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A Kalman Filter-Based Update Scheme for Road Following

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Abstract

We propose a new approach for vision based road following. The approach is tailored to a well structured highway environment with lane markers. Lane markers are detected and used for dynamic update of: (i) the lateral position and orientation of the vehicle with respect to the lane markers, (ii) the estimated road curvature, and (iii) the camera parameters (height and inclination angle) in the presence of car vibration and changes in road slope. For that purpose we model the road and hence the shape of the lane markers as quadric curves. The identification of these curves is done in a 3D reference coordinate system attached to the vehicle, rather than a 3D coordinate system attached to the road. This approach allows an unified description/estimation of the road and the vehicle parameters.

1 Introduction

The application of computer vision techniques to the automatic guidance of mobile robots is a very demanding and challenging task. In the case of a road vehicle many research programs [3, 5, 6, 10, 11] have been conducted in the fields of: (a) road modeling, detection and following, (b) vehicle guidance and (c) specialized hardware for real-time processing. This paper is only dealing with the first point, which is generally formulated as follows: creating and updating a representation of the road boundaries from a sequence of images. The detection and the tracking of the road boundaries is a major problem for visually navigating a vehicle along a road, since it permits:

(a) to estimate, for navigation purposes, the vehicle position and orientation relative to the road,

(b) to have a global perception of the road in front of the vehicle to locate and track other vehicles on the road, for obstacle detection.

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Several approaches have been adopted for this purpose [3, 6, 10, 11]. Research conducted by the group of Prof. Dickmanns [3, 4] has shown that dynamic and geometric models of both the road and the vehicle can be used to focus the image processing on gathering information about the road scene from small windows. In this approach the road and the vehicle parameters are decoupled: the road skeleton is modeled as a plane curve consisting of a sequence of N arcs with linear curvature. This model, used in road construction technology, named *clotoid model* assumes that the curvature along the road skeleton is a continuous function of arc length with a piece-wise constant variation [3, 4, 6]. The dynamical model consists of a large number of parameters including vehicle dynamics and implicit control laws.

We propose a simple model of road geometry which is used to guide the tracking of lane markers through a sequence of images. The originality of this approach is that the model chosen allows an unified description of both road and vehicle parameters. The vision system considers a non rectangular search window containing the novel section of the lane markers which are detected and used for dynamic update of (i) the road geometry parameters which implicitly define the vehicle parameters and (ii) the camera parameters (camera height and inclination angle) in the presence of car vibration and changes in road slope [6]. For that purpose we model the road and hence the shape of the lane markers as quadric curves.

The rest of this paper is organized as follows: in section 2 the road/vehicle and camera parameters are defined. Section 3 is dedicated to the dynamic model for lane markers following. The tracking algorithm is explained in section 4. Some results are finally shown in section 5.

2 Model of Road and Vehicle

The following section concerns the road structure and its geometry, the vehicle parameters and the camera parameters. All the identifications are done in a 3D reference coordinate system attached to the vehicle, rather than a 3D coordinate system attached to the road. This allows us to obtain directly vehicle parameters from road parameters. It is however

easy to transpose data to a 3D coordinate system attached to the road.

2.1 The Road

The road model has to represent the road geometry and structure (e.g. several lanes). We have chosen to model the road as a flat ground plane. Thus there is a one-to-one transformation between the 3D coordinates of a given point on the road plane and the 2D image coordinates (Figure 2). The road is assumed to consist of several lanes, each of them is delimited by lane markers, which are modeled as quadric curves:

$$X(Z) = a_0 + a_1.Z + a_2.Z^2 \qquad (1)$$

Such a curve can represent accurately straight lines and arc of circles and it is characterized by 3 parameters, as illustrated in Figure 1:

- a_0: lateral offset of the lane marker in the vehicle coordinate system (at position $Z = 0$),
- a_1: determines the angle (β) between the direction of the lane marker (tangent) and the vehicle heading (Z axis). From Eq(1) we have $\beta = \arctan a_1$, assuming that β is small we get: $\beta = a_1$,
- a_2: expresses the curvature at each point of the curve Eq(1). A constant curvature can also be determined by assuming that Eq(1) can be approximated by a circular arc of radius R. In this case a constant curvature is obtained: $C = \frac{1}{R} = 2|a_2|$.

2.2 The Vehicle

In Figure 1 the vehicle parameters are shown: the lateral position (a_0) and heading ($\beta = a_1$) with respect to the lane marker. These parameters are implicitly given by Eq(1).

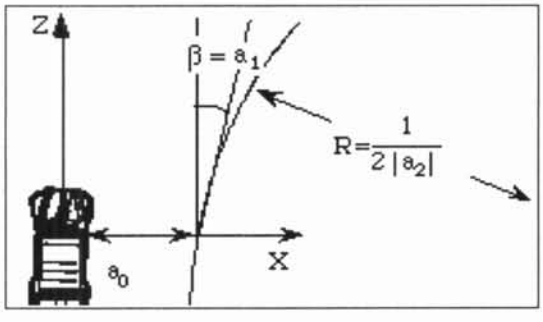

Figure 1: The Road/vehicle models.

2.3 The camera

The camera model assumes a flat ground plane and perspective projection. The camera is tilted with respect to the horizon but there is no roll. Figure 2 illustrates the geometry relating a pixel in the image plane to a point on the ground plane. Let:

- x_i, y_i the 2D image coordinate system,
- X, Y, Z be the space coordinate system fixed on the vehicle at a height h with respect to the ground and the Z axis oriented in the same direction as the vehicle,
- X_c, Y_c, Z_c the camera coordinate system with the origin at the image plane center (C_x, C_y) and Z_c lying in the (Y, Z) plane. Z_c is tilted with an angle θ ($\theta < 0$) with respect to Z.

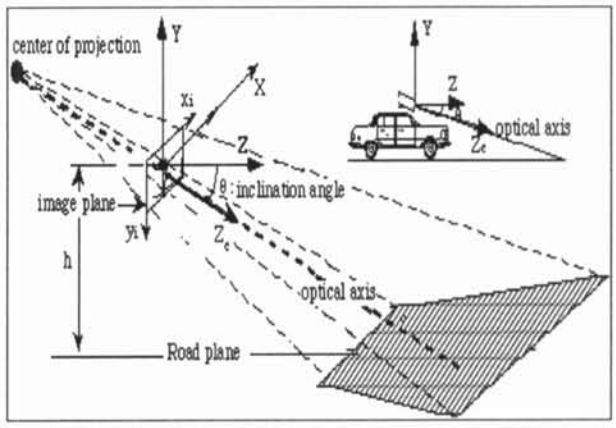

Figure 2: Coordinate systems.

The relation relating a point (X, Y, Z) and its projection (x_i, y_i) on the image plane is given by (perspective projection):

$$\begin{cases} x_i = C_x + e_x \cdot \frac{X}{Y \sin\theta + Z \cos\theta} \\ y_i = C_y + e_y \cdot \frac{Y \cos\theta - Z \sin\theta}{Y \sin\theta + Z \cos\theta} \end{cases}$$

where (e_x, e_y) are respectively the horizontal and vertical scaling factors (pixels/m).

The relations between a point $(X, Y = h, Z)$ on the ground plane and its projection on the image plane are:

$$x_i = C_x + e_x \cdot \frac{X}{Z + h.\theta} \qquad (2)$$

$$y_i = C_y + e_y \cdot \frac{Z.\theta - h}{Z + h.\theta} \qquad (3)$$

where $\sin\theta$ is approximated by its argument and $\cos\theta$ by 1 ($\theta \leq 10°$) and $h < 0$.

3 A Kalman Filter-Based Update Scheme for Road Following

The presented approach applies dynamical modeling for road following instead of static image evaluation [7, 9]. The global dynamic model comprises: the lane markers parameters (a_0, a_1, a_2), and the camera parameters (θ, h). The general dynamic system is described by the state vector

$\underline{\mathbf{x}} = [a_0, a_1, a_2, \theta, h]^t$ which is dynamically estimated using the *Extented Klaman Filter* approach.

The *Kalman Filter* (**KF**) approach [1, 2] introduces knowledge about the dynamic behaviour of a process (described by a state vector), about the measurement relations and about the noise statistics of both process and measurements in order to obtain the best estimates of the process state in a least squares error sense recursivly as new measurement data arrives.

The following paragraphs describe how the required dynamic model and measurement model are constructed for recursive estimation of the road/vehicle and camera parameters.

3.1 Road/vehicle model update

We currently assume that the vehicle runs at a constant speed (V), and a uniform translational motion along the lane marker. Figure 3 shows the position of the vehicle at two time slices $\mathbf{t}$ and $\mathbf{t} + \mathbf{\Delta T}$, $\mathbf{\Delta T}$ being the sampling period.

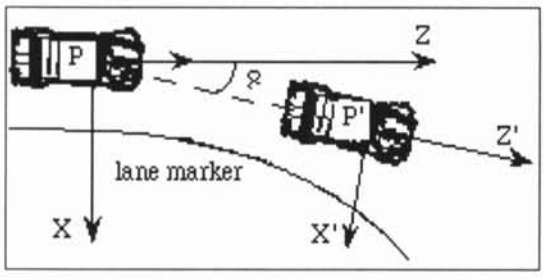

Figure 3: Vehicle movement.

Due to the way in which the vehicle centered coordinate system was defined (cf. Figure 2), a purely translational motion of the vehicle can occur along the Z direction. Starting rom a position $P(X, Z)$ at time $\mathbf{t}$, the vehicle will move to a position $P'(X', Z')$ at time $\mathbf{t} + \mathbf{\Delta T}$, at a distance $\mathbf{\Delta d}$ from P, and it will be oriented in a direction different from the old Z axis at time $\mathbf{t}$. Let α the angle between the two, its value will be close to zero provided that the motion is translational and the sampling period $\mathbf{\Delta T}$ is small.

The positions P and P' are related by (Figure 3):

$$\begin{bmatrix} X' \\ Z' \end{bmatrix} = \begin{bmatrix} X \\ Z \end{bmatrix} + \begin{bmatrix} \Delta d \sin\alpha \\ \Delta d \cos\alpha \end{bmatrix} \qquad (4)$$

the vehicle displacement Δd during the period ΔT is given by: $\Delta d = V.\Delta T$.

From Eqs(1,4) the following process model for recursive lane marker parameters estimation is obtained :

$$\begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix}_{t+\Delta T} = \begin{bmatrix} 1 & -V\Delta T & V^2\Delta T^2 \\ 0 & 1 & -2V\Delta T \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix}_t + \mathbf{r}(t) \qquad (5)$$

with $\mathbf{r}(t) = [VT\alpha, 0, 0]^t$ being the process noise.

3.2 Camera parameters update

The camera parameters, namely the camera height h and the inclination angle θ, affected mostly by vehicle vibrations and changes in road slope, are also dynamically updated [6]. The reason for this is that a small error in θ will cause a significant error on the localization of the road plane, and hence a significant error in the estimation of the lane marker parameters. A simple model based on the assumption of a constant θ and h is used:

$$\begin{bmatrix} \theta \\ h \end{bmatrix}_{t+\Delta T} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \theta \\ h \end{bmatrix}_t + \begin{bmatrix} \Delta\theta \\ \Delta h \end{bmatrix} \qquad (6)$$

in this model small variations on θ and h are expressed via $\Delta\theta$ and Δh.

3.3 The general dynamic model for road following

The following system with five state components describes the discrete-time equation constraints for road following (cf. Eqs5,6):

$$\underline{\mathbf{x}}_{k+1} = A_k \underline{\mathbf{x}}_k + \underline{\mathbf{w}}_k$$

with:

$$\begin{aligned} \underline{\mathbf{x}} &= [a_0, a_1, a_2, \theta, h]^t \\ A &= \begin{bmatrix} 1 & -V\Delta T & V^2\Delta T^2 & 0 & 0 \\ 0 & 1 & -2V\Delta T & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \\ \underline{\mathbf{w}} &= [VT\alpha, 0, 0, \Delta\theta, \Delta h]^t \end{aligned}$$

It should be noted that most of the coefficients depend on the vehicle speed V which we assume constant, the sampling period ΔT and the random variable α.

The random vector $\underline{\mathbf{w}}$ represent the process noise which is assumed to be white and with normal probability distribution. Considering that the state components are uncorrelated, the error covariance matrix $Q = E[\underline{\mathbf{w}}.\underline{\mathbf{w}}^t]$ will be a diagonal matrix. The matrix coefficients stand for the expected variation of the parameters a_0, a_1, a_2, θ and h for the transition from time $\mathbf{t}$ to time $\mathbf{t} + \mathbf{\Delta T}$. In our implementation these values are fixed, their choice is made in function of the tolerance permitted upon the prediction of each parameter.

3.4 Measurement equation

The measurement equation expresses the relation between a point along the lane marker and its projection on the image plane. The image curve corresponding to a lane marker will be obtained by

substituting equation Eq(1) in equation Eq(2), and elimination of Z from equation Eq(3):

$$\mathbf{f}(\underline{\mathbf{x}}, \underline{\mathbf{z}}) = a_0 \frac{(y + e_y\theta)}{h} + a_1 (e_y - y\theta) + a_2 h \frac{(e_y - y\theta)^2}{(y + e_y\theta)} - x\frac{e_y}{e_x}(1 + \theta^2) \quad (7)$$

where the arguments of $\mathbf{f}$ are grouped as :

$$\underline{\mathbf{x}} = [a_0, a_1, a_2, \theta, h]^t$$
$$\underline{\mathbf{z}} = [x, y]^t$$

with $x = x_i - C_x$ and $y = y_i - C_y$ are the coordinates of a lane marker edge point. Note that:

- instead of $\underline{\mathbf{z}}$ we have a measured edge $\hat{\underline{\mathbf{z}}}$ corrupted with an error $\underline{\varepsilon}$ (resulting from sampling, edge extraction,...), such that $\hat{\underline{\mathbf{z}}} = \underline{\mathbf{z}} + \underline{\varepsilon}$. For the random error vector $\underline{\varepsilon}$, we assume that its mean is zero and its covariance is known:

$$E[\underline{\varepsilon}] = 0$$
$$E[\underline{\varepsilon}.\underline{\varepsilon}^t] = \Lambda$$

  where Λ is a positive symmetric matrix.

- the measurement equation Eq(7) is nonlinear in θ and h. The **KF** requires that any nonlinear constraint on the parameters to be estimated should be linearized [1, 2].

4 Estimation Algorithm

4.1 Initialization

For the first frame of the image sequence we search for the position of potential line markers as quadric curves. The lane markers edges are extracted using knowledge of their size, shape and brightness. The potential lane markers are then located using a perceptual organization approach (continuity and smoothness of shape) and geometric reasoning (they are parallel and constrained in width). A least square technique is then applied to estimate the lane markers parameters. This procedure, described in [7, 8], can be used to reinitialize the lane markers parameters in case of detected unconsistencies during the recursive parameters estimation steps.

4.2 Recursive Parameters Estimation

While the vehicle moves, the parameter estimation process is done continually based on the **KF**. For each new frame of the image sequence the following three steps are applied:

- **Prediction:** from the current estimated state vector $\underline{\mathbf{x}}$ at time $\mathbf{t}$, a prediction is made using the prediction equation of the **KF**, yielding the expected new state (lane markers) for the next image frame at time $\mathbf{t} + \mathbf{\Delta T}$;

- **Feature detection:** in the new image frame lane marker edges are extracted as new measurements ($\underline{\mathbf{z}}$) for the **KF**, this is done in two steps:

  a) the predicted lane markers are back-projected into the image plane, and search windows are defined around the expected lane markers (see Figure 4(left)).

  b) using the same approach as described in section 4.1, the lane markers are detected within the search windows. An example of edges found is shown in Figure 4(right);

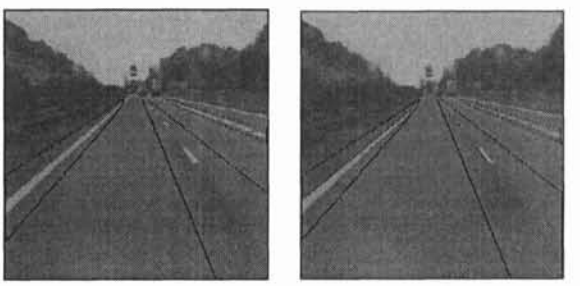

Figure 4: Feature detection: defined image windows (left), detected edges within the windows (right).

- **Innovation:** the detected edge points (measurements) and the predicted state vector are used in the updating equation of the **KF** to estimate the new model parameters.

5 Experimental Results

This paper describes our vision system for road lane markers detection and tracking. It has been successfully tested on several highway scene scenarios including sharp turns and lane change manoeuvres.

Examples of the results obtained from a sequence of 80 frames recorded during 6 seconds of highway driving are shown in Figures 5-6.

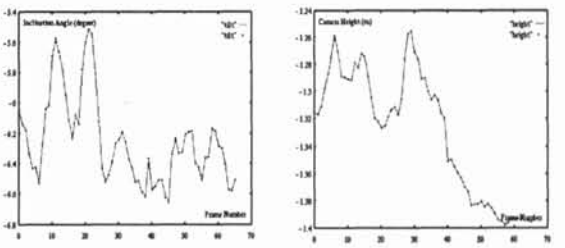

Figure 5: Estimated camera inclination angle and camera height for the image sequence of Figure 6.

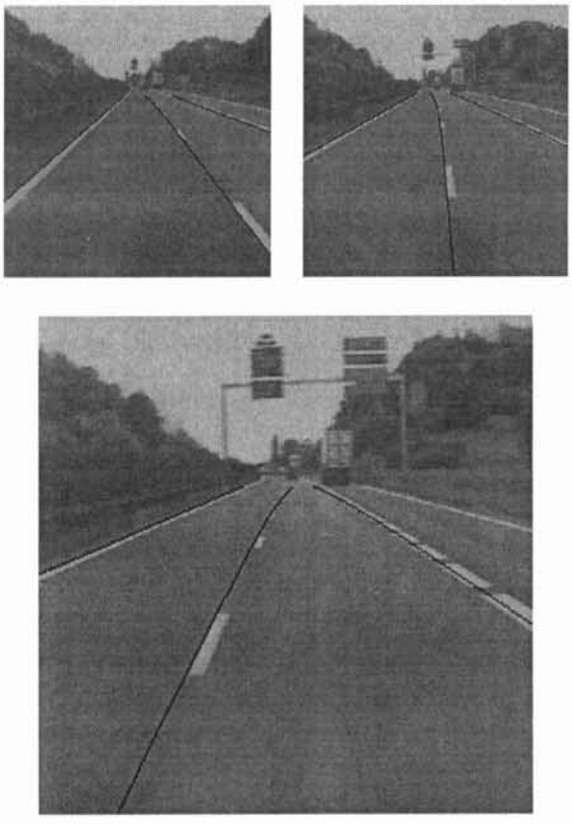

Figure 6: Estimated lane markers parameters for the 1st, 41th and 65th frame of the image sequence (80 images) corresponding to a lane change manoeuvre on a highway.

The success of our approach can be attributed to:

1. the 3D coordinate system attached to the vehicle rather than to the road,
2. the curve lane marker model which represents accurately straight lines and arc of circles, and contain explicitely the vehicle parameters (lateral position and heading),
3. recursively adjusting the camera parameters (θ and h),
4. the use of "dynamic" rather than fixed windows for global detection of the lane markers.

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