SYNTHESIS OF A SPATIAL LOOKAHEAD PATH TRACKING CONTROLLER

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Abstract: This paper investigates the synthesis of a non-linear spatial lookahead controller for path tracking of Ackerman-steered autonomous vehicles. Controller tuning is performed using stability results and optimization techniques. Controller performance is analyzed when the vehicle follows different paths at different speeds. Finally experiments have been conducted using the ROMEO 4R autonomous vehicle.

Keywords: mobile robots, autonomous vehicles, position control, controllers setup.

1. INTRODUCTION

Autonomous guidance of ground vehicles and mobile robots has been a research and development topic in the last 20 years. Many different methods have been applied to accomplish this. Some of them include the vehicle dynamic model, like the LQG/LQR techniques proposed by Elkaim, *et al* (1997) and other linear and nonlinear control laws (Canudas, et al, 1997; Peng and Tomizuka, 1993). On the other hand, there are methods based on neural networks or fuzzy logic (see Ollero, *et al*, 1999) that do not use the vehicle model. Finally, the geometric methods pure-pursuit, proposed by Amidi (1990), and vector pursuit, presented by Wit, *et al.* (2004), have also shown good performance in some conditions.

In this paper, a geometric method, called spatial lookahead controller is used for performance analysis and parameter setting. This method proposed by Castaño, *et al* (2004), is a modifed version of the ε-controller developed by Davidson and Bahl (2001). The spatial lookahead controller computes the normal distance, ε, to a point placed L meters ahead on the path (see Fig. 1). This is a better error measurement than the normal distance *e* for Ackerman-steered vehicles due to steering constraints.

This paper is focused on the parameter setting and the performance analysis of the controller, using stability results previously developed and optimization techniques.

This paper is organized as follows. Section 2 briefly describes the path tracking controller and frame notation. Section 3 describes the paths, index and scenarios for the performance analysis that is used for parameter setting. In section 4 the parameter setting is discussed and a tuning law is proposed. Simulation and experimental results are discussed in sections 5 and 6 respectively. Finally, in section 7 some conclusions and guidelines for future works are stated.

2. CONTROLLER OVERVIEW

The proportional lookahead spatial controller is a regulator that operates on the vehicle normal deviation ε (see Fig. 1) from the desired path. This normal deviation is calculated at a lookahead, *L*, distance on the path.

The controller generates a desired velocity vector $\mathbf{V_I}$ which depends on the lateral deviation from the path. This, $\mathbf{V_I}$, vector can be expressed using two vectors:

one tangent to the path (***V_t***) and other normal to the path (***V_n***). If the vehicle is near the path, the controller increases ***V_t*** and decreases ***V_n***, allowing the vehicle to get closer to its maximum speed *V*. However, when the vehicle is far from the desired path, ***V_n*** is increased and ***V_t*** is decreased, reducing the speed of the vehicle. In the controller presented, ***V_n*** is proportional to ε:

$$|\mathbf{V_n}| = K_p \varepsilon$$
$$|\mathbf{V_t}| = \begin{cases} V - |\mathbf{V_n}| & |\mathbf{V_n}| < V \\ 0 & |\mathbf{V_n}| \geq V \end{cases} \qquad (1)$$

Once $\mathbf{V_I}$ is obtained, an algorithm converts the desired velocity vector of the middle of the front axle $\mathbf{V_I}$ into vehicle control setpoints. This is accomplished by rotating the velocity vector, given in a Global Coordinate System (GCS), into the vehicle-fixed coordinate system (see Fig. 2):

$$\begin{aligned} \mathbf{V_I} &= (V_{X_G}, V_{Y_G}) \\ V_{X_B} &= V_{X_G} cos\theta + V_{Y_G} sin\theta \\ V_{Y_B} &= -V_{X_G} sin\theta + V_{Y_G} cos\theta \end{aligned} \qquad (2)$$

Finally, the steering angle setpoint is obtained from the vehicle geometry:

$$\alpha = tan^{-1}\left(\frac{-V_{X_B}}{V_{Y_B}}\right) \qquad (3)$$

And V_{Y_B} is selected as the speed setpoint.

Then, proper values for the parameters *L* and K_p should be selected to achieve a good controller performance.

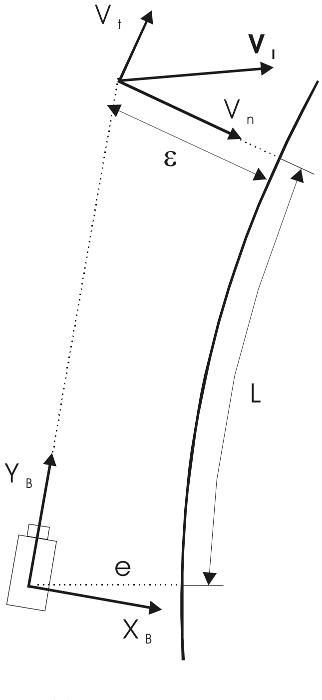

Fig. 1. Path tracking.

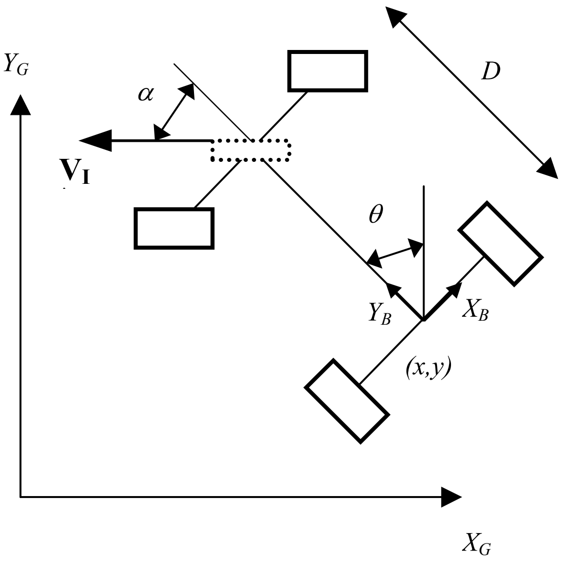

Fig. 2. Coordinate system and frame notation.

3. PERFORMANCE ANALYSIS SCENARIO

The performance of the algorithm has been studied when the vehicle follows “U” turns with radious 10, 20, 40 and 100 meters. These “U” turns are made of a 15 meters straight segment, a semicircular arc of a given radious and a 35 meters stright segment, as shown in Fig. 3. Vehicle start point is (0,0), with an initial yaw *$\theta = 0$*. The vehicle follows these paths at speeds from 1 m/s up to 20 m/s.

The integral of the lateral distance to the path *e* (see Fig. 1) is selected as the performance index to setup the controller, and will be referred as IE in figures and tables. The same conclusions are obtained if the maximum value of *e* is used as the performace index instead of the integral.

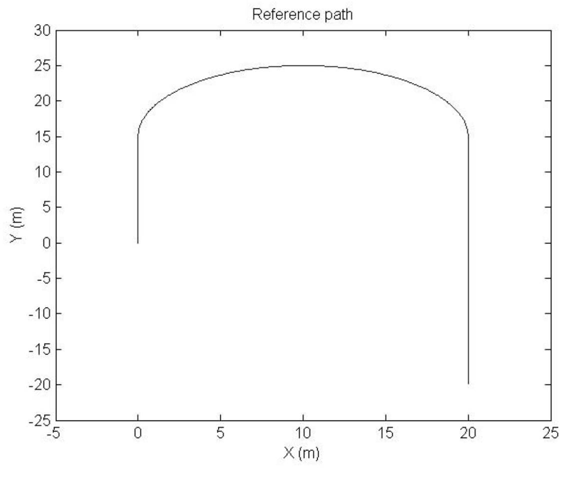

Fig. 3. Reference path.

A vehicle model that includes kinematic Ackerman-steering and actuators dynamics has been implemented in Matlab/Simulink. The conventional Ackerman steering system is approximated by a typical "bicycle" kinematic model (see Fig. 2), and steering and traction actuators dynamic are modelled as first order systems:

$$\begin{aligned} \dot{x} &= -v\sin\theta \\ \dot{y} &= v\cos\theta \\ \dot{\theta} &= v\gamma \\ \gamma &= \frac{\tan\alpha}{D} \\ \dot{\gamma} &= \frac{1}{T_\gamma}(\gamma_d - \gamma) \\ \dot{v} &= \frac{1}{T_v}(v_d - v) \end{aligned} \tag{4}$$

Parameters for the ROMEO 4R are T_γ=1 second, T_v=1.5 seconds and D=1.65 meters.

4. PARAMETER SETTING

As pointed out in section 2, the parameters L and K_p should be adjusted for a properly performance. Stability results and optimization of performance index are used for this goal.

Parameter bounds for a stable navigation have been shown in a previous work (Castaño, *et al.* 2004) and can be seen in Fig. 4. The controller is stable if $L \geq VT_\gamma$. Then, if the speed V is increased the stability limit grows towards high L values. So L should be selected greater than $V_{max}T_\gamma$ to avoid unstablity, but the "cutting corner" effect when following the path appears with large values of L, as shown in Fig. 5.

On the other hand, the controller is also stable if $L < VT_\gamma$ and $K < K_{cr}$:

$$K_{cr} = \frac{1}{T_\gamma - \dfrac{L}{V}} \tag{5}$$

In this case K_{cr} changes with speed and goes to $1/T_\gamma$ as speed V is increased (see Eq. 5). So K_p should be lower than $1/T_\gamma$ to avoid unstability. This setup reduce the "cutting corner" effect because a low value of L can be used while the system is stable (see Fig. 6).

Then, optimization techniques are applied to obtain the best performance while the vehicle follows "U" turns with radious R=10, 40, 100 meters at speeds up to 20 m/s. In all cases the performance index have a minimum in the area around $K_p=1/T_\gamma$ and bounded by L=1.0-1.5. In Fig. 7 and 8 these minima are shown for L=0, and in Fig. 9 and 10 the minima are presented for K_p=0.6.

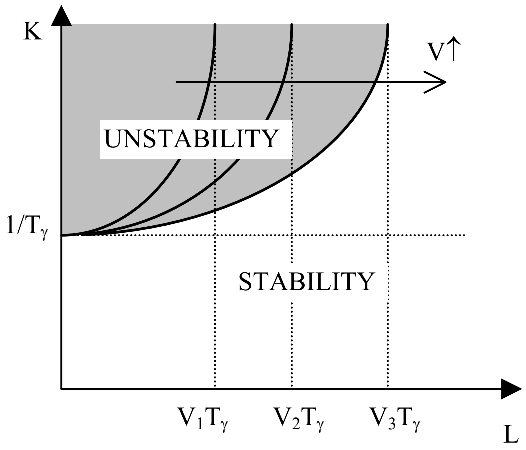

Fig. 4. Controller stability conditions.

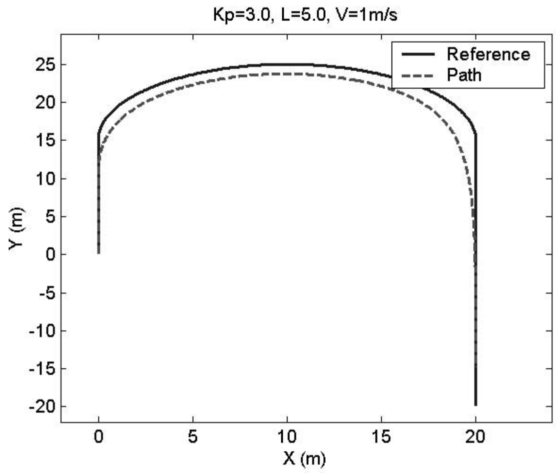

Fig. 5. "Cutting corner" effect in path tracking due to large lookahead L.

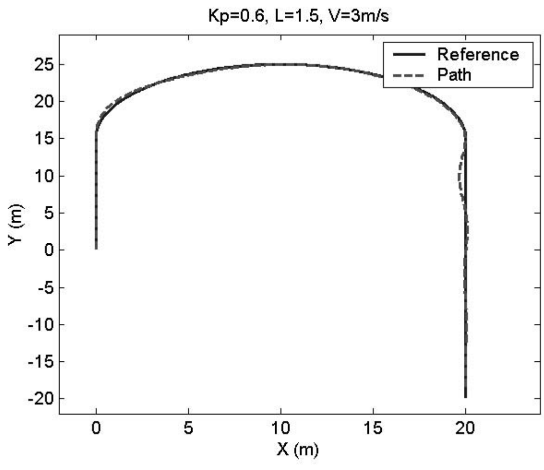

Fig. 6. Path tracking performance with low L value and $K_p < K_{cr}$=2.

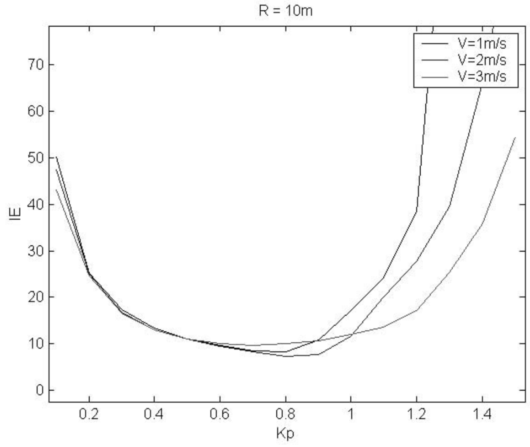

Fig. 7. Performance index vs K_p, for L=0 and R=10m at speeds up to 3 m/s.

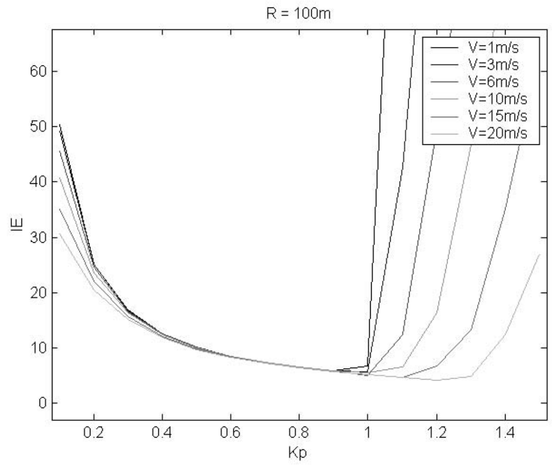

Fig. 8. Performance index vs K_p, for L=0 and R=100m at speeds up to 20 m/s.

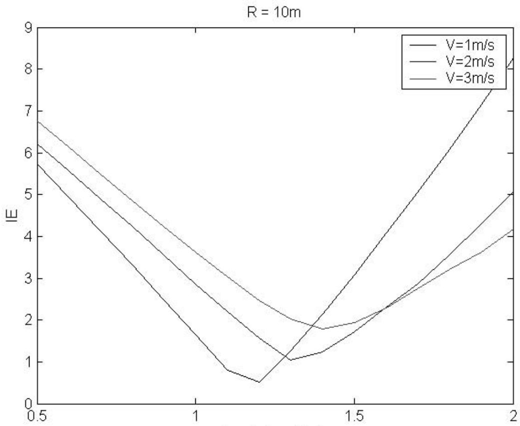

Fig. 9. Performance index vs L, for K_p=0.6 and R=10m at speeds up to 3 m/s.

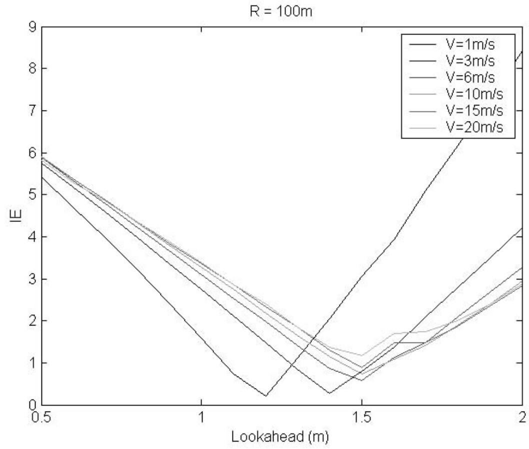

Fig. 10. Performance index vs L, for K_p=0.6 and R=100m at speeds up to 20 m/s.

These simulation and optimization techniques have been applied using other T_γ values (0.5 and 2.0) and the conclusions are the same, as shown in Fig. 11 and 12 for T_γ=0.5.

Then, the proposed parameter setting for this controller is:

$$\begin{aligned} &K_p = \alpha \frac{1}{T_\gamma} \qquad \alpha = 0.6\text{-}0.8 \\ &L = 1.0\text{-}1.5 \end{aligned} \tag{6}$$

5. SIMULATION RESULTS

The proposed controller is compared with a typical Pure-Pursuit (PP) technique (Amidi, 1990). The vehicle follows “U” turns and “8” paths (see Fig. 3 and 13) of different radious at different speeds.

The Pure-Pursuit controller has been tuned for each condition, so L is different for each speed and path in this comparison.

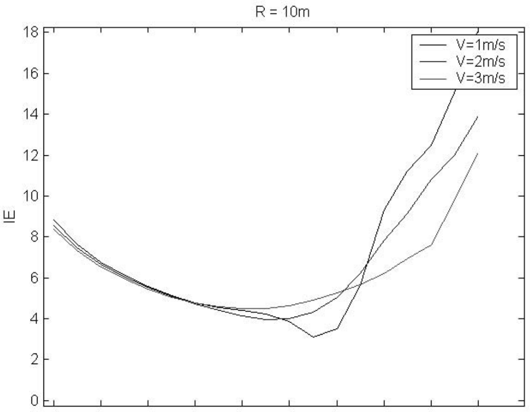

Fig. 11. Performance index vs K_p, for T_γ =0.5, L=0 and R=10m at speeds up to 3 m/s.

The spatial lookahead controller has been tuned using the proposed setting:

$$\begin{aligned} K_p &= 0.6 \frac{1}{T_\gamma} = 0.6 \\ L &= 1.2 \end{aligned} \tag{7}$$

These parameters remain constant for each simulation and condition.

As can be seen in Table 1, the performance of the proposed controller is better than the Pure-Pursuit (PP) performance, even though the Spatial Lookahead Controller (SLC) has not been tuned specifically for each condition navigation. Morover, control signals generated by the SLC are lower than the PP signals.

Table 1 Simulation results comparing Pure-Pursuit (PP) and Spatial Lookahead Controller (SLC)

Path	Speed (m/s)	PP (IE)	SLC (IE)
U R=10m	1	0.71	0.52
U R=10m	3	3.55	2.46
U R=100m	1	1.17	0.20
U R=100m	20	6.10	2.40
8 R=10m	1	1.40	1.56
8 R=10m	3	6.80	6.43
8 R=30m	1	0.85	0.97
8 R=30m	6	10.23	8.10

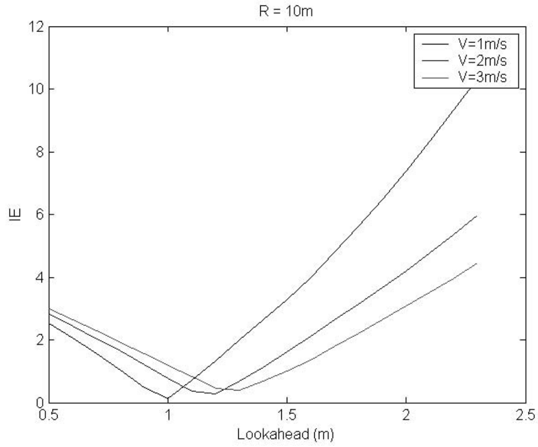

Fig. 12. Performance index vs L, for T_γ =0.5, K_p=1.2 and R=10m at speeds up to 3 m/s.

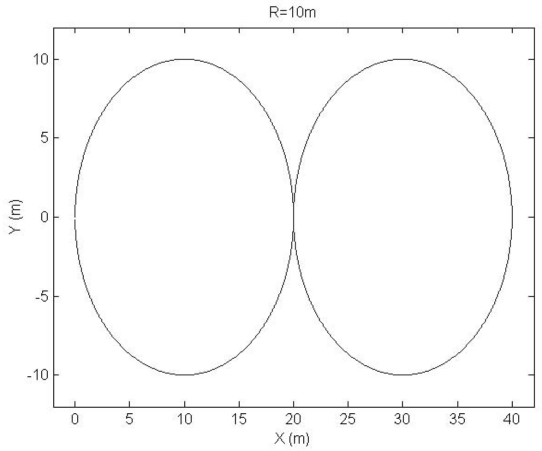

Fig. 13. “8” reference path with 10 meters radious for simulation and comparison.

6. EXPERIMENTS

The controller has been implemented and tested in the autonomous vehicle ROMEO4R (see Fig. 14). ROMEO4R is an electrical golf cart like vehicle with Ackerman steering that is adapted for autonomous navigation. It weights 700 Kg. and is 2 meters long.

Automatic steering has been implemented by using a 80W DC motor that is connected to the steering column through a reduction gear and an electromagnetic clutch. Traction power is achieved by a 2 CV DC motor. Both motors are actuated through a motion control card.

The vehicle is provided with a wide set of sensors, including a gyroscope and encoders for dead-reckoning estimation, a GPS receiver, a 2D laser range finder, 2 cameras and 10 sonars attached around the vehicle.

The on-board control system is composed of two computers connected by an ethernet link. An industrial Pentium 133 PC, with 64 Mb RAM memory, and Debian GNU/Linux 2.2.r4 carries out position estimation and low level control, i.e. speed and steering angle. Path tracking is also performed in this computer. The other computer is similar and used for image processing issues.

Experiment done tracking a 10 meters radious “U” turn at 1 m/s is shown in Fig. 15. The maximum normal deviation to the path is quite small: 4 cm in simulation and 11 cm in the real experiment. A more detailed view of the vehicle getting out of the turn can be seen in Fig. 16. Errors are greater than the ones obtained in simulation. This could be mainly due to unmodeled nonlinearities in the steering column control.

Fig. 14. ROMEO 4R autonomous vehicle.

7. SUMMARY AND CONCLUSIONS

Parameter setting for a nonlinear spatial lookahead path tracking controller has been proposed. Controller tuning has been done taking into account stability results and optimization techniques. The proposed tuning law has been tested through simulation and has been compared to a typical Pure-Pursuit controller. The performance of the proposed controller is better and more robust that the Pure-Pursuit. Morover, control signals are lower with the spatial controller, so the navigation is smoother and the vehicle steering system works less hard than with PP. Finally experiments have been done with the ROMEO 4R vehicle to validate simulation results. The experiments agree with the performance of the spatial controller, but lateral distance to the path is a little higher than obtained in simulations. Future work will include extensive experimentation and adaptive methods to optimize the controller in real-time.

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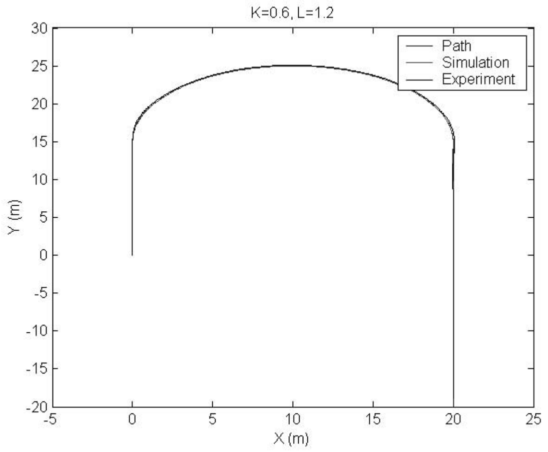

Fig. 15. Experiment with ROMEO 4R spatial lookahead controller.

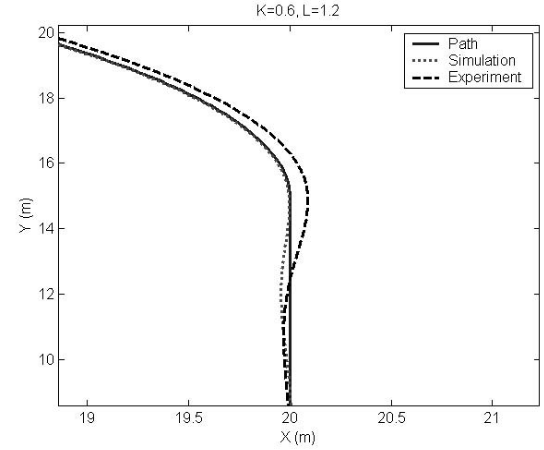

Fig. 16. Detailed view of the vehicle getting out the turn.

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