First Results Using Robust Controller Synthesis in Automatic Guided Vehicles Applications

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Abstract: We have been interested in Automatic Guided Vehicles (AGV) for several years. In this paper, we synthesize controllers for AGV applications. Particularly, we are interested in road following and direction change tasks, and in analyzing the influence of roll and pitch perturbations on vehicle behaviour. We use the bicycle as the kinematic vehicle model, and we choose the white band position of the road as the sensor signal. We define an interaction between the camera, which is mounted inside the vehicle, and the white band detected in the image space. Using this kind of interaction, we present how to use a pole assignment technique to solve the servoing task. We show the simulation and experimental results (1/10 scale demonstrator) with and without perturbations. Then, we investigate in robust controller to slow down the effect of perturbations on the vehicle behaviour.

Keywords: Visual servoing, robust control, mobile robot, vehicles, modelling, vision

1. INTRODUCTION

In the realm of intelligent systems for highways, development of AGV is necessary to enable vehicles to drive automatically along the road. In fact, the requirement is for a controller that can maintain the position and the orientation of the vehicle with respect to the centre of the road and/or apply changes of direction. The problem of vehicle control using a camera has been given considerable attention by many authors (Dickmanns and Zapp, 1987; Kehtarnavaz *et al.*, 1991; Raymond and Chaouchi, 1994; Wallace *et al.*, 1986; Waxman *et al.*, 1987). The work described in (Jurie *et al.*, 1992; Jurie *et al.*, 1993; Jurie *et al.*, 1994) is among the most notable in lateral control using monocular vision. It consists of the reconstruction of the road using the 2D visual information extracted from the image processing system (Chapuis *et al.*, 1995). In recent years, the integration of computer vision in robotics has steadily progressed, from the early "look and move" systems, to current systems in which visual feedback is incorporated directly into the control loop. These techniques of vision based control are used to control holonomic robots in different domains (Feddema and Mitchell, 1989; Khadraoui *et al.*, 1996; Papanikolopoulos *et al.*, 1991; Papanikolopoulos *et al.*, 1993).

The principle of this approach is based on the task function approach (Samson *et al.*, 1991), and many people have developed this concept applied to visual sensors (Chaumette, 1990; Espiau *et al.*, 1992; Hutchinson *et al.*, 1996). There are still few applications in mobile robots using this kind of approach. The main difficulty is due to the presence of nonholonomic mechanical connections which limit robot movements (Pissard-Gibollet and Rives, 1991).

We have proposed a new technique with a visual servoing approach, in which control incorporates the visual feedback directly (Khadraoui *et al.*, 1995; Martinet *et al.*, 1997). In other words, this is specified in terms of regulation in the image frame of the camera. Our application involves controlling the lateral road position of a vehicle following the motorway white line. A complete 2D model of both the vehicle and the scene is then essential. It takes into account the visual features of the scene and the modelling of the vehicle.
The main purpose of this study is the development of a new lateral control algorithm. We propose a new control model, based on state space representation, where the elements of the state vector are represented by the parameters of the scene, extracted by vision. Then, we use robust control approach to improve the vehicule behaviour when we introduce perturbations in the closed loop. These approaches were experimented with a 1/10 scale demonstator. It is composed of a cartesian robot with 6 degrees of freedom (built by the firm AFMA Robot) and the parallel vision system WINDIS (Martinet *et al.*, 1991; Rives *et al.*, 1993). This whole platform is controlled by a VME system, and can be programmed in C language under the VxWorks real time operating system. The CCD camera is embedded on the end effector of the cartesian robot and is connected to the vision system WINDIS. The road, built to a 1/10 scale, comprises three white lines. For each level of this vision system, we introduced parallelism allowing us to reach video rate for most of the application tasks. The vision system computes the (a, b) parameters of the projected line in image plane at video rate. In this implementation, we have identified a data flow latency of three sample periods.

2. MODELLING ASPECT

Before synthesizing the control laws, it is necessary to obtain the model of the vehicle and the one which expresses the interaction between the sensor and the environment. We just indicates the main results of modelling aspect presented in (Martinet *et al.*, 1997)

It is useful to approximate the kinematic of the steering mechanism by assuming that the two front wheels turn slightly differentially. Then, the instantaneous center of rotation can be determined purely by kinematic means. This amounts to assuming that the steering mechanism is the same as that of a bicycle. Let the angular velocity vector directed along z axis be called $\dot{\psi}$ and the linear one directed along x axis called $\dot{x}$.

The approximation to small angles gives us the relation between the differential of the lateral coordinate x and the lateral deviation ψ with regard to δ, expressed as follows:

$$\begin{cases} \dot{x} = -V\psi \\ \dot{\psi} = \dfrac{V}{L}\delta \end{cases} \quad (1)$$

The scene consists of a $3D$ line and its projected image is represented by a $2D$ line (Chapuis *et al.*, 1995).

The equation of the line expressed in the image frame is given by the following relation:

$$X = aY + b \quad (2)$$

where (a, b) are the line parameters expressed by:

$$\begin{cases} a = \dfrac{f_x x}{f_y h} \\ b = f_x \left(\dfrac{\alpha x}{h} + \psi\right) \end{cases} \quad (3)$$

and:

- h is the camera height
- α is the inclination angle of the camera
- ψ is the orientation of the vehicle
- f_x and f_y are the intrinsic parameters of the camera

3. CONTROL ASPECT

In this section, we show how to synthesize controllers. First, we establish the state equation of the system, and we define a controller with a pole assignment technique and different characteristics. We verify by simulation the system behaviour without perturbations. We then introduce some perturbations, and analyse the simulation and experimental results.

Secondly, we use robust controller synthesis to improve the ouput behaviour and the vehicle behaviour. Many authors, like (Banyaz and Keviczky, 1996; Carabelli and Malan, 1996; Doyle *et al.*, 1989; Dorato and Li, 1986), have contributed to developp this approach. (Byrne and Chaouki, 1994) has applied this technique to the Lateral Control of Vehicles.

3.1 *Pole assignment approach*

3.1.1. *Controller design*

Here, we present the application of the pole assignment technique when the state model is expressed directly in the sensor space. In our case, the sensor space is the image plane. The controller design is based on the kinematic model of the vehicle. We use the (a, b) parameters of the $2D$ line in the image plane as the state vector. We drive the vehicle with the action on the wheel angle δ. We choose b as the ouput parameter of the system and use the results of the vehicle and scene modellings to obtain the following equation:

$$\begin{cases} -V\psi &= \xi_1 \dot{a} \\ (V/L)\delta &= \xi_2 \dot{a} + \xi_3 \dot{b} \end{cases} \qquad (4)$$

The state vector, denoted by $\underline{s} = (a, b)^T$, is equal to the sensor signal vector in the state space representation. Developing, we have the following state model of the system:

$$\begin{cases} \dot{\underline{s}} = A\underline{s} + B\delta \\ b = C\underline{s} \end{cases} \qquad (5)$$

We introduce an integrator into the control law in order to eliminate the static error in case of perturbations. The visual servoing scheme is presented by the figure 1 .

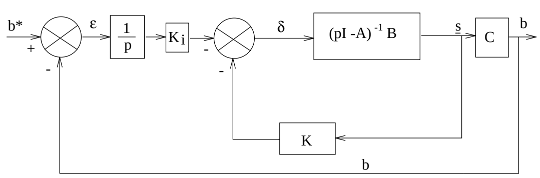

Fig. 1. Visual servoing scheme with integrator

In this case, we can express the control law by the relation:

$$\delta = -k_1 a - k_2 b - K_i \int (b^* - b) dt \qquad (6)$$

where k_1, k_2 and K_i are the gains of the control law obtained by identifying the system to a third order system characterized by the following characteristic equation: $(p^2 + 2\xi\omega_0 p + \omega_0^2)(p + \xi\omega_0)$.

3.1.2. *Simulation and Experimental results*

To validate this control law, we use a simulator developed with Matlab. We use the kinematic model of the vehicle to simulate the behaviour of the vehicle, and the perspective projection relation to obtain the sensor signal $\underline{s} = (a, b)^T$. The first results (see figure 3) illustrate the output behaviour of the system corresponding to an input value $b^* = 100$ pixels. We take into account a data flow latency (three sample periods) in all simulation tests. This was identified on our experimental site.
We chose $\omega_0 = 2rd/s$ and $\xi = 0.9$ in order to fix the behaviour of the system.

We introduce some perturbations in the α angle (from $\alpha = -5$ to $\alpha = -10$). In fact, no static error persists during servoing, but some oscillations and problems of stability appear when α is far from the reference value of α $(-7 degrees)$. The corresponding experimental results take place in right of the figure 3 and confirm the simulation trends.

3.2 *Robust Control approach*

3.2.1. *Controller design*

Here, we present the application of the robust control technique, particularly in H_∞ space.

The visual servoing scheme is presented by the figure 2 .

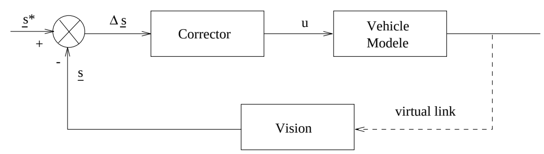

Fig. 2. Visual servoing scheme in H_∞ space

We consider an additive perturbations in frequency domain :

$$F(p) = F_0(p) + \Delta F(p) \qquad (7)$$

The aim is to determine a single robust controller $c(p)$ which insures the stability of the closed loop system. $c(p)$ insures the stability of $F_0(p)$. If the following condition is verified :

$$|\Delta F(j\omega)| \leq |r(j\omega)| \quad \forall\omega \qquad (8)$$

then we can can express the robust stability condition as (Kimura, 1984) :

$$||u(p)||_\infty = ||q(p)r(p)||_\infty < 1 \qquad (9)$$

In theses conditions, the robust controller can be expresses by :

$$\begin{cases} q(p) = \dfrac{u(p)}{r(p)} \\ c(p) = \dfrac{q(p)}{1 - F_0(p)q(p)} \end{cases} \qquad (10)$$

Considering b parameter as the oupput of the system, we define :

$$\begin{cases} F_0(p) = b/\delta = (V^2\xi_2 + p\xi_1 V)/(\xi_1\, p^2 L\xi_3) \\ \dfrac{\Delta F(p)}{F_0(p)} = \dfrac{V\Delta\xi_2 + p\Delta\xi_1}{V\xi_2 + p\xi_1} + \dfrac{\Delta\xi_1}{\xi_1} \end{cases} \qquad (11)$$

with : $\Delta\xi_2 = -\Delta\alpha\, f_y/f_x$ and $\Delta\xi_1 = \Delta h f_y/f_x$

Using the following expression of $r(p)$:

$$r(p) = \sup_{\omega} |\frac{\Delta F(j\omega)}{F_0(j\omega)}| \;\; F_0(p) \qquad (12)$$

and after some developments, we obtain the robust controller $c(p)$:

$$\frac{K\,\xi_1\; L\,\xi_3\, p^2\,(p+p_1)}{V\,(p\xi_1 + V\xi_2)\,[p^3 + p^2\lambda_1 + p\lambda_2 + \lambda_3]} \quad (13)$$

3.2.2. *Simulation and experimental results*

As for the pole assignment technique, we have developped a simulator in matlab. We introduce perturbations on α angle (from $\alpha = -3$ to $\alpha = -10$) during simulation. Figure 4 shows the simulation and experimental results of robust control approach using b parameter as the output of the system. There is no static error during servoing and the stability is well improved.

If we look at figure 5, we can compare the behaviour of the lateral position of the vehicle. In left, we have the behaviour when we use the pole assignment technique, and in right the one corresponding to robust control technique. We conclude that the behaviour is more stable with robust controller, but we observe a constant offset in the lateral position depending on the α angle variation.

To solve this problem, we use the a parameter of the line as the output of the system, to synthesize a new robust controller using the H_∞ technique. The experimental results are presented in figure 6. It illustrates the ouptut behaviour of the system corresponding to an input value $a^* = 0.4$ and the behaviour of the lateral position. As we can see, there is no static error in the output response and no offset in the lateral position when we introduce perturbations on α angle.

4. CONCLUSION AND FUTURE WORK

Controllers based on a visual servoing approach, have been developed in this paper. We designed a controller with a pole assignment technique directly in the image space. After modelling the vehicle and the scene, we obtained equations which can be used to write the state model of the system. Visual servoing is performed well when there are no perturbations. When perturbations occur, a static error and oscillations appear. By introducing an integrator into the visual servoing scheme, we suppress the static error but amplify the oscillation problem.

Then, we investigate a robust control approach. The choice of b as the ouput parameter of the system does not permit the control of the lateral position of the vehicle precisely when the perturbations appear, but insure a heading control. The choice of a parameter as the output of the system, to synthesize a new robust controller, seems to be good enough when we have perturbations on α angle. In the future, we will investigate a controller which can take into account a combination of perturbations on α angle and perturbations on camera height. We assume that experimentation on a real vehicle will be necessary to validate all of the primary results presented in this paper.

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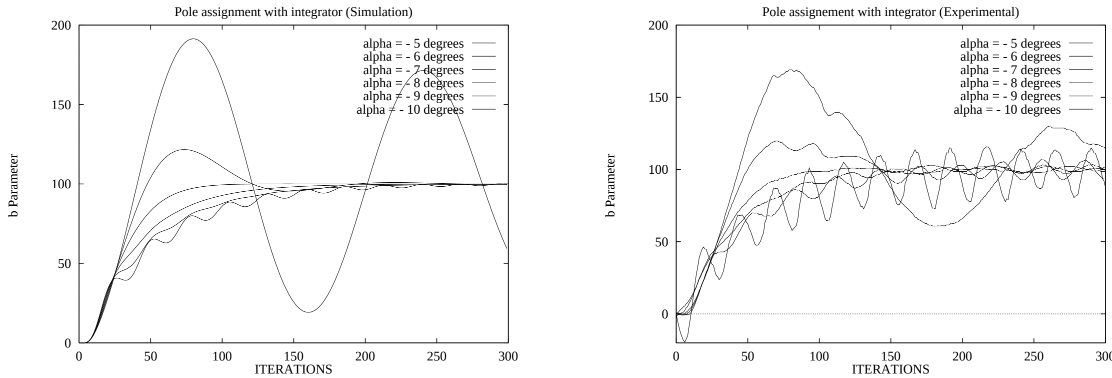

Fig. 3. Pole assignment approach: b Output behaviour (α from -6 to -10 degrees)

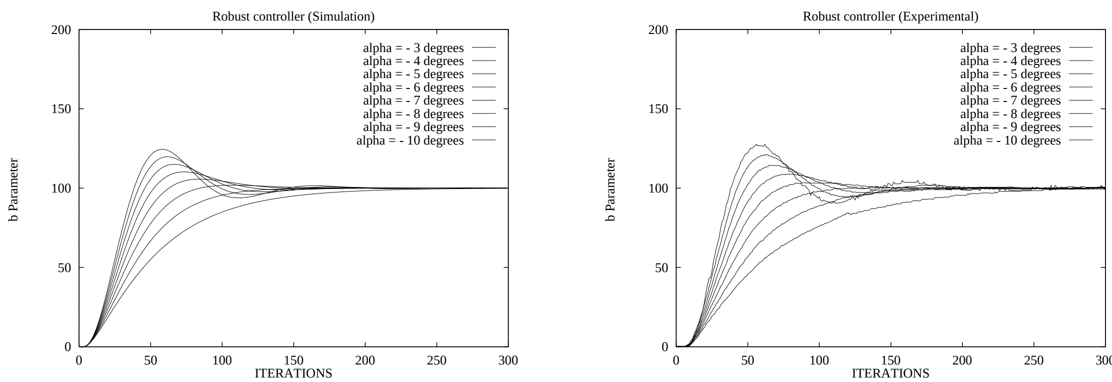

Fig. 4. Robust control approach: b Output behaviour (α from -3 to -10 degrees)

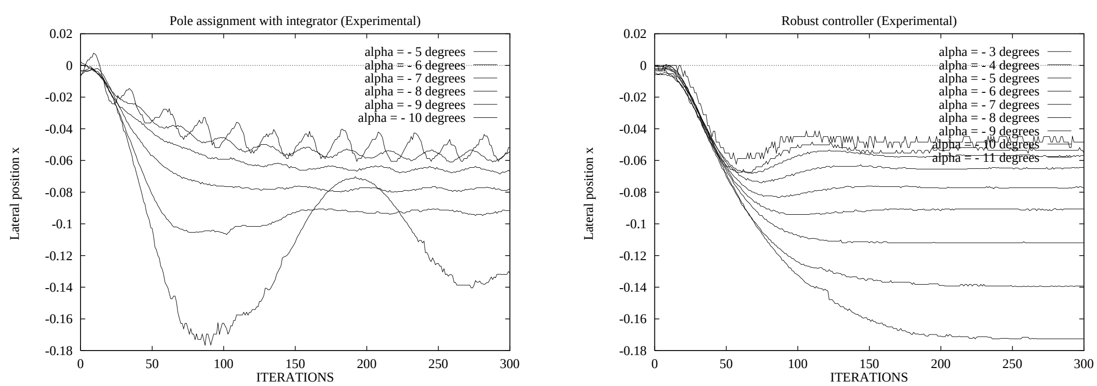

Fig. 5. Lateral position behaviour (Pole assignment and robust control approach)

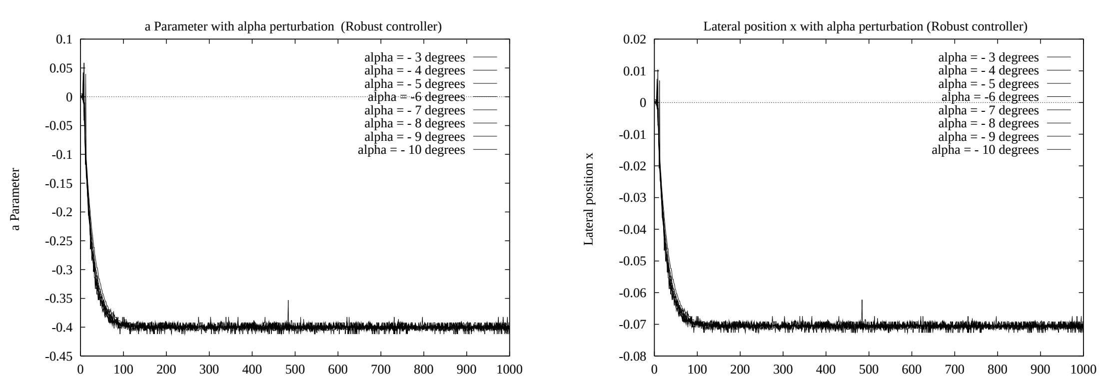

Fig. 6. a Parameter and lateral position behaviour with alpha perturbation (Robust control approach)