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# Model-Free Automated Reversing of Articulated Heavy Goods Vehicles

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**Abstract.** This paper presents a technique for automated reversing control of articulated vehicles. Reversing articulated Heavy Goods Vehicles (HGVs) can be a challenging and time consuming task for a human driver, sometimes requiring multiple forward and backward motions to reduce errors. Here, the aim is to automate the task to provide high levels of precision using Artificial Flow Guidance (AFG). AFG uses simple geometry to define a spatially distributed motion reference, requiring only short-range error corrections and possessing global convergence properties. AFG has previously been applied to rigid and articulated vehicles in forward motion, with demonstrable benefits in terms of tracking precision and robustness. Here results focus on the tractor-semitrailer, but the AFG approach is equally applicable to the reversing of longer combination vehicles.

**Keywords:** Automated Reversing · Articulated Vehicles

## 1 Introduction

Efficient goods transportation is vital to smart manufacturing, industrial automation and commerce in general. HGVs, which are popularly used for goods transportation [11] can however pose stability issues, especially when docking or reversing as the open-loop system is unstable [2,3]. The problem is three-fold: (i) the system is unstable and require the driver feedback to stabilise the vehicle [2] (ii) the trailer moves in the opposite direction to the steering applied at the lead vehicle unit and [5] (iii) the driver cannot always see the rear end of the vehicle, which makes it harder to track the vehicle state as it reaches its control limit [5].

Thus, automated reversing control of articulated vehicles is an active field of research. Notable publications include [2,3,12,13] among others. In [12] a state

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feedback controller was designed based on a linear dynamic model. The controller was seen to provide good path-tracking performance for vehicles formed of one to three trailers. Altafini et al. [2] also used linear state feedback, a switching logic was applied to allow the multi-unit vehicle to drive forward when at the risk of jackknifing. Yue et al. [13] used a kinematic model to form a Model Predictive Control (MPC) which provides path tracking for both forward and backward direction. In [3] Pure Pursuit was combined with a hitch angle compensator to provide stable reversing on tractor-semitrailers. Again a kinematic model was used. While several other methods have also been successful in providing motion control for reversing, this reliance on vehicle modelling is a common feature. Moreover, prior research have often used optimal or predictive control, which increases design complexity and the number of tuning parameters.

Artificial Flow Guidance (AFG) is a general motion planning method that uses a spatial distribution of desired motion vectors in place of an explicit target path [7,10]. AFG has minimal tuning parameters and does not rely on detailed vehicle modelling [11]. The method has previously been used for path-tracking in forward motion for a conventional car [7], 4-wheel-steering car [6] and multi-axle steered articulated HGVs [10,11]. In [9] experimental tests were carried out on a full-size articulated HGV. This showed that AFG can provide precise path-tracking and is feasible for real-time applications [9].

While previous research have demonstrated a number of advantages for AFG in forwards motion, it has not been applied to the reversing of articulated vehicles. Here, for simplicity, we focus on designing a reversing controller for a tractor-semitrailer combination.

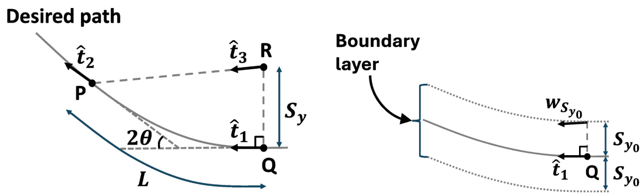
## 2 Artificial Flow Guidance

Individual 2D vectors in the AFG field are calculated using simple geometry and a reference path – see Eq. 1 and Fig. 1(a) respectively. Here, $R$ is a tracking point on the vehicle intended to follow the flow vectors and hence converge to the target path. $P$ is a preview point and $Q$ is the nearest point to $R$ on the desired path. Unit vectors $\hat{t}_1$ and $\hat{t}_2$ are tangents at points $Q$ and $P$, respectively, and $\hat{t}_3$ is a unit vector at $R$ which points towards $P$; $2\theta$ is the angle between tangents $\hat{t}_1$ and $\hat{t}_2$ [11]:

$$w = \begin{cases} \hat{t}_3 + \frac{\hat{t}_1 - \hat{t}_2}{2\cos\theta}, & \text{if } |S_y| \geq S_{y_0} \\ [\cos\varGamma \quad \sin\varGamma]^T, & \text{otherwise} \end{cases} \tag{1}$$

$$\varGamma = \varGamma_0 + \left(\frac{|S_y|}{S_{y_0}}\right)\varGamma_b \tag{2}$$

The flow is modified in the immediate vicinity of the target path in the form of a 'boundary layer', where flow angle $\varGamma$ is interpolated from the exterior flow $\varGamma_b$ at the boundary – see Fig. 1(b). $S_y$ is the lateral distance between points $R$ and $Q$, and $S_{y_0}$ is half of the width of the boundary layer. This boundary layer improves the uniformity of the flow in the presence of sharp curvature changes [11]. Also, imposing a constant magnitude for $\Gamma_b$, global convergence is assured provided local tracking errors are bounded [11].




(a) AFG vector calculation. (b) Boundary layer.

**Fig. 1.** The AFG vector $w$ is calculated based on the path geometry. A 0.1 m boundary is imposed around the desired path to improve the tracking performance.

The distance between $Q$ and $P$ is the preview distance, $L$:

$$L = \bar{v}\sqrt{\frac{|S_y|}{2a}} \tag{3}$$

where $\bar{v}$ is the vehicle speed. There are just two tuning parameters: $a = 0.2$ m/s$^2$ is a flow acceleration parameter, and the boundary-layer half-width $S_{y_0} = 0.05$ m.

## 3 Controller Design

We chose the rear end of the semitrailer as the tracking point, for which the AFG vector is found from Eqs. 1–3. The longitudinal component of all velocity vectors on the trailer centre-line are equal, and normalized to unity for interpolation. The AFG vector is also normalised to give $\hat{w}_T$ as the reference (see Fig. 2a).

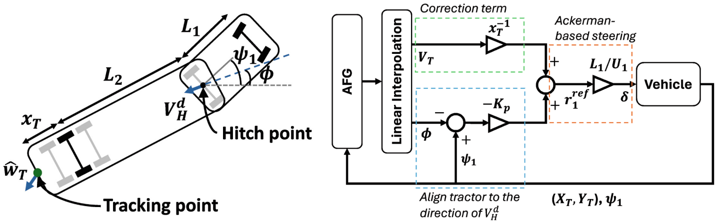
For low-speed motion we assume zero-sideslip at the 2$^{\text{nd}}$ axle on the trailer. In terms of the trailer yaw angle $\psi_2$, its normalized velocity is $\hat{v}_z = [\cos\psi_2 \quad \sin\psi_2]^T$. From this and $\hat{w}_T$, the interpolated velocity at the hitch is found:

$$V_H^d = -\frac{x_T}{L_2}\hat{w}_T + \left(1 + \frac{x_T}{L_2}\right)\hat{v}_z \tag{4}$$

Here, $x_T$ is the distance between the 2$^{\text{nd}}$ axle on the trailer and the tracking point, and, $L_2$ is the trailer wheelbase as shown in Fig. 2(a). The lower-level controller (shown in Fig. 2b) converts this to a yaw rate motion reference using the following:

$$r_1^{ref} = -K(\psi_1 - \phi) + r_2^{ref} \tag{5}$$

Here, $\phi$ is the angle of the velocity reference at the hitch point with respect to the global X-axis and $r_2^{ref}$ is the reference yaw rate for the trailer, calculated by considering the desired lateral velocity at the tracking point $V_T$ using $r_2^{ref} = V_T/x_T$. We assume that the hitch point coincides with the zero-sideslip point on the tractor. This means, lateral velocity at the hitch point cannot be controlled directly, and the tractor must be aligned with $\phi$ to give the correct directional motion. Thus the feedback control aims match the tractor yaw angle $\psi_1$ to $\phi$. $K = 10$ is a proportional gain.




(a) Vehicle on a left turn. (b) Controller design.

**Fig. 2.** The lower-level controller uses vehicle kinematics to align the tractor to the direction of the desired velocity vector at the hitch point.

This method also works for cases where the hitch point may be in front of the zero-sideslip point (such as in a 2-axle tractor) but this introduces some tracking error. Finally, the steering angle at the front axle $\delta$ is calculated using Ackermann as shown in Eq. 6. Here, $U_1$ and $L_1$ are the longitudinal velocity and the effective wheelbase of the tractor, respectively.

$$r_1^{ref} = \frac{U_1 \tan\delta}{L_1} \tag{6}$$

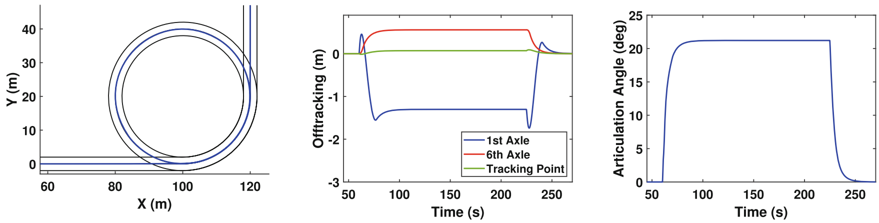
Furthermore, the steering angle is saturated within $-\pi/4 \leq \delta \leq \pi/4$. This also limits the articulation angle to prevent jackknifing [8].

## 4 Results and Discussion

All simulations were carried out in TruckMaker, which is a commercial simulation software with a library of high-fidelity models. Here, a 6x4 tractor and a 3-axle semitrailer are chosen. The performance of the controller is tested using two maneuvers: (i) a 450° roundabout of radius 20 m and (ii) a 20 m lane change formed using a cosine (equivalent radius is 250 m). The longitudinal velocity is kept constant at −1 m/s for both cases – note that this method also works for variable speeds provided slip angles at the tyres remain small. Figures 3 and 4 shows the results. Here, offtracking is defined as the lateral offset from the desired path.

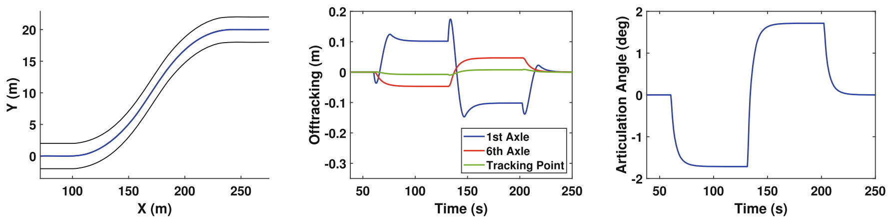
For the roundabout maneuver shown in Fig. 3, maximum offtracking at the tracking point is 10 cm. This occurs when the vehicle is exiting the roundabout due to the large change in curvature experienced. With a single steered axle, AFG can only control a single point – this is the rear end of the trailer. The rest of the vehicle follows this point passively.

Figure 4 shows the lane change, maximum offtracking is only 1 cm at the tracking point. For both cases, the vehicle remains stable throughout with the articulation angle staying within 21.2° for the roundabout and 1.7° for the lane change.




(a) Tracking point position relative to the desired path.
(b) Offtracking.
(c) Articulation angle.

**Fig. 3.** Simulation results for the roundabout maneuver. Here, 1st axle is the front axle on the tractor and the 6th axle is the rearmost axle on the trailer.




(a) Tracking point position relative to the desired path.
(b) Offtracking.
(c) Articulation angle.

**Fig. 4.** Simulation results for the lane change maneuver. Here, 1st axle is the front axle on the tractor and the 6th axle is the rearmost axle on the trailer.

## 5 Conclusion

Reversing HGVs can be a time consuming and challenging task for the human driver. Automating this process can improve supply chain efficiency and contribute positively towards smart manufacturing. AFG was used to design a controller for automated reversing control on tractor-semitrailers. A simple lower-level controller is used to convert the velocity reference at the rear end of the trailer to a yaw rate reference at the fifth wheel.

Simulations rendered in TruckMaker show good tracking performance at the rear end of the semitrailer. For the maneuvers tested, the rear end of the trailer stays within 10 cm of the desired path, even during large changes in path curvature. These results are comparable, if not better than recent publications on reversing control of tractor-semitrailers [1,4]. This, combined with the simplicity of the control method makes this an attractive solution to the reversing problem.

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