CONTROLE LINEAIRE D'UN VEHICULE A GRANDE VITESSE DANS L'ESPACE IMAGE

LINEAR CONTROL OF HIGH-SPEED VEHICLE IN IMAGE SPACE

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Résumé: Nous présentons dans ce papier, une nouvelle approche de commande linéaire d'un véhicule autonome à grande vitesse dans l'espace image. Notre application consiste en l'asservissement latéral d'un véhicule automobile par rapport aux bandes blanches d'une autoroute. Nous avons adopté une approche générale, qui consiste à intégrer les informations visuelles dans la boucle de commande. Il s'agit d'accomplir la tâche d'asservissement visuel en utilisant la caméra comme capteur unique. Le travail consiste en l'étude et l'application de cette boucle de contrôle sur la vision. Il traite les différents aspects du système: la modélisation de la scène, la modélisation du véhicule, et la synthèse d'une loi de commande linéaire.

Abstract: In this paper, we present a new approach of linear control of a high speed autonomous vehicle in image space. Our application involves controlling the lateral side of a car vehicle which follows a motorway white line. We have adopted a general approach which consists in the integration of visual information in the control loop. We plan to resolve the servoing task accomplishment by using visual information provided by a camera, used as a single sensor. The work consists in studying and applying this vision control loop. It deals with different aspects of the system: modelling of the scene, modelling of the robot, and designing of linear control law.

1. INTRODUCTION

Interest in mobile robots is growing rapidly because of the very broad range of their potential applications. The challenge is that these robots move intelligently so that they can perform various actions without human intervention. In the realm of intelligent highway vehicles, developing automated highways becomes necessary in order to have vehicles driving automatically down the road. In fact, a controller that can keep the vehicle centered in the road is required. Research efforts on automated highway systems have been conducted in many countries, in particular in the United States (Kehtarnavaz 1991), (Kanade 1987), (Waxman 1987) and in Germany (Dickmanns 1987). They include research on both lateral and longitudinal control of land and automotive vehicles, using different approaches. In France, the work of (Jurie 1992) and (Jurie 1994) is among the most notable in lateral control. He uses vision aspect and the camera is used as a single sensor. The methods, based on vision, use a general approach which separates vision from control. In other words, the vision aspect consists of extracting the 3D parameters used in the control loop. We propose in this paper, a higher performance based on a visual servoing approach, where the control is directly specified in terms of regulation in the image frame of the camera (Khadraoui 1994) and (Motyl 1993). With the visual servoing technique, we intend to reach a particular configuration in the image plane (see Figure 1) and not a situation between camera and object. Thus, a closed loop to perform from vision data makes it possible to compensate perturbations by using a robust control scheme. Our application involves controlling the lateral side of a car vehicle which follows the motorway white line. A complete 2D model of both the vehicle and the scene is then essential. It takes into account the characteristic features of the scene, the modelling of the camera,

and the modelling of the vehicle.
The main purpose of this study is the development of a new lateral control algorithm. We elaborate a new control model, based on state space representation, where the elements of the state vector is represented by the parameters of the scene, extracted by vision. For the vehicle, we establish general equations relative to an approximation of a bicycle model, taking into account its dynamic characteristics (Section 2). The scene considered here, is a straight line representing the projection of the white band of the road onto the image frame. Only the (a, b) representation of the line is treated in this paper (Section 3). A linear control law, based on pole assignment, is used to control the vehicle (Section 4). Finally, simulation results are presented in order to prove the convergence of the control scheme (Section 5).

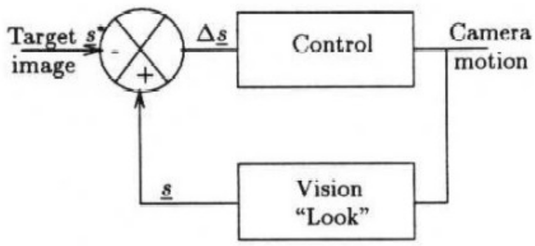

Fig. 1. Visual servoing approach

where:

- $\underline{s}^*$ is considered as a reference target image to be reached in the image frame.
- $\underline{s}$ is the value of visual information currently observed by the camera.

2. VEHICLE MODEL

In order to analyze the behavior of the system and understand its underlying physics, we need a mathematical model for characterizing the behaviors of its components and deriving the overall system behavior. A two-degree of freedom bicycle model is used for this issue. We develop the lateral model because we are only interested in the control of the lateral dynamics of the vehicle. The control point of the system is fixed at the center of gravity (c.g) of the vehicle.

2.1 KINEMATIC MODEL

In order to elaborate kinematic equations, we treat the translational and rotational motions assuming that the vehicle moves with small displacements between t and dt. In the case of a translational motion and for a uniform movement during a lapse of time dt, the vehicle moves with the distance d taking V as a longitudinal and constant velocity (see Figure 2).
We express:

$$\sin\psi = (x_{t+dt} - x_t)/d \tag{1}$$

with: $d = Vdt$
The approximation to small angles, gives us the relation between the differential of the lateral coordinate x of the c.g and the lateral deviation ψ:

$$\dot{x} = V\psi \tag{2}$$

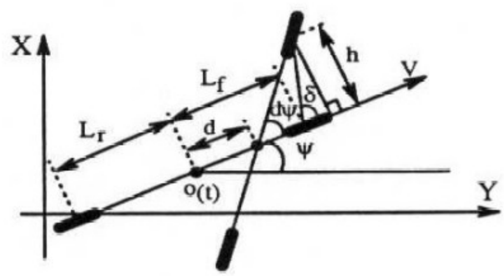

Fig. 2. Kinematic vehicle model

In the case of the rotational motion of the vehicle with respect to the c.g, it rotates with $d\psi$ angle (see Figure 2). Given the distance from the c.g to the front axle of the car L_f, we have:

$$\begin{cases} \sin(d\psi) &= h/L_f \\ \tan\delta &= h/d \end{cases} \tag{3}$$

By eliminating the variable h between the two equations of (3) and for the approximation to small angles, we express the relation between the steering angle δ and the velocity of the lateral deviation $\dot{\psi}$ as follows:

$$\delta = (L_f/V)\dot{\psi} \tag{4}$$

Finally, the car can be modeled by the following main differential equations representing the kinematic model:

$$\begin{cases} \ddot{x} &= (V^2/L_f)\delta \\ \dot{\psi} &= (V/L_f)\delta \end{cases} \tag{5}$$

2.2 MODEL OF LATERAL DYNAMICS

Differential equations are also used to model continuous dynamics of the vehicle. Thus, in Figure 3 we represent the set of the physical quantities whose identification determines the system's behaviour when it is submitted to a control. The lateral dynamic model of the vehicle is expressed by (Dickmanns 1987) :

$$\begin{cases} \ddot{x} = \frac{1}{m}[\frac{\mu}{V}(c_f + c_r)\dot{x} + \mu(c_f + c_r)\psi + \mu c_f \delta] \\ \ddot{\psi} = \frac{1}{I_z}[\frac{-\mu}{V}(c_f L_f^2 + c_r L_r^2)\dot{\psi} + \mu c_f L_f \delta] \end{cases} \quad (6)$$

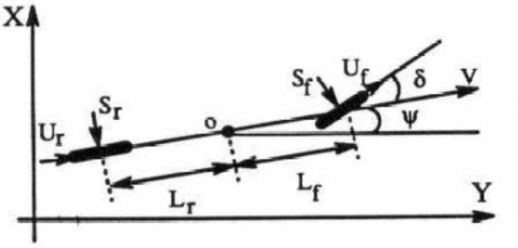

Fig. 3. Dynamics vehicle model

A description of the coefficients appears in the table below:

Parameter	Description
m	Vehicle mass (kg)
V	Longitudinal velocity (m/s)
c_f, c_r	Front and rear tire cornering stiffness (kn/rd)
I_z	Inertia ($kg.\ m^2$)
μ	Friction coefficient
L_f, L_r	Distance from front and rear axles to c.g (m)
δ	Steering angle (rd)
x	Lateral position (m)
ψ	Lateral deviation (rd)

3. VISION ASPECT

Our goal is to find an interaction between the 3D world and the 2D one. In other words, we find an interaction relation between the lateral position of vehicle x and its deviation ψ according to the (a, b) parameters of the line.

3.1 PERSPECTIVE PROJECTION

The scene is represented by a straight line in the 3D space for which we search an equation in the image frame of the camera. The passage from the 3D to the 2D space is based on the perspective projection. The transient relationship from a real point of the scene to the corresponding pixel of the image (see Figure 4) is given by:

$$p = MP \quad (7)$$

with:

- $P = (X, Y, Z, 1)^T$: coordinates of the point of the scene,
- $p = (u, v, w)^T$: coordinates of the projected point in the image frame reference,
- $x_e = \frac{u}{w}$ and $y_e = \frac{v}{w}$: coordinates of the corresponding point in the image plane.

The matrix M represents the homogenous calibration matrix of the camera-vehicle unit in relation to the real road reference.

$$M = PR_1R_2T \quad (8)$$

We take into account the intrinsic characteristics of the camera represented by P, the two rotations represented by R_1 and R_2 (vehicle lateral deviation and camera inclination), and the two translations (vehicle lateral position and camera height) represented by T.

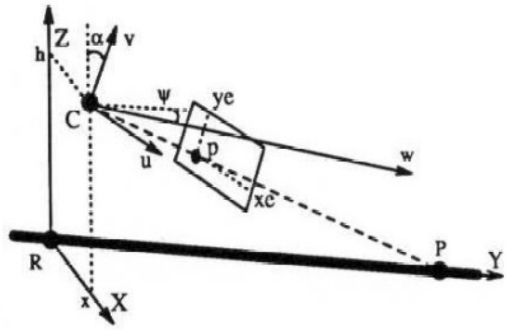

Fig. 4. Road and camera reference

We have:

$$P = \begin{pmatrix} e_u & 0 & 0 \\ 0 & e_v & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} f & 0 & 0 & 0 \\ 0 & 0 & f & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \quad (9)$$

$$R_1 = \begin{pmatrix} \cos\psi & -\sin\psi & 0 & 0 \\ \sin\psi & \cos\psi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (10)$$

$$R_2 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha & 0 \\ 0 & \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (11)$$

$$T = \begin{pmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & h \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (12)$$

where:

e_u, e_v (sensor scaling factors), and f (sensor focal) are the intrinsic constants of the camera; α is the constant camera angle of inclination; and h is the constant camera height.

- **Remark:** First, we note that the second translation and the third rotation are taken as null, and secondly that x (lateral position) and ψ (lateral deviation) are the variables of the system to control.

3.2 SIMPLIFYING HYPOTHESIS

As α and ψ are low ($< 10\,\text{deg}$), we obtain:

$$M \approx \begin{pmatrix} fe_u & -fe_u\psi & fe_u\alpha\psi & fe_u(x+\alpha\psi h) \\ 0 & fe_v\alpha & fe_v & fe_v h \\ \psi & 1 & -\alpha & x\psi - \alpha h \end{pmatrix} \quad (13)$$

The corresponding pixel coordinates of each point of the 3D line with $X = Z = 0$, are expressed by:

$$\begin{array}{l} x_e = fe_u(\psi Y + x + \alpha\psi h)/d_2 \\ y_e = fe_v(\alpha Y + h)/d_2 \end{array} \quad (14)$$

with:

$$d_2 = Y + \psi x - \alpha h \quad (15)$$

We introduce other simplifications in equations of (14) taking into account in real admissible values of different parameters of the system (Chapuis 1995). We obtain:

$$\begin{array}{l} x_e = fe_u(\psi Y + x)/Y \\ y_e = fe_v(\alpha Y + h)/Y \end{array} \quad (16)$$

3.3 INTERACTION RELATION

By eliminating Y from the two expressions (16), we find the equation of the line expressed in image frame by:

$$x_e = (e_u x/e_v h)y_e + fe_u(h\psi - \alpha x)/h \quad (17)$$

In the case of (a, b) parameters, we have :

$$\begin{array}{l} a = (e_u x/e_v h) \\ b = fe_u(h\psi - \alpha x)/h \end{array} \quad (18)$$

and thus, we express the lateral position x and lateral deviation ψ of the vehicle as follows:

$$\begin{array}{l} x = \xi_1 a \\ \psi = \xi_2 a + \xi_3 b \end{array} \quad (19)$$

with:

$$\left\{ \begin{array}{lcl} \xi_1 & = & e_v h/e_u \\ \xi_2 & = & e_v\alpha/e_u \\ \xi_3 & = & 1/fe_u \end{array} \right. \quad (20)$$

4. CONTROLLER DESIGN

We develop the problem of control, elaborating a linear control law. Here, we discuss the single input linear system in the case of (a,b) paramaters. To control such a model, a technique of pole assignment is used. We compute a complete model based on both parameters of the scene and those of the vehicle kinematic model.
We start by computing time variation of equations (19). We obtain:

$$\begin{array}{lcl} \dot{x} & = & \xi_1 \dot{a} \\ \dot{\psi} & = & \xi_2\dot{a} + \xi_3\dot{b} \end{array} \quad (21)$$

The equations of the kinematic model (5) are combined with those expressed in (21) and (19) and we find:

$$\begin{array}{lcl} V\psi & = & \xi_1\dot{a} \\ (V/L_f)\delta & = & \xi_2\dot{a} + \xi_3\dot{b} \end{array} \quad (22)$$

After some developments, we construct the system having form of state equations. This gives us:

$$\dot{s} = As + Bu \quad (23)$$

where:

- s is the visual information vector to compute at each iteration by image processing,
- u is the control variable to inject to the system at each step of servoing task,
- A and B are constant matrices.

with:

$$s = \begin{pmatrix} a \\ b \end{pmatrix} \quad (24)$$

$$A = V/\xi_1 \begin{pmatrix} \xi_2 & \xi_3 \\ -\xi_2^2/\xi_3 & -\xi_2 \end{pmatrix} \quad (25)$$

$$B = V/\xi_3 \begin{pmatrix} 0 \\ 1/L_f \end{pmatrix} \quad (26)$$

$$u = \delta \quad (27)$$

The vision based control law is given by:

$$u = G(s - s^*) \quad (28)$$

with:

$$G = \begin{pmatrix} g_1 & g_2 \end{pmatrix} \quad (29)$$

and:

$$(s - s^*) = \begin{pmatrix} a - a^* \\ b - b^* \end{pmatrix} \quad (30)$$

The coefficients g_i are computed by assimilating the behavior of the system to a second order system having ξ as a damping ratio and ω_0 as its frequency. We use the pole placement technique and we compute:

$$g_1 = -L_f\xi_1\omega_0^2(1 + \frac{2V\xi_2\xi}{\xi_1\omega_0})/V^2$$
$$g_2 = -2\xi\omega_0\xi_3 L_f/V \quad (31)$$

5. SIMULATION RESULTS

The controller is designed using the kinematic model of the vehicle but it is tested with the lateral dynamic one. The model's data of the vehicle used, corresponds to the real PSA vehicle (Citroën XM). The values of different parameters used, are presented in the table below.

Parameter	value
m	1200 (kg)
L	3 (m)
V	60 (km/h)
μ	0.1
c_r	50000 (kn/rd)
c_f	50000 (kn/rd)
I_z	2047 (kg m.m)
e_u	756.3636 (pixel/mm)
e_v	1008.48 (pixel/mm)
f	0.016 (m)
h	-1.5 (m)
α	7 (deg)
T	40 (ms)
ω_0	0.9 (rd/s)
ξ	0.7

In Figure 5.a the initial image seen by the camera is shown . It is represented by three lines, but the control law uses just one line (the middle line of the road). It corresponds to a lateral position of the vehicle of $0m$. We note that the width of the road is fixed at $3m$. Figure 5.b, shows the desired situation to reach in the image. It corresponds to a lateral position of $1.5m$ of the vehicle from the middle line. We perform the servoing task,

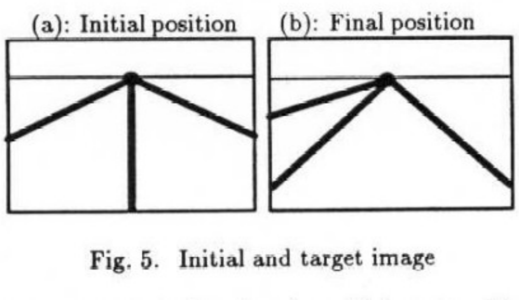

Fig. 5. Initial and target image

which consists in keeping the vehicle centered in the road in the equilibrium position. We can observe in Figure 6 that the convergence to the desired image target is well performed. Note that the noise introduced on the measurements in Figure 7 brings little perturbation to the system. We consider in our simulations that the visual information (a, b), are provided by the vision system at video rate ($40ms$). Figure 8 shows step responses (lateral position) of the closed loop system for different velocities. We remark that dynamic effects of the vehicle introduces some overshoots in the lateral position when the velocity V is high.

Simulation results without noise (V=60km/h)

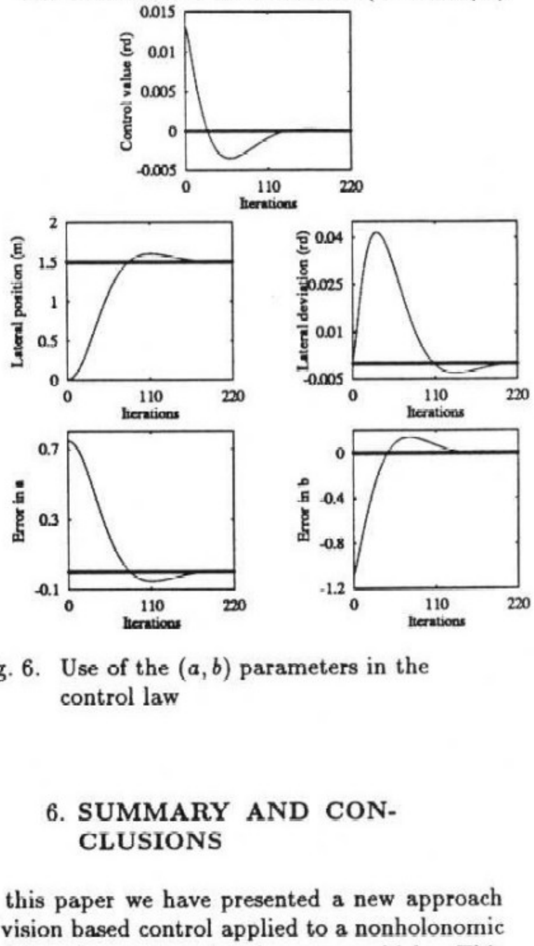

Fig. 6. Use of the (a, b) parameters in the control law

6. SUMMARY AND CONCLUSIONS

In this paper we have presented a new approach of vision based control applied to a nonholonomic mobile robot represented by a car vehicle. This vehicle is directly controlled using visual feature measured by a single camera. We elaborated a model of the vehicle in the image since the variables of the system become the information of the scene observed (the line in our case). This model needs to take into account both the vision aspect (perspective projection) and the vehicle model (bicycle model). A linear controller is designed by using a method of pole assignment. One advantage of our approach, is that the image processing is simplified and that the features measured in the same space are directly introduced in the control loop. It has the advantage of avoiding the intermediary step of 3D estimation of the

Simulation results with noise (V=60km/h)

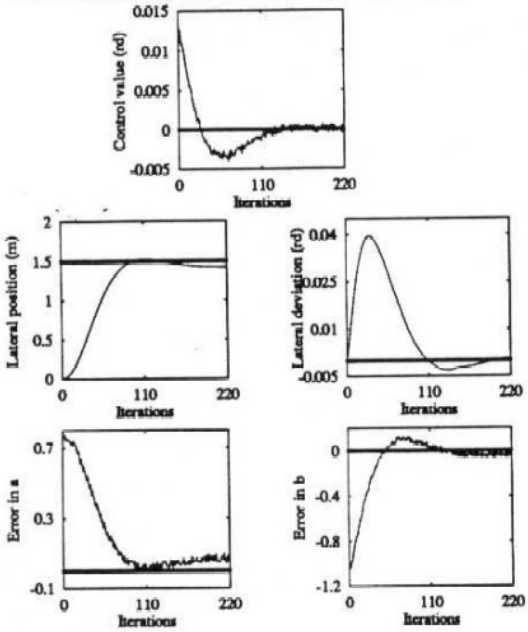

Fig. 7. Use of the (a, b) parameters in the control law (with noise)

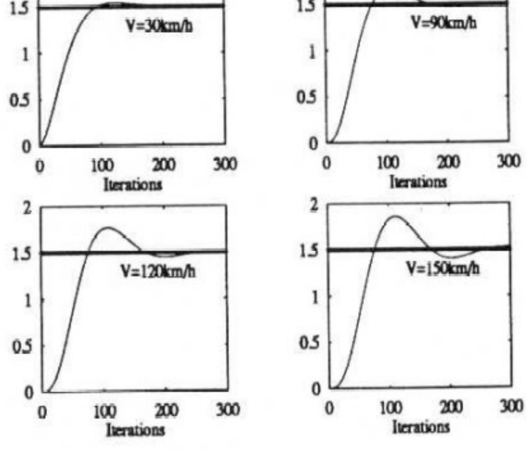

Fig. 8. Step responses of closed loop system for different velocities: lateral position (m)

workpiece with regard to the vehicle. Here we tested the feasibility of the approach and the performance of the algorithm tested in simulation is satisfactory since the convergence to the desired configuration is well performed. Future issues will consist of increasing the modelling of the steering system of the vehicle. In other words, a complete and general modelling will be done by using different representations of the line and different models of nonholonomic mobile robots.

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