MINIMUM SWEPT PATH CONTROL FOR AUTONOMOUS REVERSING OF LONG COMBINATION VEHICLES

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Abstract
A new control strategy, called Minimum Swept-path Control (MSPC), is proposed in this paper to improve the performance of autonomous reversing of long combination vehicles (LCVs). It can minimise the maximum excursion from a nominal path while guaranteeing a relatively high accuracy of path following. The Linear Quadratic Regulator (LQR) method is used to tune the controller. A relationship between the maximum path tracking error, the maximum excursion of the vehicle units and the controller weights is investigated.
Keywords: Long Combination Vehicles, Autonomous Reversing, Minimum Swept Path Control, Path Following Control, State Feedback Control, Optimal Preview Distance

1. Introduction

In recent years, there has been increasing pressure to reduce carbon footprints and fuel consumption in the road freight industry. Long Combination Vehicles (LCVs), with multiple articulation points provide an important route to improving fuel efficiency (Hulne, 2011 and Odhams etc., 2010), offering 18-32% decrease in fuel consumption in comparison with conventional articulated vehicles (Woodrooffe and Ash, 2011). Reversing LCVs into small parking bays or interchanging trailers are common tasks for drivers. However, unlike forward driving, reversing of LCVs is unstable, with non-holonomic characteristics. Moving obstacles such as cars, workers or trollies in the vicinity of the LCVs exacerbate the difficulty. Furthermore, professional and experienced drivers capable of performing those tasks are rare and very sought after, as described by Kjell and Westerlund (2009). Hence, it is important to design assistive controllers for drivers reversing truck-trailer combinations.

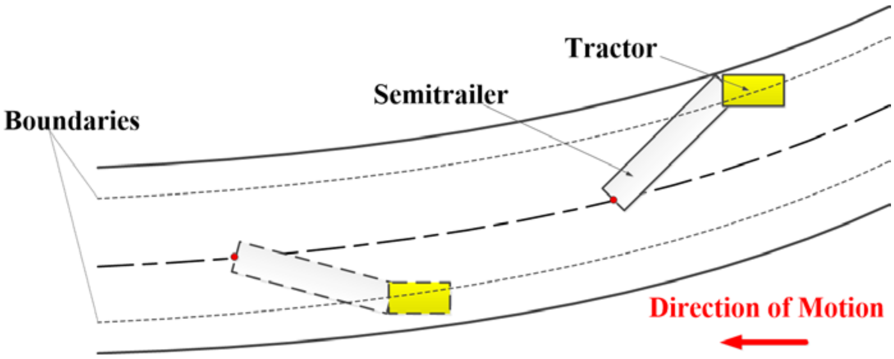

Figure 1 - Previous Path Following Control (PFC)

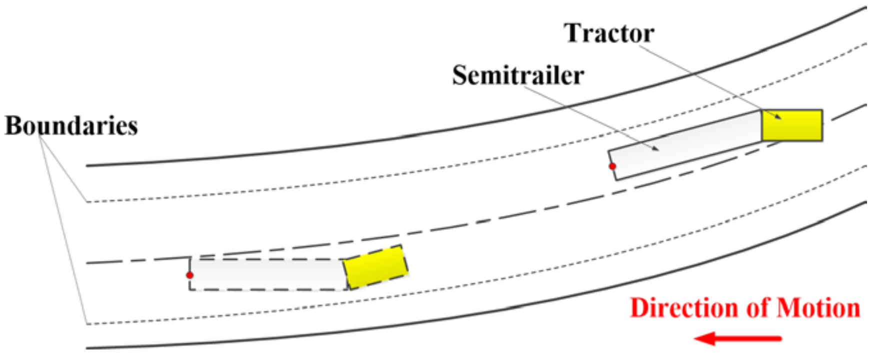

Figure 2 - Minimum Swept Path Control (MSPC)

Previous control strategies used to assist reversing, such as Path Following Control (PFC), developed by Rimmer (2014 - 2017), have been aimed at reducing lateral offsets between the rearmost axle of LCVs and a specified path. However, those strategies can cause large excursions of the other vehicle units, especially the tractor, thus increasing the overall swept path width, as illustrated in Figure 1. A new method called Minimum Swept Path Control (MSPC) is proposed in this paper, as shown in Figure 2. State Feedback Control (SFC) and the optimal preview distance were integrated into the MSPC algorithm, enabling the relationship between maximum lateral offsets of the front axle of the tractor and the rear axle of the last trailer to be varied through tuning the weights in the control cost function. Because a tractor-semitrailer combination is widely used around the world, a simulation for this case has been considered for simplicity, but the theory can be extended to a tractor with any number of trailers.

2. Research Approach

A nonlinear model of a standard UK tractor-semitrailer was created. Due to lorry loading regulations published by the Department for Transport, UK (2003), many trailers require axle-groups of 2 or 3 axles at the rear. This can cause tyre lateral scrubbing in tight corners. However, this effect was not considered in this preliminary study, because the scrubbing action is symmetric between left and right sides and does not have a strong effect on the path (Rimmer, 2014). Consequently, an equivalent, single trailer axle vehicle was considered instead. The approach proposed by Winkler (1998) was used to calculate the distance from the fifth wheel to the point of zero lateral velocity, which can be modelled as an equivalent axle to replace multiple-axle groups. Based on the concept of an 'equivalent axle' and the standard 'bicycle' vehicle dynamics model (Ellis, 1969 and Gillespie, 1992), a multiply articulated vehicle with an arbitrary number of trailers and any number of axles was developed. Because articulated vehicles typically reverse at very low speeds, the 'equivalent' (single axle) tyres stay in the linear performance regime. Linearised tyre models were therefore used for controller development. For a lane change manoeuvre, the nonlinear vehicle dynamics (introduced by large articulation and steering angles) was linearised about the equilibrium state of a straight line.

To achieve the main objective of MSPC, a linear controller was devised. A cost function was developed, with weights (W_{ra} and W_{fa}) applied to the lateral offsets of the rear axle of the last trailer (y_{ra}) and the front axle of the tractor unit (y_{fa}) respectively. The cost function J was defined as follows:

$$J = \int_0^\infty \left(W_{ra} {y_{ra}}^2 + W_{fa} {y_{fa}}^2 + \delta^2 \right) dt \tag{1}$$

The MSPC approach is to control the articulation angles, heading angle and lateral offset of the rear axle of the last trailer by feeding back those states into the system, while implementing the optimum preview distance to predict future vehicle equilibrium configurations to compensate those state errors. The Linear Quadratic Regulator (LQR) is used to tune the linearised controller. By adjusting the weights to penalise the axle lateral offsets, the emphasis placed on each axle's lateral error versus the steering angle δ was varied. The equation of the system input, steering angle δ, can be defined as follows:

$$\delta = \delta_d + K_{ya} y_{ra} + K_{\theta_{ra}} (\theta_p - \theta_{ra}) + \sum_{i=1}^{n} K_{\Gamma_i} (\Gamma_{id} - \Gamma_i), \tag{2}$$

where δ_d and Γ_{id} are the desired steering and articulation angle respectively, and Γ_i denotes the real-time articulation angle; y_{ra} and θ_{ra} are the lateral offset and heading angle of the rear axle of the last vehicle unit; K_{ya}, $K_{\theta_{ra}}$ and K_{Γ_i} are the corresponding gains for the rear lateral offset, heading angle and articulation angle errors. It is noted that $K_{\theta_{ra}}$ is calculated from the gain $K_{y_{fa}}$ for y_{fa} by the use of the transformation matrix.

3. Simulation Results and Discussion

A desired path in simulation is depicted in Figure 3, representing a lane change manoeuvre. The relationship between maximum lateral offsets and weights is shown by plotting the maximum excursion of the front axle in the lane change manoeuvre against the maximum excursion of the rear axle for MSPC as a conflict diagram. A reasonable range for the weights is from 0 to 10, but both cannot be zero at the same time, because the LQR method requires semi-positive matrices. It is noted that when $W_{fa} = 0$, the MSPC controller is similar to the Path Following Control (PFC) approach devised by Rimmer (2014) (apart from some differences in handling the look ahead distance) as only one weight plays a role in reversing. In Figure 4, the curve represents a varying W_{fa} as $W_{ra} = 1$. This diagram shows that increasing one of the weights penalises the other response. For example, increasing W_{ra} reduces $|Y_{ra}|_{max}$, but increases $|Y_{fa}|_{max}$. Likewise, decreasing W_{fa} gives the same effect, decreasing the excursions of the rear axle, but increasing those of the front axle.

The lateral offsets of both axles during the lane change manoeuvre for an MSPC controller (Point A in Figure 4) and the corresponding pure PFC controller (only $W_{ra} = 1$) are shown in Figure 5. Figure 5 shows that the front axle's maximum lateral offset (solid curve) is less than that of the dashed curve, which means the performance of the MSPC controller is better than the PFC controller. However, a trade-off with the lateral offset of the rear axle was made simultaneously, as seen in Figure 5. The MSPC algorithm generates a slightly larger lateral offset on the rear axle, than the PFC algorithm.

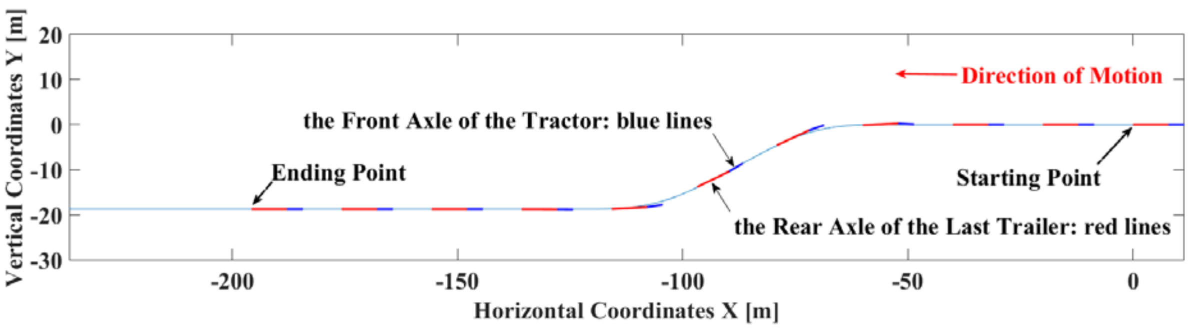

Figure 3 - Lane Change Manoeuvre

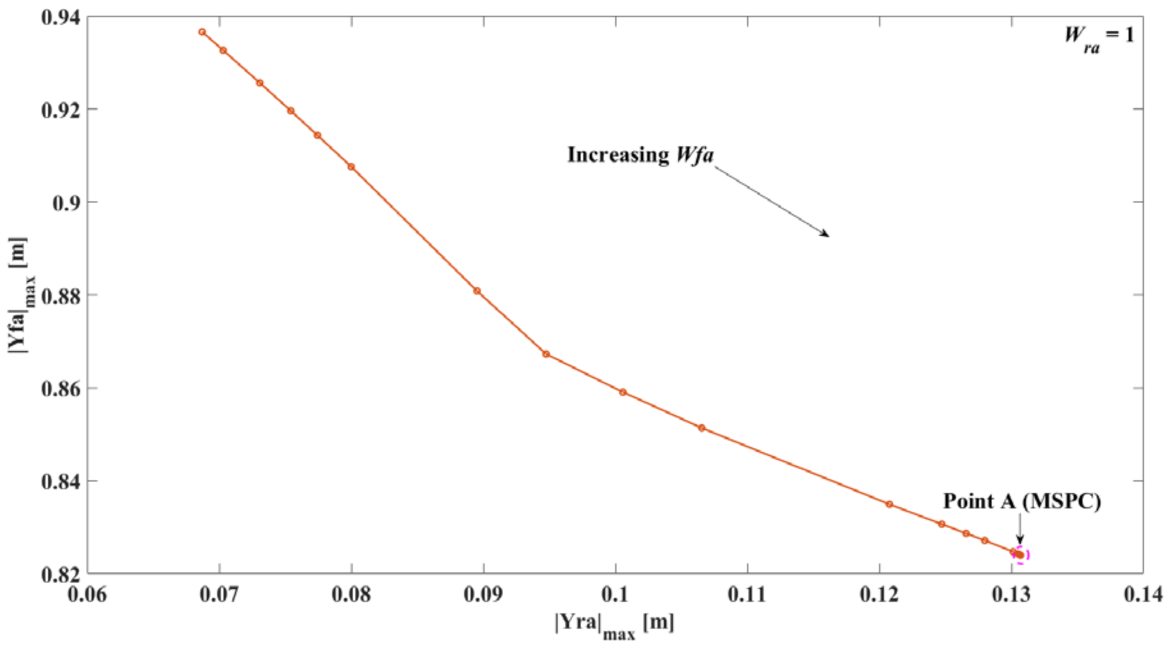

Figure 4 - Conflict Diagram of Constant W_{ra}

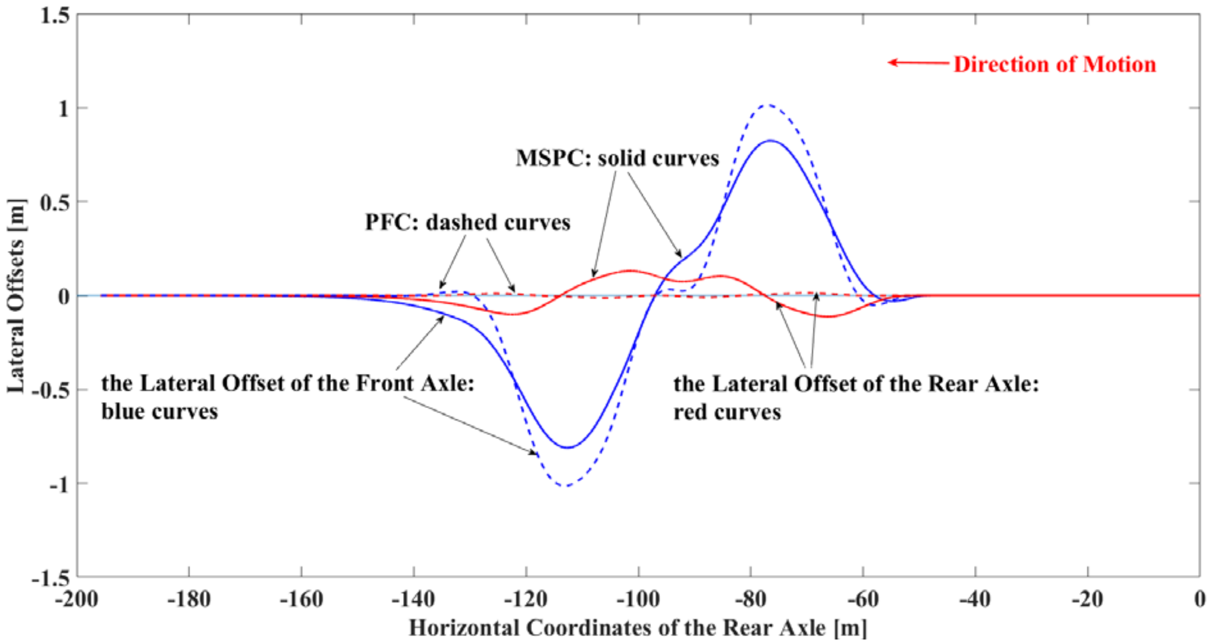

Figure 5 - Lateral Offsets of Both Axles

4. Conclusions

A Minimum Swept Path Controller (MSPC) was designed to improve autonomous reversing of LCVs. A relationship between the lateral offsets of both axles and the corresponding controller weights was found. The weighting placed on one axle decreases the maximum lateral offset of that axle, but at the expense of the maximum lateral offset of the other axle. As shown in the above diagrams, the trade-off between decreasing the maximum front axle's lateral offset and increasing the maximum rear axle's lateral offset is satisfactory. This approach cannot only guarantee the accuracy of following a desired path in reverse, but also can reduce the lateral offsets of the front axle of the tractor unit significantly. In this case, the MSPC method improves the performance of PFC controllers.

5. Acknowledgements

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