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Driver Assistance System for Backward Maneuvers in Passive Multi-trailer Vehicles

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Abstract - Drivers of vehicles with one or several passive trailers, like truck-and-trailer or articulated luggage carriers, have difficulties in backward maneuvers due to jackknife and lack of visibility. Advanced driver assistance systems (ADAS) can be helpful to improve both safety and driver comfort in these complex operations. In this paper, we propose an ADAS that adopts our curvature limitation method for backward multi-trailer vehicles, where the last trailer is considered a virtual tractor and steering limits are established to avoid jackknife and inter-unit collisions. In the proposed solution, when the driver puts the vehicle in reverse, the steering wheel and pedals can be used as if the vehicle was driven from the back of the last trailer with visual feedback from a camera. This system can be implemented in drive-by-wire vehicles, where the steering-wheel feedback force can be customized for the curvature limitation of a given combination of one or several trailers. The system has been tested to tele-operate a mobile robot with two off-axle trailers.

Keywords: Driver assistance systems, tractor, trailer, drive-by-wire, steering limitations, tele-operation, mobile robots, robot control, reverse motion, backwards, collision avoidance, jackknife avoidance, haptics, camera.

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Citation Information

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Abstract— Drivers of vehicles with one or several passive trailers, like truck-and-trailer or articulated luggage carriers, have difficulties in backward maneuvers due to jackknife and lack of visibility. Advanced driver assistance systems (ADAS) can be helpful to improve both safety and driver comfort in these complex operations. In this paper, we propose an ADAS that adopts our curvature limitation method for backward multi-trailer vehicles, where the last trailer is considered a virtual tractor and steering limits are established to avoid jackknife and inter-unit collisions. In the proposed solution, when the driver puts the vehicle in reverse, the steering wheel and pedals can be used as if the vehicle was driven from the back of the last trailer with visual feedback from a camera. This system can be implemented in drive-by-wire vehicles, where the steering-wheel feedback force can be customized for the curvature limitation of a given combination of one or several trailers. The system has been tested to tele-operate a mobile robot with two off-axle trailers.

I. INTRODUCTION

Advanced driver assistance systems (ADAS) are getting more and more attention as a key contribution to increase driver comfort and safety. This is an area where robotics research can be transferred successfully to the automotive industry. High-end automobiles already incorporate ADAS with cameras and other sensors to improve driver perception as well as actuated steering wheels for assisted parking. Articulated vehicles, such as trucks with trailers or multi-body transportation vehicles for goods and passengers, could also benefit from this technology because backing up maneuvers are complex even for skilled drivers [1].

The main reason for this difficulty is the jackknife problem, which becomes especially relevant with more than one trailer [2]. In fact, jackknife avoidance of unmanned vehicles has become a benchmark nonlinear control problem that has been approached with feedback linearization [3], fuzzy control [4] [5], or switching control [6]. However, as many theoretical approaches are difficult to implement and to tune [7] [8], practical solutions are required [9] [10]. In this sense, driver assistance is a significant practical application [1].

Apart from jackknife, drivers of articulated vehicles have difficulties in surveying the rear part of the vehicle, which not only adds to the complexity of backward maneuvering but also endangers pedestrians and other road users. For these reasons, backup cameras can be useful for driver assistance [11].

In spite of these difficulties, not many works have focused on ADAS for articulated and multi-articulated vehicles. A neural network predictor has been proposed to assist the driver in anticipating jackknife situations [2]. Furthermore, the ADAS proposed in [1] integrates motion control with a driver interface to push several passive trailers with a car.

Our previous work addressed autonomous control of multi-trailer mobile robots by imposing steering limitations on the tractor [12]. In the backwards case, jackknife can be avoided if these limitations are computed for the last trailer, which is considered as a virtual tractor [13].

In the proposed system, when the driver puts the vehicle in reverse, the steering wheel and pedals can be used as if the vehicle was driven from the back of the last trailer with visual aid from a camera. This is a practical solution that can be implemented in drive-by-wire vehicles, where inputs from steering and pedals can be processed to produce actual motion commands. Furthermore, driver assistance for jackknife avoidance is given through steering-wheel feedback force, which can be customized according to the curvature limitation computed for a given combination of one or several trailers. The driver feels the curvature limitations as emulated mechanical steering-wheel limits.

In particular, the major contributions of this paper are the following:

- Application of the steering limitations and virtual tractor concepts to backward manual driving.
- Development of a drive-by-wire ADAS interface where steering limitations are incorporated in a feedback force steering-wheel.
- Case study implementation of the ADAS to operate a robotic vehicle with two off-axle passive trailers.

The paper is organized as follows. The next section reviews the use of the last trailer as a virtual tractor for backward motion of an articulated vehicle and the application of curvature limitations for jackknife avoidance. Section III discusses the requirements for a driver assistance system that incorporates these techniques. Section IV describes the case study where the ADAS has been implemented for a two-trailer robotic vehicle and discusses experimental results. Finally, section V presents conclusions and future work.

II. VIRTUAL TRACTOR CONCEPT WITH STEERING LIMITATIONS

This section reviews the use of the last trailer as a virtual tractor for backward motion control of a multi-body
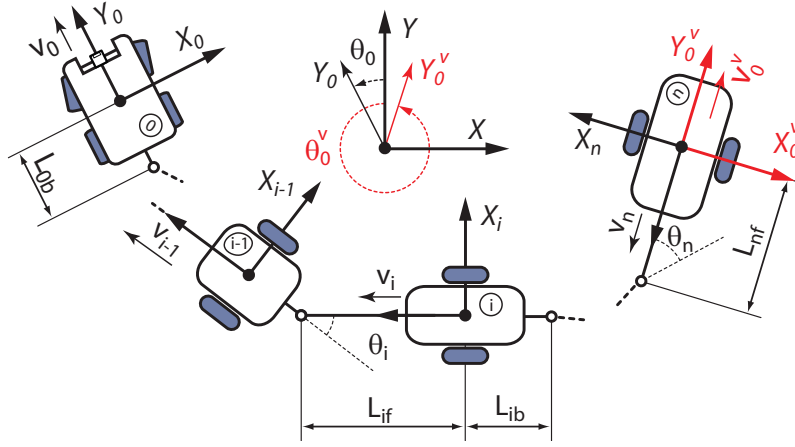
Fig. 1. Parameters of the kinematic chain. Red color refers to the virtual tractor in backward motion.

vehicle [13], which allows off-line computation of curvature limitations.

A. Kinematic Model for Virtual Tractor with Passive Off-Axle Trailers

An n-trailer system can be considered as a kinematic chain consisting of $n + 1$ units, where the tractor is unit 0 and trailers are numbered from 1 to n (see Fig. 1). The local coordinate frame of the ith unit has its X_i axis lying on the rear axle and its Y_i axis in the forward motion direction. For the ith trailer, distance $L_{i-1\,b}$ is a positive constant for off-axle hitching. Distance L_{if} is a positive or null constant. The state of the system is determined by the pose of the tractor and all joint angles.

Let θ_0 be the tractor's heading with respect to the global coordinate system XY. Then, the relative angle of the ith trailer with respect to the $(i-1)^{th}$ unit is represented by θ_i. Absolute angular velocities and longitudinal speeds are given by:

$$\Omega_i = \sum_{j=0}^{i} \frac{d\,\theta_i}{dt}, \qquad (1)$$

$$v_i = \frac{d\,s_i}{dt}, \qquad (2)$$

where s_i is the traveled distance. Furthermore, curvature γ_i (i.e., the inverse of its instantaneous turning radius) is related to Ω_i and v_i as:

$$\gamma_i = \frac{\Omega_i}{v_i}. \qquad (3)$$

Backward motion control of an articulated vehicle can be implemented by considering the nth trailer as a virtual tractor that moves forward [13]. In this case, the local axis of the virtual tractor $X_0^v Y_0^v$ is defined by a $180°$ rotation of the last trailer's frame $X_n Y_n$ (see Fig. 1).

Transforming virtual tractor set-points $(v_{0s}^v, \Omega_{0s}^v)$ into control inputs for the actual tractor (v_{0s}, Ω_{0s}) requires a propagation starting from the last trailer, whose values are:

$$v_{ns} = -v_{0s}^v, \qquad (4)$$

$$\Omega_{ns} = \Omega_{0s}^v. \qquad (5)$$

Then, set-point propagation equations through off-axle trailers are:

$$v_{i-1s} = v_{is}\,\cos(\hat{\theta}_i) - \Omega_{is}\,L_{i\,f}\,\sin(\hat{\theta}_i), \qquad (6)$$

$$\Omega_{i-1s} = -\frac{v_{is}\,\sin(\hat{\theta}_i) + \Omega_{is}\,L_{i\,f}\,\cos(\hat{\theta}_i)}{L_{i-1\,b}}, \qquad (7)$$

which only depend on the current values of the joint angles measured by encoders $\hat{\theta}_i$.

B. Steering Limitations for Inter-Unit Collision Avoidance

Imposing steering limitations for multi-trailer systems was first proposed to prevent inter-unit collisions in forward motion [12]. This was extended to obtain steering limitations for a virtual tractor to avoid jackknife in backward motion [13]. In both cases, these limitations are constants computed off-line for a given configuration of the articulated vehicle. This computation has two main steps: first, a recursive steady-state analysis establishes equilibrium, mechanical and propagation limits of all units based on kinematic parameters; then, these limits are refined by simulating transients to account for non-minimum phase responses of multi-trailer systems.

III. DRIVER ASSISTANCE SYSTEM REQUIREMENTS

This section discusses the requirements for implementing the virtual tractor and steering limitations in a driver assistance system for multi-trailer backward motion. These are considered in the proposed ADAS architecture depicted in Fig. 2.

First, the driver needs visual feedback from the back part of the vehicle. This requires placing a camera in the last trailer to display real-time images from the backward direction on a dashboard screen. A wireless camera would allow a simple and flexible set-up in case of changes in the multi-trailer configuration.

With this visual feedback, the vehicle can be steered backwards as if the driver was sitting in the last trailer (i.e., the virtual tractor). To achieve this, drive-by-wire controls
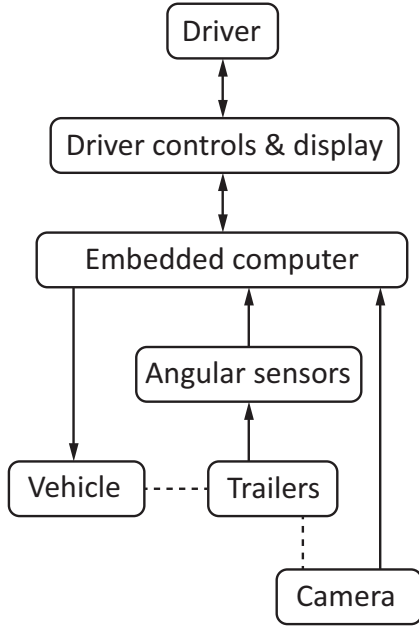
Fig. 2.   ADAS architecture overview.

Fig. 3.   Auriga-α multi-trailer vehicle with PTZ cameras for driver assistance. The last trailer (left) is considered as a virtual tractor.

(i.e, pedals, reverse/forward selector, and steering wheel) are necessary. In this way, the provided speed and steering commands can be translated to actual tractor motion using (4)-(7).

An embedded computer is required to interface with the driver controls and to perform propagation of commands in real time. Furthermore, this computation implies reading angle sensors from hitches.

The steering limitations method can be implemented to avoid inter-unit collision both forwards [12] and with the virtual tractor [13]. Virtual tractor limitations can be incorporated into the ADAS using a steering wheel with force feedback so that the driver feels these limits as if they were mechanical bounds.

IV. CASE STUDY

A. Auriga-α Two-Trailer Vehicle

The proposed ADAS sytem has been tested to tele-operate the Auriga-α mobile robot with two passive trailers (see Fig. 3). The tractor weights $258\,\mathrm{kg}$ and its dimensions are $1.24\,\mathrm{m}$ (length), $0.75\,\mathrm{m}$ (width) and $0.84\,\mathrm{m}$ (height). This tracked tractor uses skid steer locomotion with two geared DC motors with incremental shaft encoders. An approximated differential drive kinematic model [14] has been obtained for odometric estimations and control. The maximum speed of the vehicle $(1\,\mathrm{m/s})$ can be achieved in straight-line motion. An on-board DSP controls motor speeds every $10\,\mathrm{ms}$ and gives odometric data every $30\,\mathrm{ms}$.

This vehicle tows two passive single-axle trailers with off-axle hitches: a load carrier and a sprayer. Hitch angles $\hat{\theta}_i$ are obtained from inter-unit draw-wire displacement sensors. The kinematic parameters are $L_{0b} = 0.71\,\mathrm{m}$, $L_{1f} = 0.99\,\mathrm{m}$,

$L_{1b} = 0.61\,\mathrm{m}$, and $L_{2f} = 0.81\,\mathrm{m}$. The mechanical inter-unit collision limits of the hitches are $\theta_{1\,m} = \pm68°$ and $\theta_{2\,m} = \pm43.6°$.

The curvature limitation computed for the tractor to avoid inter-unit collisions with this configuration is $\gamma_{0m} = 0.44\,\mathrm{m}^{-1}$ [12]. In backward motion, the curvature limitation for the virtual tractor results in $\gamma_{0m}^v = 0.45\,\mathrm{m}^{-1}$ [13].

In the experiments, the global pose of the actual tractor (x_0, y_0, ϕ_0) is recorded every $270\,\mathrm{ms}$ by correcting odometric estimations with an accurate laser scan matching technique [15]. To this end, an onboard Sick LMS 200 rangefinder is placed at a distance of $0.5\,\mathrm{m}$ ahead of the tractor coordinate origin.

B. ADAS Architecture Implementation

The drive-by-wire hardware architecture of the Auriga-α vehicle is summarized in Fig. 4. An onboard control computer with a real-time operating system issues differential drive commands for the DSP motor controller and receives hitch angles. This computer implements the virtual-to-actual tractor set-point conversion for backward motion [13]. For this, it requires velocity and curvature commands, as well as the forward/reverse mode selection from the ADAS interface. Onboard driving is not possible with the robotic vehicle used for the case study, so a remote ADAS interface is managed by a dedicated computer with wireless connection.

The ADAS interface is shown in Fig. 5. It consists of a display for camera images and a commercial kit of driver controls which consists of a steering wheel, a manual lever, and pedals. Values from the driver controls are read with a Labview application running in the interface computer.

The display offers images from two pan-tilt-zoom (PTZ) cameras for visual feedback (see Fig. 3). These images are received through a local wireless TCP-IP network, which is independent from the link between the interface and control computers. One camera is mounted on the last trailer for backward motion assistance. A second camera on the tractor allows remote forward driving. These cameras have been
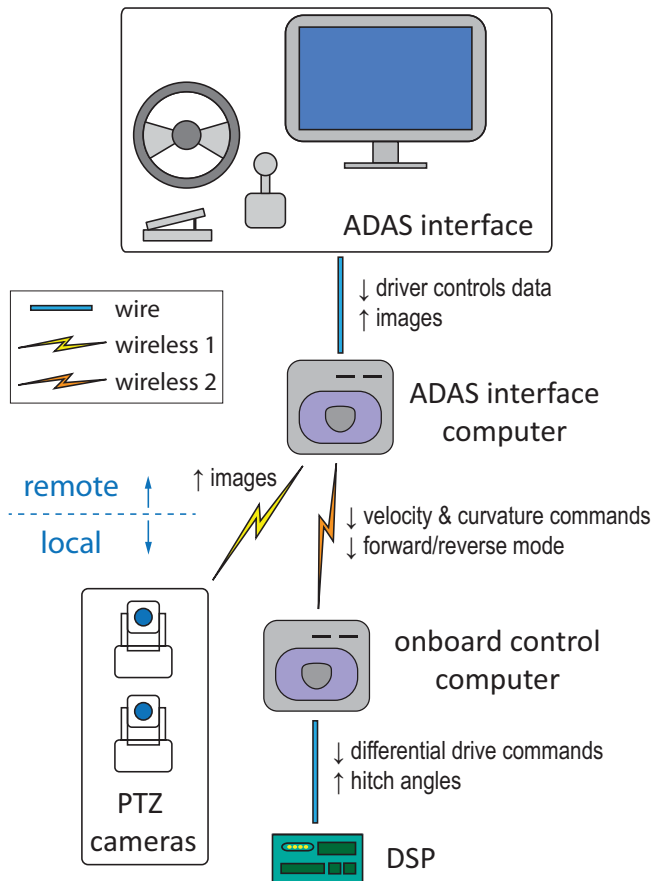
Fig. 4.   Drive-by-wire hardware architecture.

Fig. 5.   ADAS Driver Interface.

Fig. 6.   Experiment site.

placed at an overhead position and their tilt can be adjusted to include part of the vehicle in the display. If necessary, camera and PTZ parameters can be adjusted from the driver display.

The steering wheel has an optical encoder and two motors with feedback force. This allows programming a centering spring effect as well as rotation limits. The steering rotation limits have been set to $\pm 60°$ independently of the forward/reverse selection. The steering wheel angle range is processed by the control computer to give proportional curvature setpoints according to the inter-unit collision avoidance limits computed for forward and reverse motion.

The manual lever has been programmed to select the forward and reverse driving modes. As for pedals, only the accelerator is used to produce linear speed setpoints.

C. Experimental Results

This section presents results from an experiment in which a driver uses the remote ADAS for reversing the articulated Auriga-α vehicle. In this experiment, the vehicle is driven backwards through a gate from inside a warehouse (see Fig. 6) to an outdoors parking position aligned with the building wall. The traversable zone has been delimited by cones for the driver, who had no previous experience with this ADAS interface. The driver uses the image from the back-facing camera to steer the vehicle as if sitting in the last trailer.

The path recorded for Auriga-α and its trailers is presented in Fig. 7. This path has a length of about 21 m. The estimated paths for the trailers appear with more noise because they are obtained from the tractor path using noisy hitch angle measurements.

Further data from the experiment is shown in Fig. 8. The steering-wheel and accelerator pedal commands for the virtual tractor are shown in Figs. 8a and 8b. The steering limitations are reached, and felt, by the driver in several moments during the turns. These limitations succeed in avoiding that mechanical hitch limits are reached (as seen
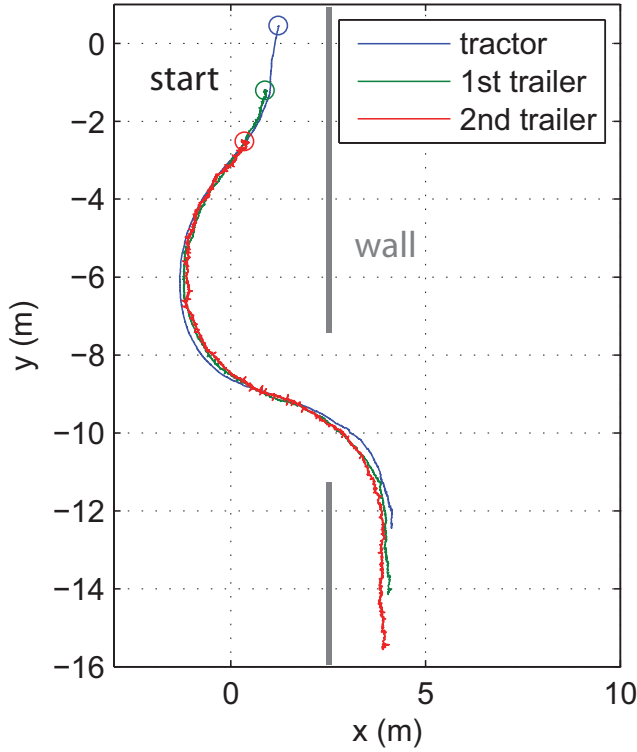
Fig. 7.   Driven path.

Fig. 8.   Experiment results

in Fig. 8c). The driver commands are translated though the kinematic chain to produce the tractor set-points shown in Figs. 8d and 8e, respectively. The negative tractor speed reflects the accelerator pedal variations but adds the effects of the hitch angles (which is particularly noticeable between 70 s and 80 s in spite of an approximately constant v_{0s}^v).

After the experiments, the driver impressions about the system referred to the similarity between forward and reverse steering. He made special remarks about feeling easy about not having to worry about jackknife or inter-trailer collision in backward motion.

V. CONCLUSIONS AND FUTURE WORK

This paper has presented an application of mobile robot technology to advanced driver assistance systems (ADAS). The proposed system serves to avoid inter-unit collisions and jackknife in vehicles with one or more passive trailers both in forward and reverse motion. The case of reverse multi-trailer steering has been explicitly addressed because it is a difficult maneuver with visibility problems where ADAS can improve both safety and driver comfort.

The proposed ADAS incorporates the curvature limitation method for backward multi-trailer vehicles. In this method, the last trailer is considered a virtual tractor and steering limits are established to avoid jackknife and inter-unit collisions. In this system, when the driver puts the vehicle in reverse, the steering wheel and pedals can be used as if the vehicle was driven from the back of the last trailer with visual feedback from a camera.
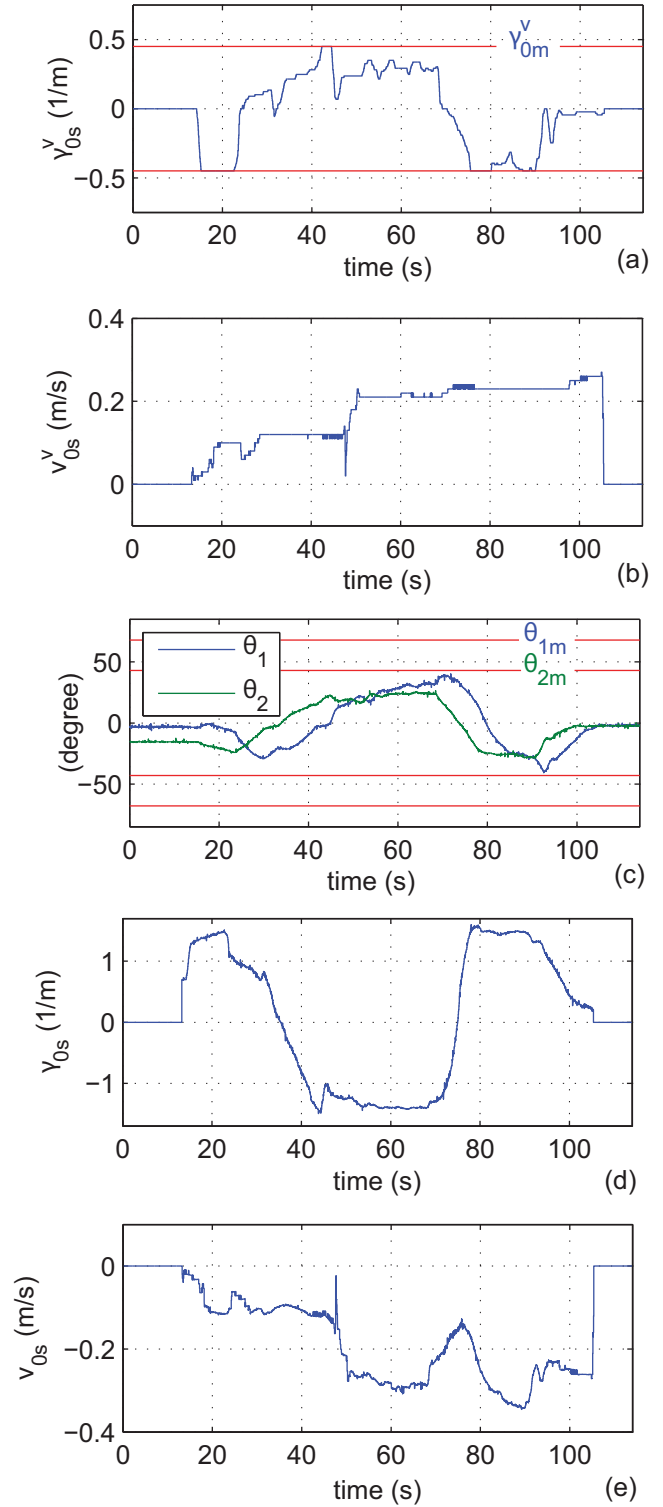
The system requirements and architecture have been identified in the paper. These consist of a backward oriented camera in the last trailer to feed images to a dashboard screen, drive-by-wire controls with a feedback-force steering-wheel, hitch angle sensors, and an embedded computer for mo-

tion control and virtual tractor command propagation. The steering limitations are calculated off-line for a particular kinematic configuration of the articulated vehicle.

The system has been implemented as a remote driver interface to manually control a two-trailer robotic vehicle. Details about the hardware architecture have been given. Experimental results have shown the good behavior of the system for backward driving.

Future work includes improving the driver assistance system with automatic tasks such as parking. Moreover, it would be interesting to implement the system in a car with bounded curvature, as in Ackermann steering.

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