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An Improved Pure Pursuit Algorithm for the Automated Steering Control of Road Vehicles

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Abstract. Pure Pursuit (PP) is the most popularly used path tracking algorithm for automated steering. In its classic form, PP requires careful tuning of the preview distance. A small preview generally improves the vehicle path tracking but can cause instability issues at high speeds. Considering this, we introduce an automatic adjustment technique for the preview distance which improves both path tracking and lateral stability of the vehicle. This is combined with a yaw rate feedback to form an improved PP controller. Simulations in TruckMaker show that the designed controller can successfully keep an articulated HGV (a tractor-semitrailer) stable, even at higher speeds. Path tracking performance is also improved, here by 60.6% for an SAE J2179 lane change maneuver, compared to classic PP.

Keywords: Pure Pursuit · Path Tracking · Heavy Goods Vehicle · Automated Steering

1 Introduction

Driver-less vehicles are no longer a construct of the future, only seen in science fiction. In fact, the last few years have seen an increased amount of interest in autonomous vehicles, including commercial vehicles. Heavy Goods Vehicles (HGVs) may particularly benefit from automation, addressing safety issues and a shortage of human drivers willing to take on arduous long-haul journeys. Several truck companies, e.g. Volvo Trucks [1], Einride [2], Scania [3] and Daimler [4], are in the process of unveiling autonomous HGVs, and these are expected to be in commercial operation in the next few years.

Autonomous driving involves several layers: environmental sensing, path mapping, path following and corresponding actuation level control [5]. Path following for articulated HGVs is especially challenging, due to the lateral instabilities which can occur, especially at high speeds [6]. Several research articles have been published on automated path following control for HGVs, using methods

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such as Model Predictive Control (MPC) [7], PID control [8], Sliding Mode Control (SMC) [9] and H_∞ [10]. However, such methods typically use gain scheduling and/or controller mode switching, and in cases such as MPC the controller relies on a parameterized vehicle model. This increases the complexity of the controller as well as its sensitivity to parameter changes.

In contrast, simple steering controllers such as Pure Pursuit (PP) avoid such complexity and model parameter dependency. Consequently, PP is a popular path following algorithm for automated light vehicles [11,12] and mobile robots [15,16]. PP calculates a reference path curvature based on target path geometry and the vehicle pose (location and heading angle). For 'classic' PP, only the preview distance needs tuning. However, both path tracking and lateral stability performance are found to deteriorate at high speeds [13,14], limiting their use for articulated HGVs. And the few research papers that do apply PP to the automated steering of articulated HGVs tend to focus on low-speed applications [17–19].

Therefore, the objective of this paper is to improve path tracking and stability performance of PP for use on articulated HGVs. We approach this in two ways: (i) by introducing a variable preview distance and (ii) by introducing yaw rate feedback. The control method is expected to be applicable to a broad range of speeds and path curvatures.

The next section will describe the modifications proposed. Section 3 describes the lower level control method. Section 4 shows simulation performance and finally, Sect. 5 concludes the paper.

2 Pure Pursuit With Variable Preview

PP works by making the vehicle pursue a goal point defined some distance ahead, following these steps: (i) identify the current vehicle pose (location and heading angle), (ii) define the goal point at a given preview distance on the target path, (iii) calculate the reference curvature of the circular arc that connects the vehicle to the goal point [15].

The goal point is defined on the target path, at distance L from a reference point defined on the vehicle. The 'look-ahead' distance L is a tuning parameter which influences both tracking and stability performance. The method is considered to be analogous to a human driver who follows a target point on the road when driving [15].

By placing the reference point at the centre of the rear axle on the tractor, the curvature is calculated from geometry, as shown in Fig. 1(a). Applying the sine rule to this, we find:

$$\frac{L}{\sin 2\alpha} = \frac{R}{\sin\left(\frac{\pi}{2} - \alpha\right)} \tag{1}$$

Further, applying $\cos\alpha = \sin(\pi/2 - \alpha)$ and $\sin 2\alpha = 2\sin\alpha\cos\alpha$ to Eq. 1:

$$R = \frac{L}{2\sin\alpha} \tag{2}$$

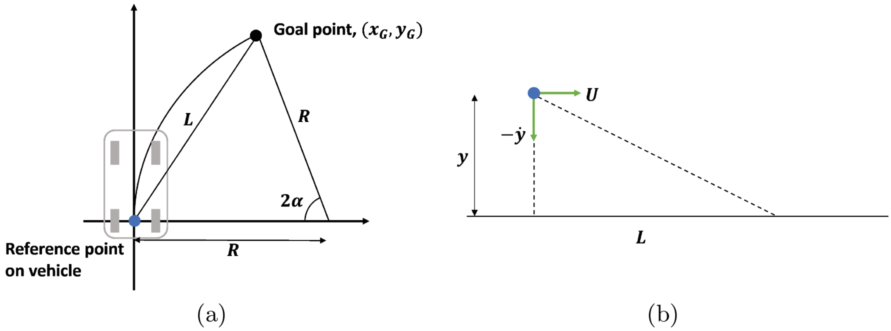

Fig. 1. (a) Classic Pure Pursuit uses path geometry and vehicle heading angle to estimate the path curvature and (b) particle motion equation is used to derive L.

Then path curvature κ is found:

$$\kappa = \frac{1}{R} \tag{3}$$

From the above, it is clear that the choice of L plays a crucial role in the κ calculation. A small L is generally preferred, as it improves the path tracking performance. However, when L is too small it can lead to instabilities in the form of oscillatory behavior and large steering requests. Similarly, a large L can improve lateral stability but at the cost of deteriorated tracking performance with corner-cutting behaviour. Consequently, it is common practice to use a speed dependent L, with a minimum and a maximum saturation[12]. Here, we go a step further and introduce dependency on the lateral deviation y from the desired path – larger deviations should intuitively lead to larger values of L.

Considering only lateral motion (Fig. 1(b)) assume a constant acceleration parameter a which bring the motion of the particle to rest at $y = 0$. From elementary kinematics:

$$\dot{y}^2 = 2ay \tag{4}$$

Assuming small angles, the longitudinal velocity U is constant and the resultant velocity points towards the preview point, hence:

$$\frac{y}{L} = \frac{-\dot{y}}{U} \tag{5}$$

Eliminating $\dot{y}$ then yields:

$$L = U\sqrt{\frac{y}{2a}} \tag{6}$$

This provides the basis of a novel variable preview distance for PP which depends on both speed and lateral offset. To be sufficiently general, an 'effective deviation' y is now defined, to be substituted into this equation. It is to take account of both curved road geometry and the potential for increased deviations due to lateral motion. This lateral deviation therefore employs curvilinear coordinates (S_x, S_y), which represent the distance measured along and orthogonal to the desired path, respectively. Here $S_x > 0$ indicates the direction of intended motion and $S_y > 0$ signifies a lateral offset to the left. Hence we introduce the modified definition of $y \geq 0$ which accounts for lateral motion as well as instantaneous offset:

$$y = \begin{cases} |S_y + T\frac{dS_y}{dt}| & if\ sgn(\frac{dS_y}{dt}) = sgn(S_y) \\ |S_y| & otherwise \end{cases} \tag{7}$$

Here $T > 0$ is a suitable time constant and lateral velocity is only included when it has the same sign as S_y (tending to increase $|S_y|$ in subsequent motion).

Finally a minimum preview distance L_0 is introduced:

$$L = max\left\{U\sqrt{\frac{y}{2a}}, L_0\right\} \tag{8}$$

In the above, parameter a represents the 'aggressivity' of lateral control in the form of a maneuvering acceleration parameter. The time-constant T is another tuning parameter, representing sensitivity to lateral velocity $\dot{S}_y$.

Equation 8 previously appeared in [20–22], but was derived from Artificial Flow Guidance (AFG) equations, which is an alternative geometric path following technique. In [20] $y = |S_y|$ and Eq. 8 is obtained by setting a constant maneuvering acceleration. The modification introduced by Eq. 7 is novel and specific to PP, designed to improve performance when $|S_y\frac{dS_y}{dt}| > 0$ so that lateral deviation is expected to increase.

Notice in Fig. 2, L is no longer given by the chord of the curved path; instead L is the arc length along the target path. This is in accordance with the definition given in [20].

Finally, to avoid rapid changes in L, a 500-point moving average filter is applied. Here, we set $a = 0.5$ m/s^2, $L_0 = 3$ m and $T = 3$ s.

3 Controller Design

At the lower level, the controller is formed of a simple 'feedforward+feedback' structure. The feedforward uses the Ackerman geometry with small angle considerations, as shown below:

$$\delta_{FF} = l_{Wb}\kappa \tag{9}$$

Here, δ_{FF} is the feedforward steering angle and l_{Wb} is the effective wheelbase of the tractor. For the feedback, a reference yaw rate, r_{ref} is calculated by using the curvature calculated by PP. Assuming steady-state cornering:

$$r_{ref} = U\kappa \tag{10}$$

A PID controller is used to remove any error between the measured yaw rate at the tractor, r_1 and the reference. This error is given by:

$$e_{FB} = r_{ref} - r_1 \tag{11}$$

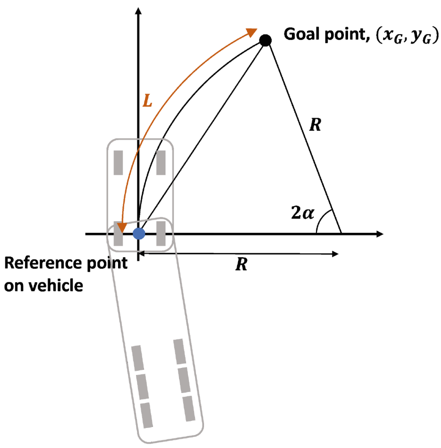

Fig. 2. The modified PP uses the arc length of the curved path as L.

And, the feedback steering angle, δ_{FB} is:

$$\delta_{FB} = K_p e_{FB}(t) + K_i \int_0^t e_{FB}(t)\ dt + K_d \frac{d}{dt} e_{FB}(t) \tag{12}$$

Here, K_p, K_i and K_d represent the proportional gain, the integral gain and the derivative gain, respectively. Finally, the total steering angle to be applied is:

$$\delta = \delta_{FF} + \delta_{FB} \tag{13}$$

The controller schematic is shown in Fig. 3. Here, we set $K_p = 0.0$, $K_i = 0.05$ and $K_d = 0.01$. The integral term is expected to gurantee 0 steady-state error for the yaw rate feedback.

3.1 Defining the Desired Path

Traditionally, the reference path used for PP is discretised into a number of 'waypoints', in the form of an array of *(X, Y, heading, curvature, D)*, here D represents the straight line distance between the waypoint and the path starting point [15], though other formats for waypoints also exist, such as $(X, Y, heading, velocity)$ used in [12]. The distance between the waypoints is important as smaller discretisation can lead to improved path tracking but requiring larger memory space. Here, instead of using discrete points, we use a smooth $TRACK$ definition which represent the nodes of the path i.e. the path is decomposed into a number of sections with different curvatures, an example of this is shown in Fig. 4. $TRACK$ is given in the form of $(S_x, X, Y, t_x, t_y, n_x, n_y, c)$, where, S_x is the longitudinal distance along the path in curvilinear coordinates, (t_x, t_y) is the tangent vector at the nodes, (n_x, n_y) is the normal vector at the nodes and c is the path curvature.

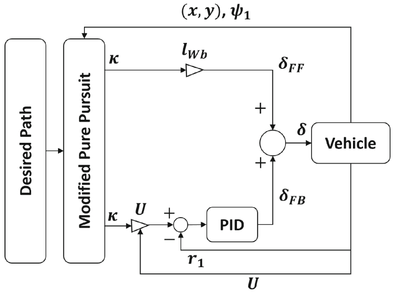

Fig. 3. Schematic of the designed PP controller.

The obvious advantage of using this format is that the matrix *TRACK* can be defined with sparse node points (saving memory) and interpolation for the goal point is achieved to arbitrary accuracy, maintaining smoothness in the controller.

S_x	X	Y	t_x	t_y	n_x	n_y	c
0	0	0	1	0	0	1	0
20	20	0	1	0	0	1	0.05
51.42	40	20	0	1	-1	0	0
81.42	40	50	0	1	-1	0	0

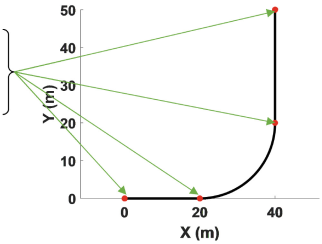

Fig. 4. Example *TRACK* configuration used to define the desired path.

4 Performance Analysis

All simulations were performed in the TruckMaker/MATLAB co-simulation environment. TruckMaker is a commercial software with a large library of high-fidelity truck models and built-in sub-models of tyres, suspensions, powertrain etc. A standard 2-axle tractor *(Demo2AxleSemiTruck4x2_Volvo)* and a 3-axle semitrailer *(Demo3AxleSemiTrailer_Volvo)* were chosen for the tests. Speed control is done by using a PI controller which keeps the speed constant [23].

Three maneuvers are simulated: (i) roundabout with radius 11.25 m, at a speed of 10 km/h, (ii) SAE J2179 lane change at 88 km/h and (iii) vehicle is accelerated from 0 to 100 km/h on a circle with a 393 m radius [24]. The roundabout maneuver tests for low-speed steady-state tracking performance of the vehicle, the large curvature change when entering/exiting the roundabout also tests for the transient performance. The high-speed lane change evaluates both lateral stability and path tracking performance. Finally, the large circular path evaluates the high-speed steady-state path tracking performance of the controller. These maneuvers were taken from [24].

Controller performance is evaluated based on: (i) *Offtracking:* defined as the lateral offset between the reference point (centre of 2^{nd} axle) and the desired path and (ii) *Rearward Amplification (RWA):* which is the ratio of the peak yaw rate at the trailer and the tractor. RWA gives a measure of the lateral stability of the vehicle. At low to moderate speeds RWA ≤ 1 and effects of instabilty are suppressed.

Lateral performance of the above defined controller is evaluated by comparing with a simpler baseline PP controller with a speed dependent preview distance, given by $L = max\{Ut_p, L_0\}$, with $t_p = 0.5$ s. For ease of identification we will refer to the designed controller as 'Variable preview Pure Pursuit' (varL+PP) and the baseline as Pure Pursuit (PP).

Roundabout: The resultant plots are shown in Fig. 5, with Table 1 summarising their performance. As the speed is low and the offtracking is small, the preview distance for both PP and varL+PP become fixed at $L_0 = 3$ m throughout the maneuver. At this speed, the only difference between the controllers is the use of the yaw rate feedback for varL+PP, however, due to the low speed this feedback has small effect on the controller.

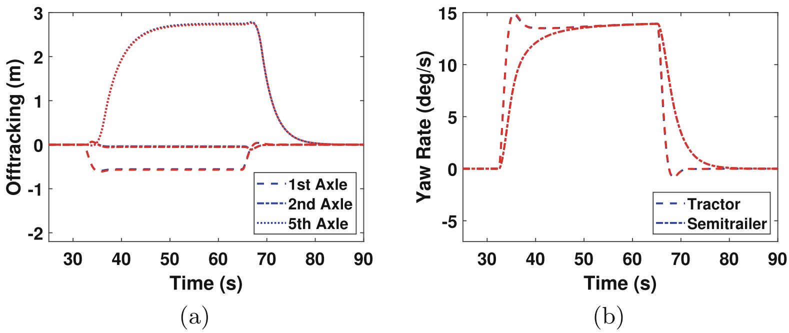

Fig. 5. (a) Offtracking and (b) yaw rate comparison for the roundabout maneuver. The blue and red lines represent varL+PP and PP, respectively.

Lane change: varL+PP provides substantial path tracking improvements and slight stability improvement (see Fig. 6), with lower RWA compared to PP. Faster yaw rate response is observed with varL+PP as it reacts quicker to the curvature change and settles faster.

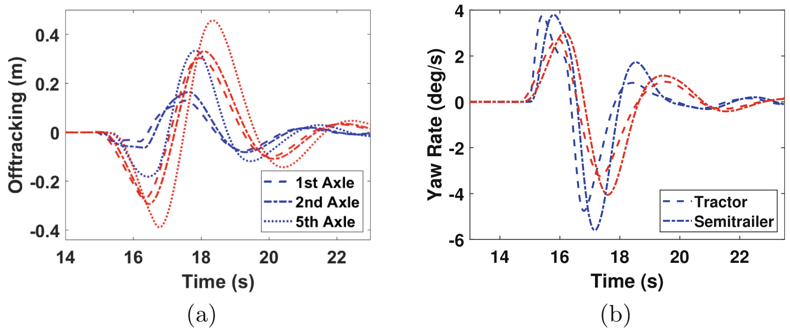

Fig. 6. (a) Offtracking and (b) yaw rate comparison for the lane change. The blue and red lines represent varL+PP and PP, respectively.

Large circle: At high speeds, the preview distance for both controllers are large and this leads to increased steady-state offtracking as seen in Fig. 7. varL+PP outperforms PP in terms of both path tracking and stability.

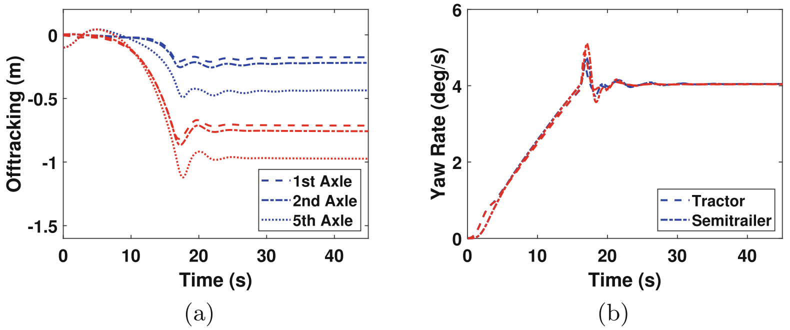

Fig. 7. (a) Offtracking and (b) yaw rate comparison for the large circle. The blue and red lines represent varL+PP and PP, respectively.

Table 1. Performance comparison between varL+PP and PP. Offtracking values are measured at the reference point.

Maneuver	Criteria	PP	varL+PP
Roundabout	Max. offtracking	0.11 m	0.10 m
	Steady-state offtracking	0.05 m	0.04 m
Lane Change	Max. offtracking	0.33 m	0.13 m
	RWA	1.25	1.18
Large Circle	Steady-state offtracking	0.76 m	0.22 m
	RWA	1.05	1.03

5 Conclusion

A controller was developed for automated steering control of HGVs for a broad range of speeds; Pure Pursuit was used for this. Pure Pursuit is a popularly used path tracking algorithm. It is advantageous due to its simplicity of implementation and effectiveness. The choice of the preview distance plays a crucial role in Pure Pursuit, with a larger preview leading to increased stability but reduced path tracking performance. Here, a variable preview distance equation is introduced which automatically adjusts the preview distance based on the vehicle speed, lateral deviation and maneuvering acceleration. A yaw rate feedback is also added for improved performance at moderate-to-high speeds. Simulations rendered in TruckMaker demonstrate superior tracking and stability performance compared to classic Pure Pursuit.

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