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INTRALOG – intelligent autonomous truck applications in logistics; single and double articulated autonomous rearward docking on DCs

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Abstract: Vehicle automation opens opportunities toward the improvement of people, planet, profit value in applications on distribution centres (DCs). Despite vision and drive for innovation in logistics, the lack of knowledge prevents the application of autonomous applications. Intelligent Truck Applications in Logistics (INTRALOG) contributes to this deficit and generates valuable insights for a future application in public environments. Current operational automated guided truck applications are bound to fixed infrastructure and do neither operate in the public domain nor offer opportunities to do so. Nowadays, in-vehicle intelligent systems are focused on driver support, opening opportunities such as truck platooning. INTRALOG cross-borders on DCs in relatively low-complex traffic environment, bridging the gap between autonomous driving in the public domain. The multi-agent system developed within INTRALOG aligns logistical movements on DCs, controlling single or double articulated container trailers (longer and heavier vehicle) between the public parking area and cross-docks. This study elaborates on the experiments on automated manoeuvring on a DC with single (SAVs) and double articulated vehicles (DAVs). The experiments comply with business requirements, e.g. manoeuvrability, time to dock and positioning accuracy. The research focuses on the effects of these aspects and control strategies of SAVs and DAVs.

1 Introduction

Throughout the years, sustainability, effectiveness, cost and innovation have been the leading drivers in logistics in the Netherlands. Owing to this, 57% of all American and Asian distribution centres (DCs) on the European continent are located in the Netherlands [1]. The first container terminal having automatic guided vehicles (AGVs) was ECT in Rotterdam. In 1985, the first prototype container carrying vehicles appeared at the Maasvlakte in the Port of Rotterdam (PoR). Several companies have developed AGVs for port applications. Automated reversing and docking of tractor–trailer combinations has been a subject of research for a long time [2]. However, all successfully installed and operational AGV systems for port logistics are running in a fenced and separated area.

The Intelligent Truck Applications in Logistics (INTRALOG) project investigates the added people, planet, profit value (PPP) of automated guided trucks (AGTs), and the way they can add value with respect to PPP to logistics operation at DCs and inter-terminal/intermodal traffic hubs [3].

To plan and control these logistic operations on DCs in an environmentally friendly and effective way, a multi-agent system (MAS) has been developed [4]. It did, however, not result in commercial applications due to various reasons: manoeuvring (multiple) trailers using a (terminal) truck is complicated, especially when performing reverse movements that require turns. It has been subject to scientific research for the last three decades [5, 6]. However, the volume of goods transported as well as the number of commercial vehicles in Europe has increased substantially over the past decade [7]. As the Dutch experience reveals, the legalisation of longer and heavier vehicles (LHVs) on highways makes transportation of goods more efficient, sustainable and is applicable even in highly populated regions [7]. Currently, the number of double articulated vehicles (DAVs) (LHVs) in the Netherlands is estimated on ∼1500 (Source: Transport and Logistics Netherlands is the business organisation for road transport companies and logistics service providers) LHVs.

A commonly used LHV combination is the tractor with a semi-trailer and a central axle trailer [8] (see Fig. 1). From a logistic perspective, these combinations are economical and efficient; however, these combinations are complicated to handle, compared with the conventional tractor semi-trailer combination especially during reversing [9]. AGVs, taking over the drivers role on DCs, can do this more accurate.

This paper focuses on an innovative application of unmanned aerial vehicle (UAV)-controlled AGVs in DCs in the hinterland of the Netherlands. More specifically on controller assessment during manoeuvring of single AVs (SAV) and DAVs (DAV or LHV), matching the business requirements in terms of controller behaviour resulting in positioning accuracy and docking speed.

2 Background

2.1 Business perspective

AGVs for public transportation are operational for outdoor and indoor applications, e.g. Park shuttle Capelle a/d IJssel [10], Masdar City [11] and Heathrow airport [12]. The biggest challenge is the safety validation of the application. A preliminary safety case needs to be reviewed before on-site tests can be conducted to further collect data that is necessary to construct the safety case.

According to the World Economic Forum, the Netherlands is the country of choice for European DCs: 57% of all American and Asian DCs on the European continent are in the Netherlands [1]. Owing to all this, the Netherlands has become one of the leading road transport nations in Europe. In addition to the sheer large volume, this is caused by taking aspects such as sustainability, effectiveness, cost and innovation into consideration. Megatrends such as globalisation and increasing worldwide economic integration, technology – above all the growing speed of

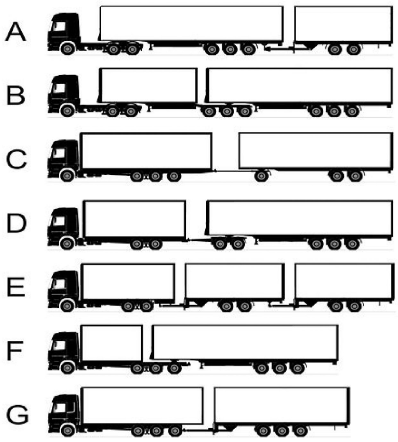

Fig. 1 *LHV combinations [8]*

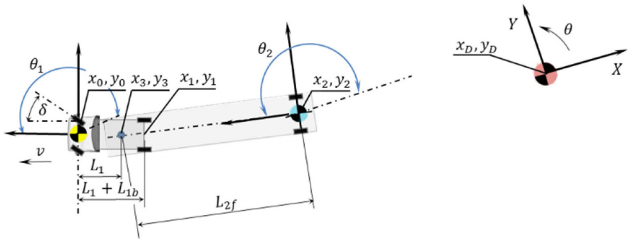

Fig. 2 *Vehicle parameters and states [15]*

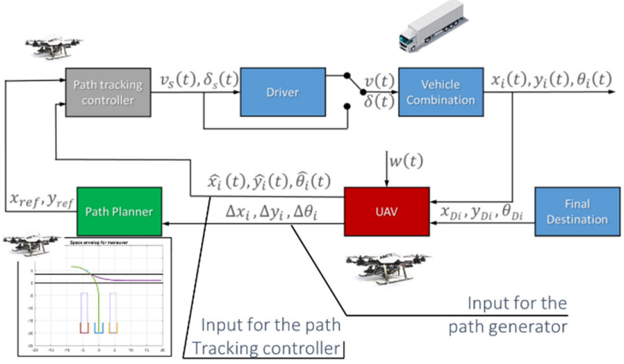

Fig. 3 *Control diagram [15]*

technological development and climate change all have a major influence on today's developments in mobility [13].

The increasing use of information systems in logistics has improved operations' efficiency dramatically. An appealing new development is related to the transportation trucks themselves: autonomous driving. The potential of this technology is recognised by politicians and by the transportation sector, motivated by the business potential. Autonomous driving will reduce cost, fuel consumption and carbon dioxide emission (air drag reduction by close distance driving and efficient traffic routing) and safety (crash avoidance). To make various autonomous driving functions available, research and development have to be carried out in various disciplines: truck design (braking and steering), IT (software reliability, fail safe and standardisation), legislation (liability), science (trajectory planning, vehicle dynamics modelling and control), social science (taking care of drivers' interests), logistics (integrate new features in logistic operation and allowing automated vehicle use) and business (earn money with new and advanced possibilities).

As mentioned Section 1, the first (1985) container terminal having AGVs was ECT in Rotterdam. This application operated AGTs applications bound to fixed infrastructure (passive magnetic or radio-frequency identification transponders). These AGVs were not intended to operate in the public domain and neither offered opportunities to do so.

In a next step, INTRALOG introduced an UAV as a sub-system in a video-based AGV guidance system, raising the opportunity for DCs to flexibly operate AGV systems in transporting single and double articulated (container) trailer vehicles [14].

Local real time kinetic (RTK) could replace fixed infrastructure and/or camera observations; however, built environments will affect connectivity and accuracy. Additionally, manoeuvring between two parked truck/trailer combinations will require additional sensors to maintain accuracy.

2.2 Controller perspective

In a global perspective, the controller functionality is described in terms of vehicle states and the relevant parameters [15, pp. 6, 7]. The position of the tractor (see Fig. 2) is defined by the position of the front (x_0, y_0) and rear axle (x_1, y_1). The tractor is defined by the wheel base ($L_1 + L_{1B}$) and the distance between the rear axle and the fifth wheel (L_{1B}) and its orientation (yaw angle: θ_1). The inputs for the truck are longitudinal velocity (v) and steering angle (δ).

The semi-trailer is defined by the distance between the kingpin and the centre of the axle group (L_{2f}) and the semi-trailer orientation (yaw angle: θ_2), the position of semi-trailer kingpin (x_3, y_3) and the centre of axle group (x_2, y_2). The docking gate is given by position: x_D, y_D and orientation: θ_D.

In general, the role of the UAV is to guide the tractor–trailer combination from 'any point' to the docking gate (see Fig. 3).

As described in Buning *et al.* [15, pp. 6, 7], the UAV acts as an optic sensor, using visual input ($x_{1,2,D}$, $y_{1,2,D}$, $\theta_{1,2,D}$), leading to:

- Initial position and orientation of tractor ($\widehat{x_1}$, $\widehat{y_1}$, $\widehat{\theta_1}$) and semi-trailer ($\widehat{x_2}$, $\widehat{y_2}$, $\widehat{\theta_2}$), with respect to the destination (x_D, y_D), enabling the input to the path planner (Δx_i, Δy_i, $\Delta\theta_i$), generating the reference path x_{ref}, y_{ref}.
- Position and orientation of all axles and fifth wheel [$x_i(t)$, $y_i(t)$, $\theta_i(t)$], input to the path tracking controller which will calculate the steering angle to minimise the error between the reference path and actual position of the vehicle combination.

Morales *et al.* in their study [16] defined a way to control trailers with on-axle and off-axle hitching. This paper proposed a pragmatic approach for reversing a vehicle combination, wherein the last trailer was defined as the virtual tractor. The virtual set points of the virtual tractor were propagated kinematically through the chain up to the actual tractor using the articulation angle measurements. They studied the effects and limitations of on-axle and off-axle hitching. The curvature limitations were also considered which was proposed in their previous paper [17]. The application of the proposed controller was shown by an application on an Auriga-α mobile robot and two passive trailer combinations. They also concluded that the on-axle hitching caused driving difficulties as compared with other combination.

Kim *et al.* [18] studied the vehicle's lateral control behaviour when driving reverse. They proposed three methods of controlling a vehicle when driving in reverse. The first was the Stanley method which used the geometric path tracking algorithm to determine the steering angle to the nearest goal point. The second method was the pure pursuit method which also used a geometric method of fitting circular arcs between the rear axle and the goal point and determining the angle between them. Moreover, the third was a model-based state feedback control method. All the proposed methods showed optimal results when driving in forward, but when driving in reverse the results were below par. The study concluded that the desired steering angle should not be calculated with respect to the front axle of the vehicle when reversing.

Martinez *et al.* [19] studied the path tracking strategy for mobile robots. The notable difference here was that this study did not consider the kinematic model. Owing to this, the approach could be also used when driving on irregular terrains and with vehicles with tracks instead of wheels.

This pure geometric method follows the pure pursuit method of path tracking as used in [18]. The study also considered the inter-

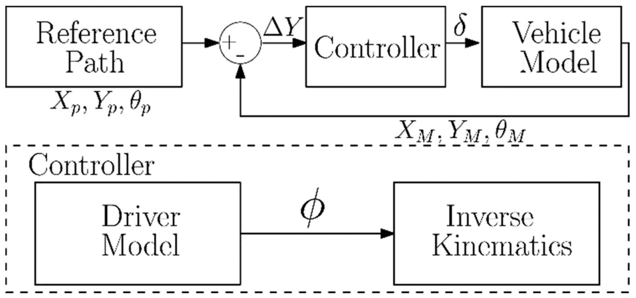

Fig. 4 *Control algorithm*

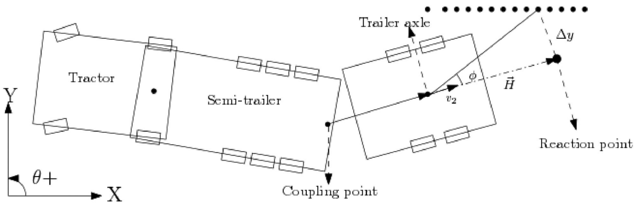

Fig. 5 *Reverse control concept*

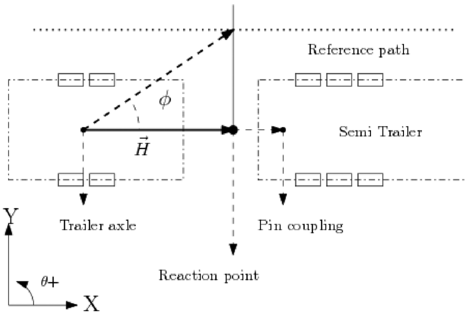

Fig. 6 *Forward control concept*

collision between units and defined a steady-state articulation angle for constant inputs using the dimensions of the vehicle units for both forward and reverse driving. The study concluded by demonstrating the path tracking strategy by implementing it on the Auriga-α mobile robot and the results showed the successful addressing of the issues such as inter-collision and the efficient path tracking.

Hertogh's study [20] followed a similar method as [16] for providing driver assistance while docking. The virtual tractor concept was used in this paper to determine the steering angle required at the trailer axle. Since it was not a steered axle, this angle was to be translated into the steerable axle of the tractor which was done by the inverse kinematic equations which consisted of the kinematic translation of the steering angle at trailer axle to the actual steering angle of the tractor. The application of this controller was also tested on a DAV [20] and it was found that the controller had an optimal performance with respect to path following in reverse, but with a low tracking efficiency especially for a double articulated combination. In his paper, he also assumed of directly equating the steering angle required at the trailer axle to the tractor axle steering angle when driving forward. This assumption did not perform as it was supposed to and the relationship did not seem entirely correct considering the lateral error that existed in the path followed by the trailer.

2.3 Controller methodology – virtual tractor

Two manoeuvres are involved when docking a vehicle combination: forward and reverse. When driving in the forward direction, the tractor is the driving unit and the trailers follow the path as per the steering angle at the tractor. However, when driving reverse the last trailer or the draw-bar trailer, in this case, can be treated as a virtual tractor and the semi-trailer and the actual tractor will be considered as a trailing unit.

The control algorithm for an articulated vehicle combination involves three steps (see Fig. 4) which are:

i. Compute the global position (X_M, Y_M) and orientation (θ) of the virtual tractor. In the multibody body model, it can be determined by using body sensors and in the kinematic model, it can be computed using the geometrical relationships.
ii. Determine the steering angle by applying the forward motion control to the virtual tractor and determine the virtual steering angle (ϕ).
iii. Transform the virtual steering angle to the actual tractor steer angle ($\delta_{\text{TRACTOR AXLE}}$) using the inverse kinematic relationship between the tractor and trailers.

The goal is to achieve the trailer axle to follow the predefined path. The driver model calculates the lateral error between the driver preview point and reference path (see Fig. 5) from which the virtual steering angle (ϕ) will be calculated [20–22]. The inputs to the driver model are the trailer axle and coupling point positions. However, since the trailer axle is not steered in this vehicle combination, it is necessary to have a conversion of the angle required at the trailer axle to the steerable axle of the tractor.

2.3.1 Reversing controller: The driver model is provided with the position inputs of the pin coupling of the draw-bar trailer and the trailer axle. From the position input, a normalised unit truck vector is created for every time step from which the orientation of the trailer is determined by the controller. The controller parameter defined as 'lookahead (LA) time' is provided as the input to the controller. LA time multiplied with the velocity of the trailer gives the preview distance of the driver from the trailer axle. A heading vector (***H***) is generated from the trailer axle to the reaction point as shown in Fig. 5 and given by (1).

If the trailer had a steerable axle, then the virtual steering angle (ϕ) can be determined from the lateral error (Δy) as shown in Fig. 5 calculated between the reaction point created using the preview distance and a point on the reference path. The steering angle required at the trailer axle ($\delta_{\text{traileraxle}}$) is given by multiplying the virtual steering angle (ϕ) by a proportionality constant (K_s)

$$\boldsymbol{H} = \mathrm{LA}\,\boldsymbol{v}_2 \qquad (1)$$

$\boldsymbol{v}_2$ is the trailer velocity and LA is the lookahead time.

The virtual steering angle is the input that is to be provided at the trailer axle for the trailer to follow the path. This must be translated to the steerable axle of the tractor using the inverse kinematics.

2.3.2 Forward controller: The forward controller uses the same concept as that of the reverse controller, but with a change in direction and initiation point of the trailer vector and heading vector. Since the direction of travel is forward, the trailer vector is now created from the trailer axle to the draw-bar coupling point. The heading vector in case of the reverse control starts from the end of the trailer vector, but this is reversed in case of forwarding control, the heading vector now starts from the initial point of the trailer vector as the goal is to have the trailer axle follow the path (Fig. 6). The rest of the calculation of the virtual steering angle ϕ is the same as the reverse controller.

If the same concept as the reverse controller would be used, then this would calculate the error with respect to the path at the draw-bar coupling point and not the trailer axle. However, it is necessary to control the trailer axle; the heading vector is created from the trailer axle and not the coupling point.

3 Method – use case introduction

As mentioned in Section 1, in this case study we focus on rearward docking on DCs, using single and DAVs. The case study is based on elaborating daily logistic movements and manoeuvring on DCs at the PoR [23] and ROTRA Logistics at Doesburg (NL) [4], using:

- Survey interviews etc., with stakeholders.
- Simulations.
- (model) Experiments.

3.1 Use case description

According to the study of Salet [8], it was found that during the pilots of the LHV's on the Dutch roads three of the seven mentioned combinations in Fig. 1 are the most commonly used [8]. About 63 out of the 100 participants [8] combinations were of Type-C (Fig. 1), which was a combination consisting of a truck with a dolly and a semi-trailer. The second most used combination was of Type-A [8] which consisted of a tractor with a semi-trailer and a central axle trailer (Fig. 1). These combinations are economical and efficient from the fleet owner's perspective, but the drivers are the ones who handle these trucks. So, from their perspective, these combinations are complicated to handle as compared with the conventional tractor semi-trailer combination especially during reversing [9].

When the driver is less experienced and has to backup, these trucks onto a docking gate; it is not an easy task especially when he is at a high-frequency warehouse, where there could be several vehicles queued up to park in adjacent gates. The other issue is also that due to the limited field of view the manoeuvring could result in the trucks colliding with the adjacently parked trailers or the docking rails or even the docking gates all of which results in a financial loss to the fleet owners and the warehouses. A conversation with a warehouse manager revealed that according to their survey it was found that they approximately have 1 of every 3000 trailers crashing onto the dockyard gates incurring a loss of over €1,000,000/year. The only way to solve this problem is either providing the driver with a better field of vision through cameras or automating the parking systems in the tractor/truck such that the trailer is appropriately parked in the assigned gate.

As mentioned above, docking of the trailer is one of the important issues to be solved by providing the driver or the tractor/truck the required inputs for easy manoeuvring around the docking gates.

To solve the docking problem, two requirements are necessary to be fulfilled:

- An accurate means to localise the vehicle with an accuracy level higher than standard global positioning system which is at least 3.5 m at best conditions with respect to the distribution gate. Several approaches can be taken to localise the vehicle such as transponders or laser scanners; however, both require additional instrumentation on the vehicle or directly on the docking gate, which, in turn, limit the flexibility. Additional instrumentation on the vehicles itself is not a feasible solution as this would not be economical for the fleet owners, and in most cases the tractor/truck and the trailers might be owned by two separate parties.
- Most of the manoeuvres in a dockyard involve both forward and reverse motion. Hence, it is necessary to have a controller able to perform the forward and reversing manoeuvres such that the trailer axle can follow a predefined path from its initial position to the docking gate.

Insight on the above can be gained by answering the following research questions:

- What kind of controller is going to be used/developed?
- Which image sensor/camera is going to be used on the UAV?
- How does the image sensor/camera detect and determine the position and orientation of the truck?
- What kind of markers is necessary for accurate detection?
- What kind of communication is to be developed for the transmission of data from the UAV to warehouse management systems (WMS) and WMS to the truck?
- Is it possible to deploy the developed controller on a scaled setup?

3.2 Vehicle anchoring – video guidance

In this conceptual study, we propose the usage of an UAV, which will be responsible for providing a top-view image of the commercial vehicle combination, operating in an MAS.

The UAV is working in several regimes which are depicted in Figs. 7–10. The idea is that the UAV will be based at the DC and directly connected to a MAS. When the commercial vehicle will enter the area of the DC, the UAV is going to find an arriving vehicle combination proposing support to the driver and guidance

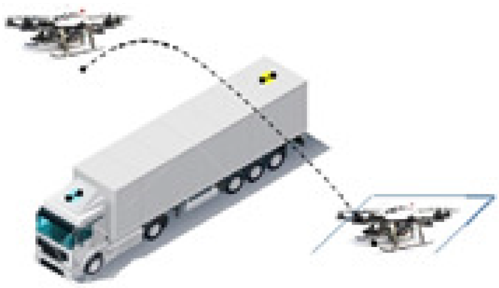

Fig. 7 *UAV vehicle anchoring - step 1: Find the vehicle*

Fig. 8 *UAV vehicle anchoring - step 2: Anchor and follow the vehicle*

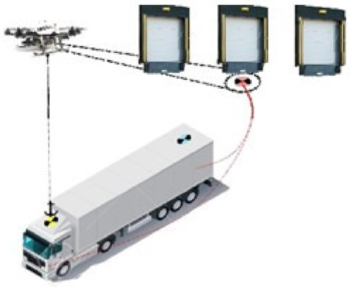

Fig. 9 *UAV vehicle anchoring - step 3: Identify, measure, and plan the path*

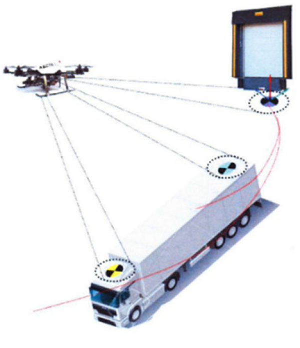

Fig. 10 *UAV vehicle anchoring - step 4: Autonomous path following*

to a particular receiving dock such as small boats which assist big container ships at the harbours.

Step 1: Find the vehicle

In step 2, we consider that the driver has accepted the support and the UAV is going to a virtual anchor above the vehicle.

Furthermore, from now, video signals from UAV cameras can be accessed by the driver, for example, by means of the tablet, so that he/she can obtain precise positional information of the vehicle and its surrounding space. Cameras are also used to identify dedicated markers on the vehicle roof for high-level control of UAV's speed enabling to copy the movement of the vehicle combination while providing a uniform angle of view to the driver.

Step 2: Anchor and follow the vehicle

In step 3, the vehicle arrives near the receiving dock gate, which is first localised also by means of dedicated markers by UAV's cameras and accurate mutual position of the vehicle and its destination is being determined. Subsequently, a path to reach the destination is proposed, which will respect kinematic constraints of the vehicle combination.

Step 3: Identify, measure and plan the path

Finally, in step 4, the vehicle combination will be navigated along the planned path either autonomously by directly actuating the steering angle and the reverse speed of the tractor by the controller or semi-autonomously.

Step 4: Autonomous path following

In this case, the driver is being instructed by haptic or visual interface how the tractor should be controlled to bring the semi-trailer to the desired position and orientation at the docking gate. It is expected that the altitude of the UAV will be controlled according to the distance between the destination point and semi-trailer. It enables to increase the accuracy of the position and orientation estimate during the last meters before reaching the destination, because of the smaller field of view covered with the fixed resolution of the camera.

4 Results

4.1 Business requirements

The overall haul at the PoR, during an average working day, shows 19,340 trips, carrying 20,765TUE, of which are ∼20% short trips and DC traffic [23]. However, at ROTRA the number of trips on DCs are ‘limited’: ∼150/day [4, p. 32], the number of trips at PoR over 800/day [23].

Analysis of the stakeholder interviews showed a set of control aspects of these trips are [23]:

i. Response time

    a. <0.25 s on detected environmental warning signals.
    b. <0.25 s control commands.

ii. Positioning capabilities: <10 cm.
iii. Maximum distance trailer rear end – dock: 25 cm.
iv. Limitation on manoeuvring speed, ∼3 km/h.

Observations during a scholarly INTRALOG sub-project at ROTRA DC on docking time showed a strong dependency on ambient conditions and driver skills. During observations only, manoeuvres of tractor–trailer SAV combinations were used, with a starting position parallel to the docking station (aligned with simulations) and limited articulation angles.

Results must be considered as indicative, whereas values for docking time varied from minimum 45 s to ‘not relevant’ for two or more attempts. Distance travelled varied from just over 2×tractor–trailer combination length.

Observations on DAVs are left out; an additional observation at ‘a DC’, showed a docking time of >900 s.

4.2 Simulation results

The controller was developed with the end goal of being used in a closed space such as a dockyard or a warehouse. Hence, it was necessary to test the controller with respect to manoeuvres that would be commonly performed in the warehouses. Different types of warehouses have different parking layouts. The common manoeuvres in a docking yard would be mostly a 45°, 60° or 90° turn. Hence, two test cases were developed based on the requirements which were first being a 90° curve and the second one being the offset test. This was considered as the benchmark for this controller as a 90° curve test involves both straight line path to curve and curve to straight path. If the controller can perform this manoeuvre, then it could be used in most of the cases as this was one of the complicated manoeuvres involved in parking.

It can be seen from Fig. 11 that the controller is able to maintain the draw-bar trailer axle on the reference path with a deviation at the curve. The path following is more efficient in case of higher radius as the controller can provide sufficient input to the steering with the yaw rate in control without the jack-knife condition. With a constant speed, the yaw rate of the trailer reduces with increasing radius. Hence, a better path following is achieved at a higher radius than at lower radius. With low radius, the trailer will have to yaw at a higher rate to follow the path which would cause instability in the system.

4.2.1 90° Turns: The forward controller was tested for the same manoeuvres as that of the reverse controller which was the 90° curve test. Fig. 12 shows the forward driving test with a radius of 35 m, where the controller can keep the draw-bar trailer axle in the path as per requirement. When the radius is increased further, the oscillating behaviour of the tractor and semi-trailer is reduced. This is due to the high steering input from the controller as it requires a higher steering angle since the yaw rate of the trailer will increase with decreasing radius (Fig. 13).

4.3 Scaled environment experiments

One of the primary objectives of this project was to prove the functionality of the controller on a radio-controlled scaled truck (RC vehicle). For this purpose, a localisation system was necessary. This was fulfilled by using a camera coupled with ArUCo markers [24]. These markers were binarily coded markers used in the world of augmented reality for localisation of robots and other applications. Using these markers, the position and orientation of the scaled model could be determined. The camera retrieved the pixel positions of these markers and these were converted to length domain for standardisation purpose using a gain value. The steering angle was calculated by the controller for the provided reference path. The steering signal along with the traction signal was communicated to the scaled model via the XBee module. The flow of data is represented in Fig. 14.

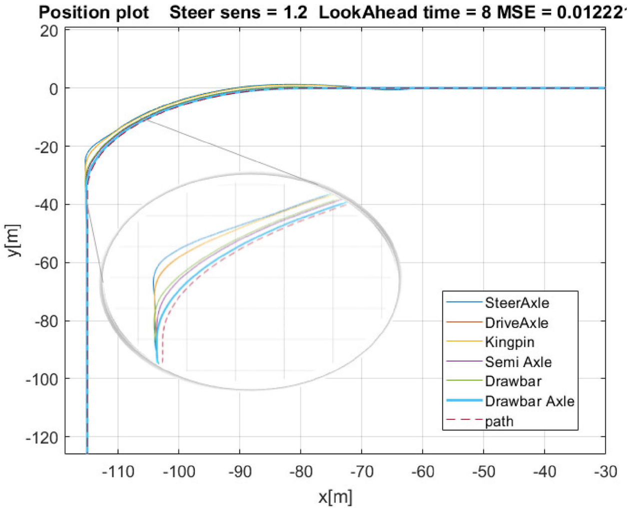

Fig. 11 *Global position plot for reversing motion*

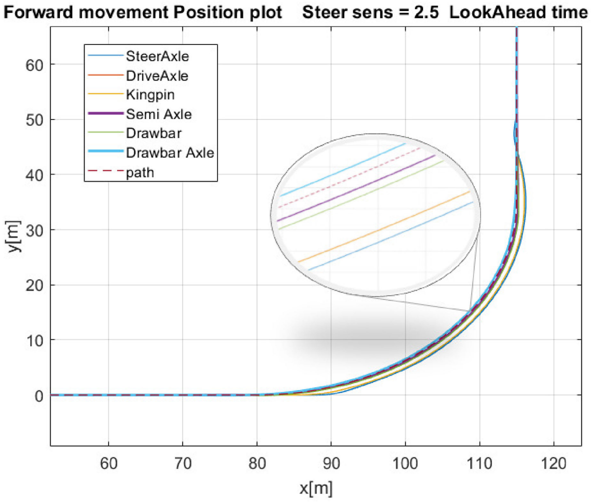

Fig. 12 *Global position plot for forward driving*

Fig. 13 *ArUCo marker [24]*

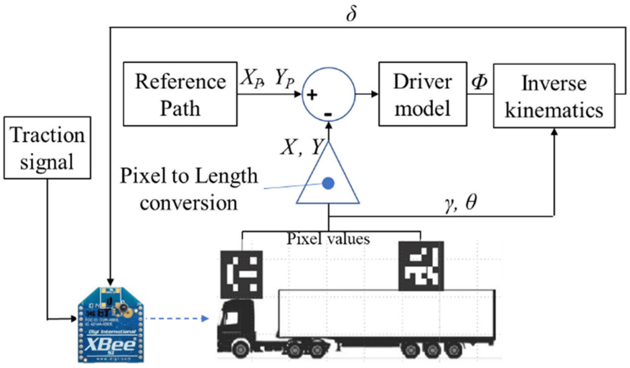

Fig. 14 *Implementation architecture*

4.4 Single articulated combination tests

The SAV was tested first for the simplicity of inverse kinematics and to understand the working of the RC vehicle (Fig. 14). The controller had one inverse kinematic translation of ϕ to δ as compared with the two translations that exist in the double articulated combination. The gain values for optimum path following were determined by using simulations and fine tuning by performing multiple tests on the RC combination.

The first test was performed for the semi-trailer which had a wheelbase of 0.62 m and was coupled to the tractor via a fifth wheel coupling. The optimum gains were found for this setup and the testing was done using the Grasshopper3 camera setup. From Figs. 15 and 16, the controller can keep the semi-trailer axle in the path with deviations in the curve. The velocity of the tractor was maintained (straight line speed with a fixed pulse-width modulation value, velocity control was not available on this model tractor) at 0.08 m/s, which when scaled up by 14 (scaling ratio of the RC vehicle combination) results at a velocity of 1.12 m/s, higher than the designed controller speed of 1 m/s.

The ability of the controller was also tested with varying the speed of the tractor, i.e. by increasing the speed of the RC tractor to 0.12 m/s. The controller could keep the trailer on the designated path. However, the yaw oscillation amplitude of the tractor was increased at higher speed due to the higher steering input provided by the controller to maintain the path. The same test was performed on the draw-bar trailer with a wheelbase of 0.435 m, which was coupled by a pin coupling. The test yielded the same result: the yaw oscillations were noted to be increasing at higher speeds, but the path following was efficient.

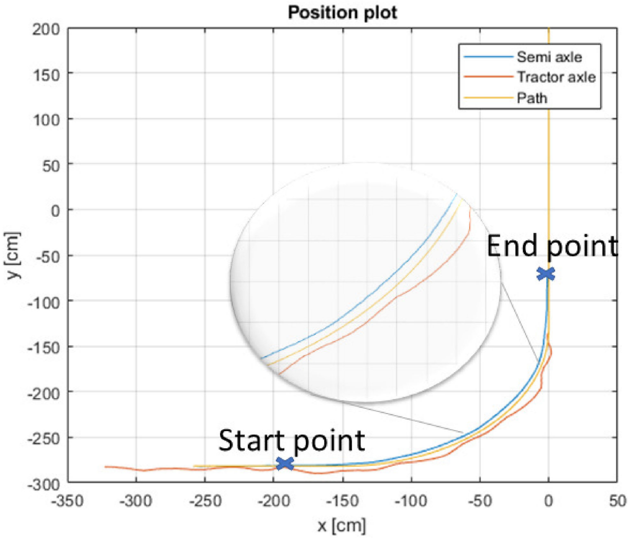

Fig. 15 *Position plot-reversing scaled SAV*

The forward controller was also tested with draw-bar trailer attachment with different radii. The controller could keep up with the path at all points in a 90° curve of radii 1.5 m as seen in Fig. 16. When the limits were tightened, and the radius of the path was reduced to 0.9 m without changing the controller gains, a deviation of 0.1 m of the path was noted at the curves. However, the controller could maintain the path in a straight line even with the shorter radii curve as seen in Fig. 16.

The vehicle speed is kept constant during the simulations at 0.08 m/s. With respect to docking time, the time to dock from initial position to the docking gate, the SAV took 24 s, and the achieved positioning accuracy at the dock is $\leq$0.01 m in front of the dock.

4.5 Double articulated combination tests

The double articulated combination was the second step of implementation. After testing the controller for single articulated combination, the controller was tested for the setup with a smaller combination, i.e. with a tractor and two draw-bar trailers attached one after another by pin coupling.

Initially, due to the lack of the velocity control, the testing was not possible due to the high torque demand in the curves. The inability of the vehicle to provide the required torque caused the model to stop at the curves. A work around in the hardware of the scaled tractor was found to increase the torque when the above-mentioned issue occurred. With this fix, the double articulated combination was tested which was of the type LHV-E (see Fig. 1). This combination was chosen since the curvature limit of this combination was higher than the LHV-A. The camera region of interest (ROI) restriction was to be considered and the implementation was to be performed. As seen in Fig. 17, it can be noted that the trailer is able to follow the predefined path as seen earlier with single articulated combinations.

With respect to docking time, the time to dock from initial position to the docking gate, LHV-E DAV took 54 s. The vehicle speed during simulation is 0.08 m/s. The achieved positioning accuracy at the dock is $\leq$0.025 m for the LHV-E DAV in front of the dock.

5 Discussion

Results of the simulations showed a stable controller behaviour, with an acceptable deviation at the 90° curve from the draw-bar trailer axle. As could be expected, path following was more efficient at higher curvature. This was mainly due to the controller complying with steering angle demand.

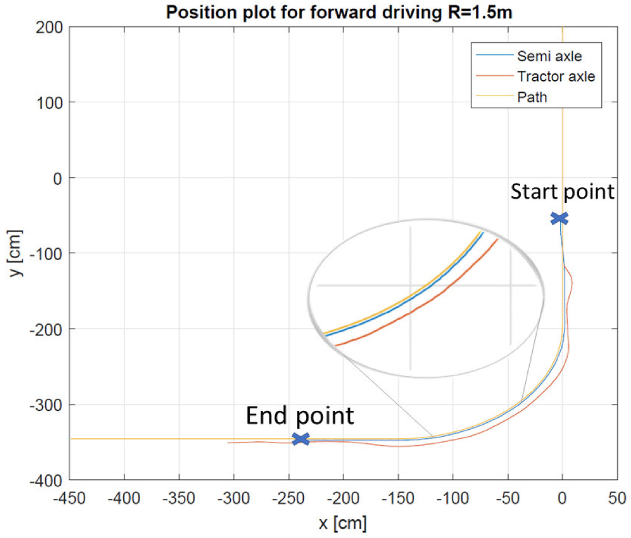

Fig. 16 *Forward drive scaled SAV*

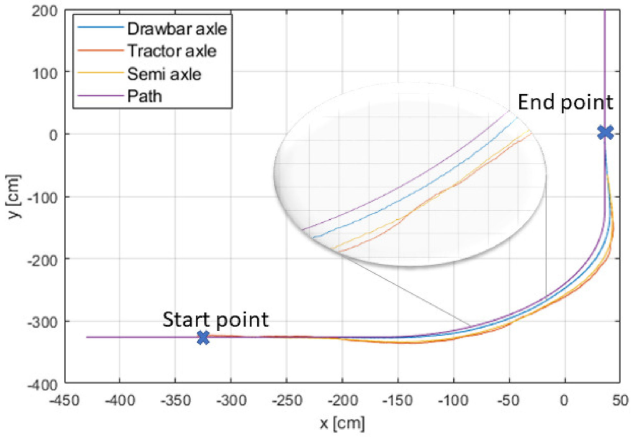

Fig. 17 *Position plot-reversing scaled DAV*

At a simulation level, the goal was to achieve a path following accuracy of $<10^{-3}$ m at the docking gate. The conditions in the simulations were ideal and measurement inaccuracies did not occur, but in the practical applications the case would not be the same. The required accuracy at the gate as mentioned earlier had to be restricted at <0.1 m. The simulation tolerance was set based on the expected level of disturbance in the designated positioning system for implementation.

The distance travelled on a simulation level for a standard 90° curve for a full-scale SAV is ∼30 m and for a DAV it is ∼60 m. The DAV figures only represent the LHV-A combination. Other combinations could have shorter travel distances due to larger curvature limitation and mechanical bounds.

On the application level, the controller proved to be able to efficiently follow the designed path at low speeds (0.08 m/s). When increased to 0.12 m/s, an increased yaw oscillation at the tractor raised due to a higher steering input by the controller to maintain the path.

The achieved positioning accuracy at the dock is ≤0.01 m for the SAV and 0.025 m for the DAV in front of the dock, which is feasible since the required deviation is 0.1 m. This shows the capability of the controller and the robustness of our implementation strategy.

It was observed that the DAV required a larger space as compared with the SAV due to geometrical aspects, leading to curvature limitation. The total path length or the distance travelled by the scaled model for SAV is ∼2.5 m and for DAV it was found to be around 5.5–6 m for the complete manoeuvre.

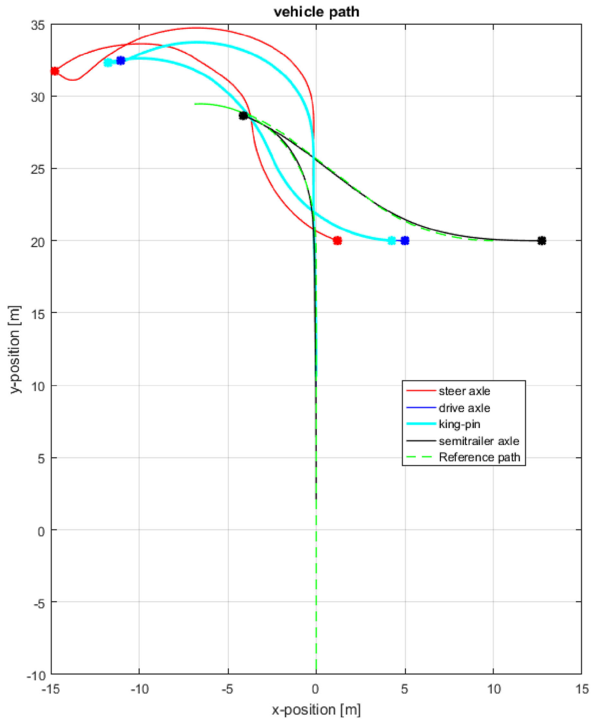

Fig. 18 *Generalising the path planner*

Docking time of the RC vehicle showed a 30 s difference; the DAV took more time as could be expected due to more complex control inputs – two articulation angles affecting the path deviation and docking accuracy. The docking time – 24 s for the SAV configuration and 54 s for DAV – could not be compared with full-scale results, since these values could not have been recorded and established with significant validation.

6 Concluding remarks and research outlook

This paper focuses on an innovative application of UAV-controlled AGVs in DCs by elaborating on the manoeuvrability of single and double (LHV) articulated vehicles, matching the business requirements in terms of controller behaviour resulting in positioning accuracy and docking speed.

INTRALOG aims at establishing significant contributions to the opportunities for society and the private sector of autonomous driving in the commercial transport sector. By making use of the expertise at knowledge institutes in the fields of logistics, automotive engineering, vehicle dynamics modelling and control, human machine interfacing and rapid control prototyping, supplemented with the knowledge and experience of private partners within the field of logistics, INTRALOG works on making autonomous driving available to the transport sector, starting with auto-docking and aspects of automated inter-terminal/intermodal traffic.

Currently, the controller is based on the lateral error at a fixed preview point. However, the path following efficiency could be enhanced by using two preview points and finding an optimum between the two during the operation. Another approach could be by incorporating the curvature of the path and the orientation correction into the controller such that the path is followed optimally hence reducing the space envelope and the overall time of the manoeuvre. This approach will be investigated to find the advantages, if any, and incorporated by also considering the number of tunable parameters.

The localisation of the vehicle combination is currently based on a stationary camera and ROI of the camera could be an issue when implemented on a larger scale. However, the camera guided truck/trailer manoeuvring does offer flexibility and maintains accuracy in build environments and free space lacking DC areas, compared with infrastructure-bounded transponders or RTK solutions.

The results shown in this paper as seen are from an ROI of $5 \times 5\ \text{m}^2$ which will be insufficient. The way to tackle this issue is by implementing an UAV with the camera. This approach could be a solution since the camera will be able to move with the UAV helping to localise the vehicle and the dock and return when the operation is complete. An experiment on the platooning of the scaled trucks using the ArUCo markers was performed by following a lead vehicle. The same approach could be implemented in driving reverse and placing the markers on the docking gate.

All simulations and tests on scaled models are based on standard 90° curves with a fixed radius. However, an approach at generalising the path planner is currently under investigation as shown in Fig. 18. This approach uses the Dubin's curve to determine the shortest kinematically viable path to the destined gates to dock the trailer.

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