SAD metric[11] computed on a 7x7 pixels neighborhood in a 3x9 search interval. The vertical offset between two correlated contour points is computed at sub-pixel using 2-nd order polynomial interpolation around the SAD function minimum. This will be the vertical component of the motion field vector (*dyp*) for every feature point. Their horizontal motion field component is the correlation value of the horizon segment computed in the first step (dxm).

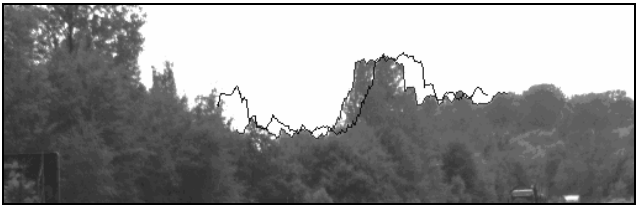


Fig. 2. Spatial correlation of current and previous horizon lines

3 Estimating the camera rotation from the motion field

3.1 The theory of the rigid body motion

In what follows the mathematical formalism for estimating the relative motion of a moving rigid body (in particular our camera) in a static scene knowing the motion field of some static 3D points [9, 10] will be presented. Let $\mathbf{P} = [X, Y, Z]^T$ be a 3D point in the camera reference frame. The image of a scene point **P**, is the point **p** of coordinates $[x, y, f]^T$ in the camera coordinate system:

$$\mathbf{p} = f\frac{\mathbf{P}}{Z} \tag{3}$$

The relative motion between point **P** and the camera (or the relative velocity of **P** regarding to the camera frame) is described in equation (4):

$$\begin{cases} V_X = \dfrac{\partial X}{\partial t} = -T_X - \varpi_Y Z + \varpi_Z Y \\ V_Y = \dfrac{\partial X}{\partial t} = -T_Y - \varpi_Z X + \varpi_X Z \\ V_Z = \dfrac{\partial X}{\partial t} = -T_Z - \varpi_X Y + \varpi_Y X \end{cases} \tag{4}$$

where: **T** is the translational component of the motion, and $\boldsymbol{\omega}$ is the angular velocity. As the motion is rigid, **T** and $\boldsymbol{\omega}$ are the same for any **P**.

To obtain the relation between the velocity of **P** in space and the corresponding velocity of **p** in the image plane we take the time derivatives of both sides of (3) which gives an important set of equations – *the basic equations of the motion field*. [10]:

$$\begin{cases} v_X = \dfrac{-T_X f + T_Z X}{Z} + \varpi_X \dfrac{xy}{f} - \varpi_Y (\dfrac{x^2}{f} + f) + \varpi_Z y \\ v_Y = \dfrac{-T_Y f + T_Z Y}{Z} + \varpi_X (\dfrac{y^2}{f} + f) - \varpi_Y \dfrac{xy}{f} - \varpi_Z x \end{cases} \tag{5}$$

3.2 Estimation of the angular velocities of the camera

From equation (5) we can notice that the motion field is the sum of two components: one depends on translation only (first term from the right side); the other on rotation only (last two terms from the right side). This discloses an important property of the motion field: *the part of the motion field that depends on angular velocity does not carry information on depth.*

For our particular case, when we are using horizon line feature points which are very distant features we can ignore their translational component of the motion field. Thus the motion field of these far features can be characterized only by their rotational components. Combining equations (1), (2) and (5) we can write the following pair of equations for every tracked horizon feature point *i*:

$$\begin{cases} \varpi_X \frac{x_i y_i}{f} - \varpi_Y \left(\frac{x_i^2}{f} + f\right) + \varpi_Z y_i = x_i - x_i^O = \partial x_i \\ \varpi_X \left(\frac{y_i^2}{f} + f\right) - \varpi_Y \frac{x_i y_i}{f} - \varpi_Z x_i = y_i - y_i^O = \partial y_i \end{cases} \qquad (6)$$

Taking at least two pairs of horizon points the above system can be solved in a least squares fashion. The solution $\varpi = [\varpi_X \quad \varpi_Y \quad \varpi_Z]^T$ represents the instantaneous angular velocities of the camera (measured between the current and previous frame), expressed in [rad/frame] (ω_X – pitch angle rate; ω_Y – yaw angle rate; ω_Z – roll angle rate).

4 Results

In order to validate the method the application was tested on a vehicle equipped with damper height sensors and a stereovision based lane detection module [12]. The rotation angles detected with these sensors were used to asses the current method. In the plot from figure 3 the pitch angle rates are presented. As it can be seen the results obtained with the current method and with the lane detection module have approximately the same shape and are in phase. The pitch angle rate estimation from the height sensors has a near shape but differs both in amplitude and phase which prove that this measurement is not quite relaible. Therefore the proposed method can be, for example, an alternative measurement for the lane parameters tracking process in a complex lane detection algorithm.

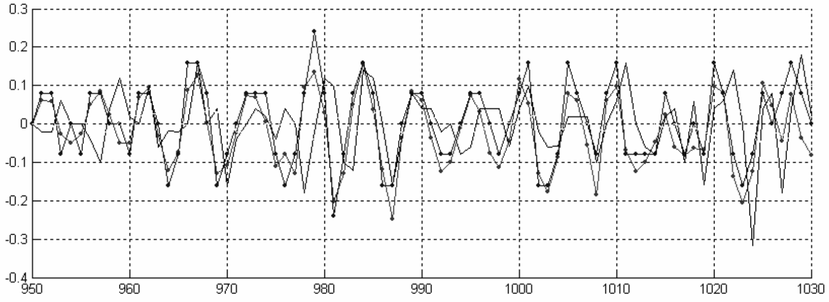


Fig. 3. Pitch angle rates [rad/frame] estimations comparison

5 Conclusions

A method for a moving camera rotation angles estimation using the motion field of horizon line features was developed. The advantage of the horizon line points is there static nature, therefore exhibiting only the rotational components of the motion field. This simplifies the computational effort and along with an efficient feature extraction and matching algorithm leads to a processing time at about 1ms/frame on a P4 PC. The computed rotation angles of the camera can be used as measurements in the image stabilization of video sequences or more complex applications as obstacle and lane detection for real-time autonomous robot/vehicle guidance systems.

The limitations of the method are scenarios where is impossible to detect the horizon line: horizon is overlapped by high trees or buildings (some tight curves, downtown scenarios), driving under bridges, tunnels etc. Further improvement can be done in the estimation of the motion field vector of the horizon line points. Horizon contour line matching in a polar coordinate system could improve the accuracy of the estimated motion field and thus to improve the degree of confidence for the yaw and roll angles. As an extension of the method in scenarios where horizon line or is not available would be the usage of some static local features (road marking) and by taking into account the complete model of the rigid body motion equations system.

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