Lateral Control of a Trackless Road Tram 'ART' Using Multi-axle Steering

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Abstract. Autonomous rail Rapid Transit (ART) is a novel trackless-tram urban transport system with high flexibility, capacity, and low implementation cost. All-axle steering capability brings additional control freedom to tackle the manoeuvrability, lateral stability, and off-tracking issues for such a long combination vehicle. This paper presents a lateral control approach with three levels: 1) Ackermann based feed-forward; 2) articulation feedback; and 3) yaw rate feedback control. The relative contributions of these controllers are analysed with simulation, and the overall tracking and stability performance of the proposed controller is found to be satisfactory, even without parameters re-tuning for different operating conditions.

Keywords: Multi-axle steering · Lateral stabilty · Road/Rail · Long combination vehicle · Guided transit systems · Steer-by-wire · ART vehicle

1 Introduction

Articulated vehicles offer substantial benefits over normal rigid single-unit vehicles: reducing traffic congestion, transport cost and energy consumption. For passenger transport, the example can be Bus Rapid Transit (BRT), and Guided Transit Systems (GTS), sometimes referred as trackless tram, as distinct from a rail-guided tram. These systems combine the capacity&quality of rail transit systems, maintaining the similar level of speed and capacity as rail-guided transit systems/trains on one hand, and the flexibility of rigid trucks/buses, lowering the construction cost&time significantly on the other hand, especially for urban scenarios [1,2]. Autonomous rail Rapid Transit (ART) is a novel GTS system, developed by CRRC Zhuzhou Institute of China, featuring virtual guidance and all-wheel steering. As with conventional long combination vehicles, the length and mass of ART raise challenges of manoeuvrability, off-tracking, and stability. Designing proper control system to improve safety of such articulated vehicles has long been considered necessary. Meanwhile, multi-axle steering of ART does offer a higher degree of freedom of control, but it is inherently unstable without

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Fig. 1. A 3-unit Autonomous rail rapid transit vehicle on the track.

an appropriate steering controller, which makes a well-designed controller for daily operation even more crucial.

Researchers have been working on improving the lateral stability of long combination vehicles, e.g., preventing snaking, potential jack-knifing or even rollover, via braking and/or steering of one or more axles, to assist driver manoeuvring and avoid accidents [3–10]. In [3], Kharrazi proposed delay based yaw rate response feedforward and feedback control for long combination trucks. However the feedforward approach stays in the linear region so not applicable for large steering angles under small-radius turning scenarios. In [4], the reference model uses a steady-state bicycle model for front unit yaw rate and a zero-sideslip target. Target articulation angle is based on a target yaw angle: each trailer should point to its prior position after a distance travelled equal to its length. Once the target was fixed, the authors used LQR as a benchmark controller with feedback of front yaw rate, front sideslip, articulation angles and articulation rates. The authors then used sliding mode control with sliding variables based on tracking four references (tractor yaw rate, tractor sideslip, two articulation angles) for control. Similar to LQR and SMC, MPC was used in [5], which showed very good rearward amplification (RWA) performance but this was again formulated in the linear region only. The paper [10] also uses MPC, with MPC providing target yaw moments and control allocation being used for the lower level control. In [11], a steering controller was proposed to control a bi-articulated bus, which is quite similar to ART in terms of vehicle structure. There the steering controller was composed of two parts, i.e., 1) the fourth and sixth axles' steering angles were derived based on Ackermann geometry aiming to track the path set by the first unit, and then 2) the 3rd and 5th axles were used for minimizing the two articulation joints' forces. In [12], Feng et al. designed a path following controller for the rear axles of an ART based on kinematics analysis, aided by computer vision based path deviation detection.

This paper presents a novel lateral control approach for ART-like articulated vehicles. With the first axle being controlled by a human driver or a driver model, the proposed approach works as a stabilizing controller on the rear axles to improve lateral stability and off-tracking performance. The controller is of three levels: 1) Ackermann based feedforward; 2) articulation feedback; and 3) yaw rate feedback control. The remainder of this paper is structured as follows: In

Sect. 2, the modelling of ART is introduced, and the controller design is presented in Sect. 3. Section 4 is devoted to simulation and results analysis. Conclusions are drawn in Sect. 5.

2 Modelling

The chassis configuration of a 3-unit ART is as shown in Fig. 2. Each axle is steered by an independent hydraulic actuator. The two articulation joints are passive hinges with internal passive damping. To be more specific, the parameters list for the 3-unit ART is presented in Table 1.

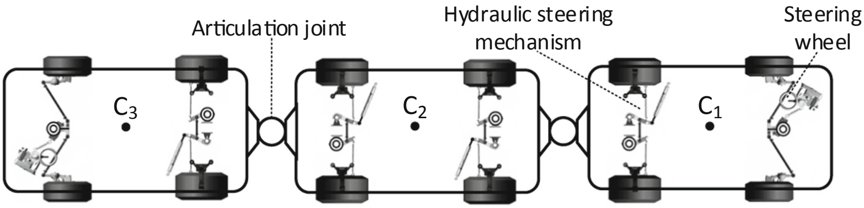


Fig. 2. Chassis configuration of a 3-unit ART.

Table 1. Parameters list of a 3-unit ART

	Item	Value	Units
Geometry	body length	9.53/8.24/9.53	m
	body height	3.2	m
	longitudinal distance between axles	6.5/6/6.5	m
	distance from rear axle to artic. joint	2.02	m
	track width	2.06	m
Inertias	Mass (total)	1e4	kg
Steering	maximum steer angle (front axle)	20°	deg
	maximum steer angle (rear axle)	14°	deg

A reduced-order Lagrangian dynamics models was used to controller development, but controller design was not specifically based on the formulated equations of motion. Hence, in the following we are able to develop the controller using simple kinematics and control concepts, then turn to a high-fidelity simulation model for test and evaluation. Details of the integration of the path tracking and the three levels of control will be presented in the next section. In order to simulate vehicle response and examine the performance of the proposed lateral control approach, a high-fidelity model is built in TruckMaker based on the parameters shown in Table 1. The controller is implemented in Matlab/Simulink and connected to TruckMaker via CM4SL interface.

3 Controller Design

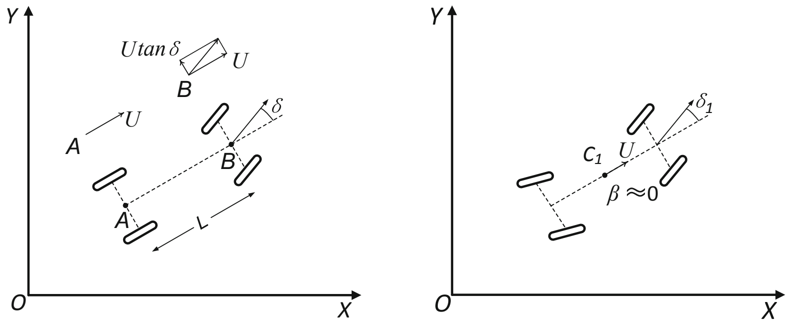
The proposed controller is based on a simplified path geometry as reference, using the travelled distance versus heading angle. Information such as curvature and yaw rate are then populated along the reference path for control purposes. Then feedforward and feedback targets for different axles are interpolated according to estimated position on the reference path accordingly. The controller comprises three parts: 1) feedforward based on Ackermann geometry analysis, 2) feedback control of articulation angles, and 3) feedback control of yaw rates. For the desired articulation angles derivation, Ackermann geometry is adopted, a common approach in handling dynamics control, normally for 2WS vehicles, assuming minimal sideslip angle at rear axle centre. For all-axle steering, which is more complicated, assumption is made that sideslip at unit geometric centre points C_1, C_2, C_3, are zero-see Fig. 2. Then the desired articulation angles is calculated based on low speed geometry. Yaw rate target is defined as a standard steady-state cornering reference. Given steering angle δ_1 from the first axle,

$$r_{des} = \frac{U\delta_1}{L' + g^{-1}K_u U^2} \tag{1}$$

where U is the forward speed, K_u is the understeer gradient and $L' = 0.5L$ is the effective wheelbase of the front unit.

3.1 Reference Path Integration

The reference path is the estimated track followed by the front unit, based on distance and heading information. Define A and B as the centre of the rear and front axle of a standard front wheel steering vehicle, as shown in Fig. 3(a).



(a) (b)

Fig. 3. Reference positions for (a) a front-wheel steering vehicle, and (b) a full-wheel steering vehicle.

The motion of point A is given by $\dot{x}_A = U\cos\psi, \dot{y}_A = U\sin\psi, \cdot\dot{\psi} = L^{-1}U\tan\delta$, where ψ is the yaw angle of the vehicle relative to Oxy. In general, the paths at A and B are not the same, and sharp steering (e.g. step steer) can lead to path angle discontinuity (infinite curvature) along the path of B. Hence, reference path generation it is most convenient to use A as a reference. From the above equations, the path curvature at A is given by

$$\kappa_A = L^{-1}\tan\delta \tag{2}$$

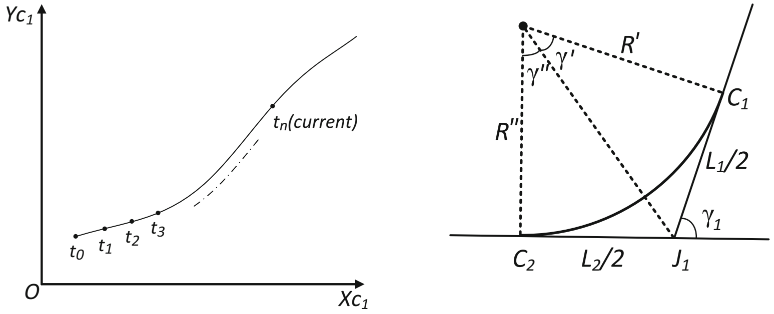
which is therefore only subject to curvature discontinuity but has continuity in path angle.

For the ART front unit, as shown in Fig. 3(b), with both axles steering, in low speed manoeuvring the front and rear axles will steer in opposite directions, making the geometric centre C_1 move without sideslip. Hence Eq. 2 becomes

$$\kappa_{C1} = 2\,L^{-1}\tan\delta_1 \tag{3}$$

Integration of curvature with respect to path distance (behind the current location of C_1) gives a target path angle for the geometric centres of the following units, as depicted in Fig. 4(a).

$$\psi\left(t_2\right) - \psi\left(t_1\right) = \int_{t1}^{t2} d\psi_1 = \int \kappa(t)\frac{ds}{dt}dt = \int \kappa_{C1}(t)U(t)dt \tag{4}$$



(a) (b)

Fig. 4. (a) Integration of the ad-hoc reference map. (b)Ackermann geometry analysis for adjacent units, where C_i is the *cg* of *ith* unit, and L_i is the unit length.

Assuming a discrete-time controller and writing $\kappa(t_i) = \kappa_i$ etc., the following equations can be used to populate arrays for reference path angle and distance travelled:

$$\psi_{i+1} = \psi_i + \frac{1}{2}\left(\kappa_i U_i + \kappa_{i+1}U_{i+1}\right) \tag{5}$$

$$s_{i+1} = s_i + \frac{1}{2}\left(U_i + U_{i+1}\right) dt \tag{6}$$

where trapezoidal integration has been used. The desired yaw rate is also stored as $r_{des_i} = U_i \kappa_i$. And since only relative motion is being considered, initial state of the path is set as $s_0 = 0$, $\psi_0 = 0$.

3.2 Targets and Low-Level Controller Design

Once the reference path is built, interpolation is applied to find the change in path direction as a function of curvilinear path distance (behind the current position of C_1 at time t_n). For the second unit, again assuming zero body sideslip at the geometric centre, the path distance travelled between unit centres is required, as well as the mean curvature between the centre points. As shown in Fig. 4(b), mean curvature is obtained via

$$R^{-1} = \frac{\psi\left(s\left(C_1\right)\right) - \psi\left(s\left(C_1\right) - d\right)}{d} \tag{7}$$

where $d = (L_1 + L_2)/2$ is the approximate distance between C_1 and C_2. For constant curvature there is no error in this approximation, and for slowly changing curvature the error is minimal.

From simple geometry shown in Fig. 4(b),

$$\tan \gamma_1' = L_1/(2R) \tag{8}$$

$$\tan \gamma_1'' = L_2/(2R) \tag{9}$$

$$\gamma_1 = \gamma_1' + \gamma_1'' \tag{10}$$

which is the required articulation angle between units 1 and 2.

The 's-position' of C_2 is then obtained from circular geometry:

$$s\left(C_2\right) = s\left(C_1\right) - \gamma_1 R \tag{11}$$

The same procedure as for C_1 is taken to derive the curvature, desired articulation angle, and yaw rate for both C_2 and C_3.

The feedforward control is based on Ackermann geometry,

$$\delta_i = \mathrm{atan}(\kappa L) \tag{12}$$

where i =2,...,6 indexes the following axles, κ is the curvature at the geometric centre of the unit of axle i, and L is the relative distance from the geometric centre to axle i, positive for front axle and negative for rear axle.

For articulation angle feedback control, corrections are made via in-phase steering of adjacent axles, i.e., 2/3 axles and 4/5 axles, and PID control is adapted to implement the low-level control.

As introduced in the last sub-section, desired yaw rate for the following units are based on estimated curvature and current speed. On the front unit, corrections are made via the rear steering, while on the other units an out-of-phase front/rear steering action is assumed (negative front and positive rear providing negative feedback for yaw-rate tracking). A simple proportional controller is then used to track the reference. Tuning of the low-level controllers for feedback of articulation angles and yaw rates was straightforward, and for reasons of space this is not detailed here. The resulting steer angles (open-loop, articulation feedback, yaw-rate feedback) are simply added and applied to the vehicle axles.

4 Simulation Results

As aforementioned, simulation is conducted in the co-simulation environment of TruckMaker and Matlab/Simulink. Two categories of simulation are performed mainly, i.e., open loop test and close loop test. Open loop indicates the steering angle of the front axle is commanded directly, for example a step or sinusoidal signal, etc., while in closed loop test, the steering angle is from the driver (human, or driver model) and the aim is to follow certain desired path.

4.1 Open Loop Tests

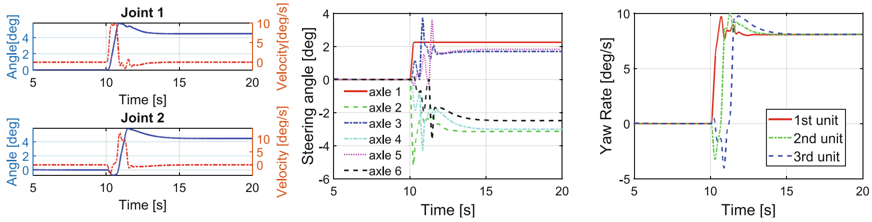
Start with the open loop test and consider a step input of 2.25 deg on the front axle. The understeer gradient in Eq. 1 is 1.5 deg, which is set to match steady-state yaw rate tests, conducted as a calibration exercise. The target speed for the first unit is constant of 60 km/h.

With all three levels of control enabled, the results are shown in Fig. 5. Figure 5(a) shows the angular displacement and velocity of the two articulation joints. Figure 5(b) shows the steering angle of all 6 axles, with the first being step input. As expected, anti-phase steering is observed on the same unit. and the following axles reach steady state quite quickly. The yaw rate of each axle is illustrated in Fig. 5(c); almost no rearward amplification (RWA) can be found in both transient and steady state. Similar response can be observed also for lateral acceleration in Fig. 5(e), though certain amount of rearward amplification can be found in side slip. From the high-fidelity TruckMaker model, roll motion response is illustrated in Fig. 5(f). Rearward amplification is also shown for roll motion, while the amplitude is mild, considering the speed and axle steering angle.

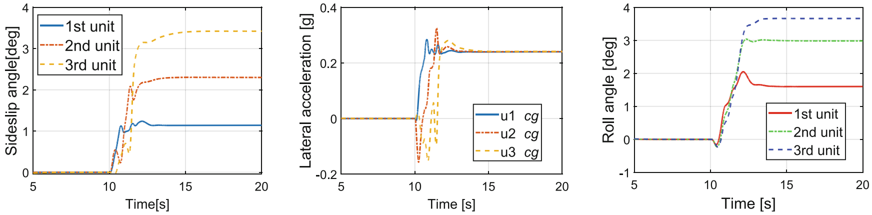
This is illustrated more clearly in Fig. 6, where both controllers can track the reference precisely, overshoot and steady state error are minimal.

4.2 Closed Loop Test

Then a closed loop test is conducted to traverse through a spiral track. A spiral track is defined as track with continuously increasing/decreasing curvature, which is quite commonly adopted in modern transport system design, enabling smoother steering wheel manoeuvre for driver. Specifically, a spiral track, whose curvature steadily increase from 0 to a maximum of 1/40 then decrease to 0, is adopted. The target speed is 30 km/h, leading to a nominal steady state lateral

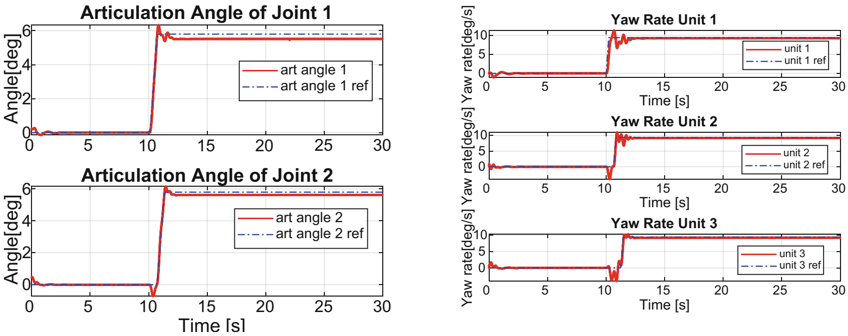


(a) Articulation angle (b) Steering angle (c) Yaw rate



(d) Side slip angle (e) Lateral acceleration (f) Roll angle

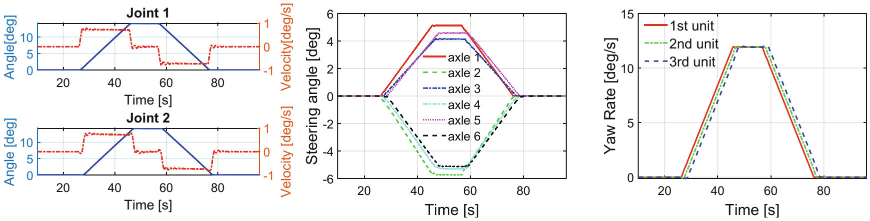
Fig. 5. Open loop test result with step steer input, and all three levels of control enabled.



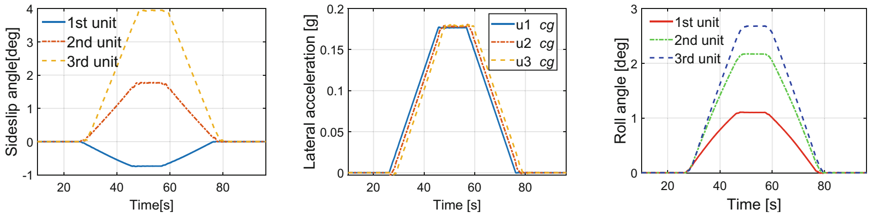
(a) Articulation angle (b) Yaw rate

Fig. 6. Reference articulation angles and yaw rates VS. actual ones, with all three levels of control enabled.

acceleration v^2/R of 0.18 g. An artificial flow guidance(AFG) based autonomous driver is adopted for the first axle, and details of the AFG approach will not be covered in this work, but can be found in [13]. Controller parameters are kept the same as the open loop case. The simulation results are depicted in Fig. 7. As can be observed in Figs. 7(c) and 7(e), yaw rates and lateral accelerations change smoothly with increase/decrease of curvature, even during the transit phases. The RWAs in both are effectively suppressed, hardly exceeding 1. The peak magnitudes of the lateral acceleration is around the nominal value 0.18 g. With smooth articulation joints trajectories and roll angle, it can be concluded that the proposed lateral control approach performs well in terms of lateral stability. And it's worth note that the controller parameters, i.e., the feedback gains for articulation angle and yaw rate stays the same as in open loop case. Indeed, across a wide range of speed and curvature conditions the fixed-gain controller was found to be highly satisfactory.



(a) Articulation angle (b) Steering angle (c) Yaw rate



(d) Side slip angle (e) Lateral acceleration (f) Roll angle

Fig. 7. Close-loop test result on a spiral track.

5 Conclusion

A novel simple yet effective lateral controller with three levels, i.e., Ackermann based feedforward, articulation feedback and yaw rate feedback, is proposed for lateral control for multi-articulated vehicles. Simulations of a 3-unit ART vehicle were carried out in TruckMaker, and results show that the proposed controller works well for a wide range of operating conditions. Rearward amplifications of yaw rate and lateral acceleration are successfully suppressed, requiring no re-tuning of parameters for difference cases. Given the performance of the proposed controller, future real vehicle test and algorithm development is anticipated, for example to integrate the control of all axles as a fully autonomous vehicle controller.

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