Autonomous Vehicle-Following Systems : A Virtual Trailer Link Model

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***Abstract*— Through the use of a virtual trailer link model, autonomous vehicle following capabilities have been demonstrated. The principle is based on the modelling of the trailer link, used in the off-hooked trailer system, as a virtual link between the leading and led vehicles. The leader vehicle is modelled as the tractor (towing vehicle) and the follower vehicle as the trailer (towed vehicle). This method enables our autonomous vehicle to follows the estimated trajectory of the virtual trailer, which is predicted from observations of the maneuvers of the lead vehicle. Unlike conventional methods, in our system, neither communication links between two vehicles nor the installation of special road infrastructures are needed for the implementation. Communication system may failed and the installation of road infrastructures are costly. We will show that system response of the virtual trailer link model is much smoother. A series of simulations and experimental results have indicated the validity of the proposed method.**

***Index Terms*— Vehicle following, Virtual trailer system.**

I. Introduction

Research in vehicle following has attracted the attention of several researchers in the past decades, particularly in the USA and Europe where safety, energy consumption and traffic congestions are the primary motivators [1], [2]. Major contributions are from the Chauffeur Project (Europe), the PATH program (USA), the Intelligent Transportation System program in Japan and the CyberCar project in France (INRIA), [3], [4]. In the Chauffeur project, Borodani [5] developed an electronic tow-bar vehicle following system for a platoon of vehicle. All vehicles in a platoon follow a leader, independent of any road infrastructure, with the inter-vehicle communication system installed in the vehicles. For the PATH project, Swaroop [6] proposed to use the real-time trajectory curvature information of the leader vehicle for vehicle following. The information were generated and transmitted by the leading vehicle via inter vehicle communications link to the follower vehicle. In the same project, Fujioka [7] implemented a longitudinal controller for vehicle following. The follower vehicle used on-board sensors to acquire its own velocity, yaw rate and sideslip angle and at the same time located the position of the leader vehicle. In addition, wayside vehicle communication and inter vehicle communication were used. Besides the above mentioned initiatives, some other works on vehicle following had been done. Wang et al. [8] implemented a vehicle following system by imitating human driving practices. Stefan [9] proposed a trajectory-based method by making use of the time history associated with the lead vehicle. Both systems from Wang [8] and Stefan [9] used neither inter-vehicle communication system nor the road infrastructure. Ng [10], [11] has implemented vehicle following with obstacle avoidance capabilities in natural environment. A path planner was used to track the leader vehicle. Although the road infrastructure was not used in the system, inter-vehicle communication system was used in his system.

There were few endeavors on the modelling of the entire vehicle following system. It seemed from the literature review that most research efforts in this domain center on the controllers of the follower vehicle. Two common controllers, longitudinal controller and lateral controller, were implemented to guarantee that the vehicle trailed the leader, but paid little attention to the trajectory of the lead vehicle. The longitudinal controller maintained a set distance between the two vehicles, and the lateral controller minimized the alignment angles between the two vehicles. The combination of both controllers achieved a ”towing” effect [5].

Techniques that use wayside or inter-vehicle communications, or embedded markers on road networks to achieve vehicle following have various disadvantages. For example, the use of information from the lead vehicle transmitted to the led vehicle may not be available in certain conditions. This requires additional costs and confines the use of the system to a certain type of leader vehicles. To address the above limitations, a new model, known as a *virtual trailer link* model, is proposed in this paper. The concept of the ”virtual trailer link model” has been inspired from the tracking capability demonstrated in actual tractor-trailer systems [15]. The remainder of this paper presents details of this concept.

II. Evaluation of tractor-trailer link system

A trailer system is regarded as an articulated vehicle made of two or more bodies connected by king-pin hinges. In general, the trailer system can be classified into two general configurations, namely the direct hooked trailer and the off-hooked trailer as shown in Figs 1 and 2.

To apply the concept of the trailer system in vehicle following, the trajectory tracking capability of the trailer in following the towing vehicle has to be studied. The trailer system will be evaluated under a steady state configuration in which the towing vehicle moves at a constant speed with a constant angular velocity. The system is examined under circular motion. An optimized trailer system will then be proposed as the virtual trailer model for vehicle following. The leader vehicle will be modelled as the towing vehicle and the follower vehicle as the trailer.

A. *Steady State Performance of the Trailer Link*

The steady state configuration of the direct hooked trailer system is shown in Fig. 1. It clearly shows that the trailer does not follow the tractor in this configuration. The instantaneous radius of rotation for the tractor, R_2, is always greater than that of the trailer, R_1. The tracking error can be represented as:

$$\varepsilon = R_2 - R_1 = R_2 - \sqrt{R_2^2 - L^2}, where R_2 > L \quad (1)$$

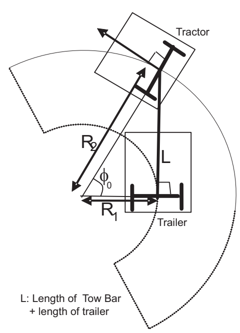

Fig. 1. Direct Hooked Trailer system under a steady state configuration. Both the tractor and trailer are moving on respective circular paths with radii R_2 and R_1 respectively.

Unlike the direct-hooked trailer, in the off-hooked trailer system, the trailer is not directly attached at the center of the tractor rear axle but at a distance D from it. Fig. 2 shows the steady state configuration of an off-hooked, single-trailer system. For the tractor and trailer to maneuver on the same

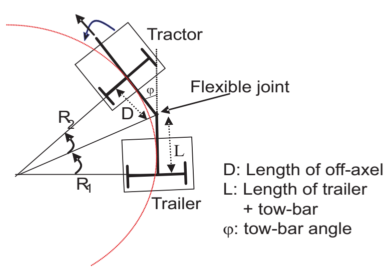

Fig. 2. Off-hooked trailer system under a steady state configuration. Both tractor and trailer are moving on the same circular path if $D = L$.

curve, i.e, their radius of rotation are equal, $R = R_1 = R_2$, the condition, $L = D$, must apply. From geometry properties:

$$\tan\varphi = \frac{2RL}{R^2 - L^2}, where R \neq L \quad (2)$$

The constraint, $R \neq L$, implies that the minimum turning curvature of the off-hooked trailer system is equivalent to the length of the link, L, between the tractor and trailer. Therefore, it is possible for the trailer to follow the reference trajectory traced by the tractor, without error. This is represented in Fig. 2. This suggests that the tracking error converges to zero in the steady state configuration. Therefore, theoretically, if the tractor moves along a path consisting of lines and circles, there is no steady state tracking error. This observation suggest an attractive solution for vehicle following, where minimum tracking following error is desired.

B. *Virtual Trailer Link Design*

Two parameters, the number of virtual trailers and the length of the virtual link, are needed. As discussed in section II.A, the off-hooked model with single-trailer configuration theoretically has zero steady state tracking error if $D = L$. The result can be extended to a more general case, an n-trailer system. However, measurement uncertainties and other external disturbances will affect the performance. The existence of errors, such as steady state tracking errors or measurement errors, in the $(i+1)^{th}$ tow-bar will propagate down to the $(i+2)^{th}$ link and so on. This error propagation will affect the "string stability" [13] of the connected trailer system. Therefore, it can be concluded that the optimized trailer systems should consists of a single-trailer with the front and rear connection link being equal in length (i.e, $D = L$ in Fig. 2).

III. VIRTUAL TRAILER LINK MODELLING FOR VEHICLE FOLLOWING

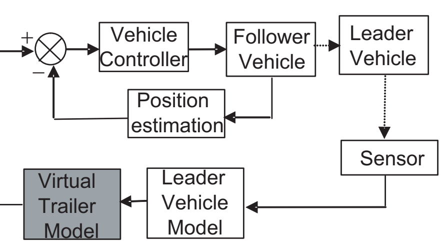

Fig. 3. Control block diagram for the proposed vehicle following system

A simplified block diagram of the vehicle following system consists of two feedback loops as shown in Fig. 3. The inner loop comprises a motion controller that maintains stable traction of the vehicle. The outer loop guides the vehicle to follow the estimated trajectory of the leader vehicle. This paper focuses on the modelling and performance analysis of the virtual trailer link. The virtual trailer link model is used to estimate the pose of the leader vehicle with respect to the follower vehicle and hence the trajectory of the leader. The kinematics, of the trailer under the influence of the tractor's motion, are used to form the virtual trailer concept. The follower vehicle task becomes to behave as the virtual trailer. As there are no physical links in the virtual trailer model, the trailer dynamics will be ignored, thus simplifying the modelling process. When the vehicles travel, they either move in straight line or occasionally make turns. This makes the off-hooked system an attractive solution for vehicle following. To validate this assumption, clothoids [12] or road transitions, between straight road and turns are studied. This is presented in section IV.

The follower vehicle is assumed to have on-board sensors, capable of acquiring range, azimuth and orientation of the leader vehicle with respect to the follower vehicle's reference frame. The modelling of the vehicle following system is sub-divided into the following tasks:

1) Update the vehicle poses: : acquires the relative pose of the leader vehicle with respect to the follower vehicle.

2) Model the virtual trailer: : for every updated position of the leader vehicle, it is necessary to model and predict the manoeuver of the virtual trailer. The previous and current poses of the leader vehicle are important, they provide the context.

3) Command the follower vehicle: : pursues the virtual position of the trailer.

Fig. 4 shows a typical configuration of the positions of the leader and follower vehicles plus the estimated pose of the virtual link. At any time step t, the controller in the follower perceives the position of the leader using on board sensor to compute the pose of the leader vehicle with respect to the follower. This can be obtained as:

$$\mathbf{L} = \begin{bmatrix} L_x \\ L_y \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} a + d\cos\phi \\ d\sin\theta \end{bmatrix} \quad (3)$$

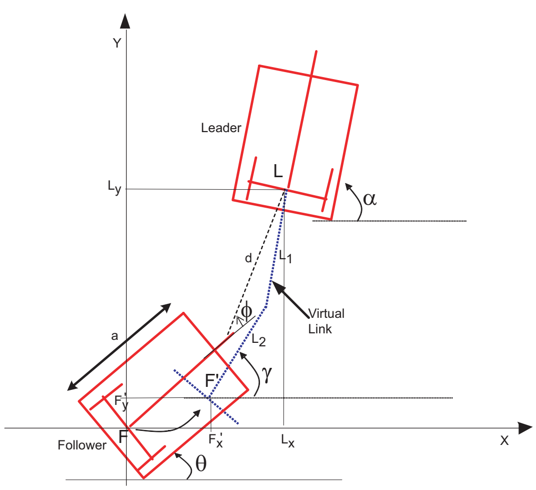

Fig. 4. At any time instance, the follower perceives the pose of the leader with the onboard sensor. The pose, $F^{'}$, of the virtual trailer link is then estimated. The follower will be commanded to the new position, $F^{'}$. The whole process will be repeated at the next time instance

The position of the virtual trailer at time step t is :

$$\mathbf{F}^{'} = \begin{bmatrix} F_x' \\ F_y' \end{bmatrix} = \mathbf{L} - L_1 \begin{bmatrix} \cos\alpha \\ \sin\alpha \end{bmatrix} - L_2 \begin{bmatrix} \cos\gamma \\ \sin\gamma \end{bmatrix} \quad (4)$$

The follower is then commanded to move to the virtual point F'. At the next time step, $t+1$, the follower will re-acquire the new pose of the leader and the whole process is repeated iteratively. However, the pose of the virtual trailer is related to the motion of the leader as shown in Fig. 5. The pose of the virtual trailer at position $T^{'}$, can be formulated using geometry properties, and will not be discussed here due to space limitation.

Effect of Measurement Errors The sensor observations are

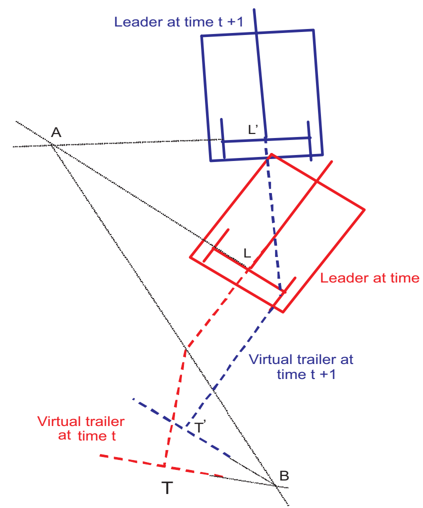

Fig. 5. The leader vehicle moves from L to $L^{'}$ (from time step t to t+1), with an instantaneous center of rotation, A. In response, the virtual trailer would have travelled from T to $T^{'}$, with an instantaneous center of rotation B

transformed into a Cartesian observation, referenced to the follower vehicle's coordinate system. These transformations are non-linear and the error is compounded as shown in Fig. 6. Therefore, the error covariance matrix is significant in estimating the pose of the virtual trailer. The covariance of the observation from the follower vehicle can be written as:

$$\sum_z = \begin{bmatrix} \cos\phi & -r\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} \sigma_r^2 & 0 \\ 0 & \sigma_\theta^2 \end{bmatrix} \begin{bmatrix} \cos\phi & \sin\phi \\ -r\sin\phi & \cos\phi \end{bmatrix} \quad (5)$$

where σ_r^2 and σ_θ^2 are the variances in range and bearing from the sensor. The position of the virtual trailer point T is formulated as:

$$\begin{bmatrix} T_x \\ T_y \end{bmatrix} = \begin{bmatrix} L_x \\ L_y \end{bmatrix} - D \begin{bmatrix} \cos\alpha \\ \sin\alpha \end{bmatrix} - D \begin{bmatrix} \cos\beta \\ \sin\beta \end{bmatrix} \quad (6)$$

The final observation variance of interest at point T is

$$\Sigma_T = \Sigma_L + R_T Q R_T^T \quad (7)$$

where Q is the predicted state covariance for the bearing of both leader and follower vehicles and

$$R_T = \begin{bmatrix} \frac{\delta T_x}{\delta\alpha} & \frac{\delta T_x}{\delta\beta} \\ \frac{\delta T_y}{\delta\alpha} & \frac{\delta T_y}{\delta\beta} \end{bmatrix} \quad (8)$$

which is the Jacobian matrix of the observation function. The Extended Kalman Filter (EKF) can be implemented in this case for pose prediction and error estimation.

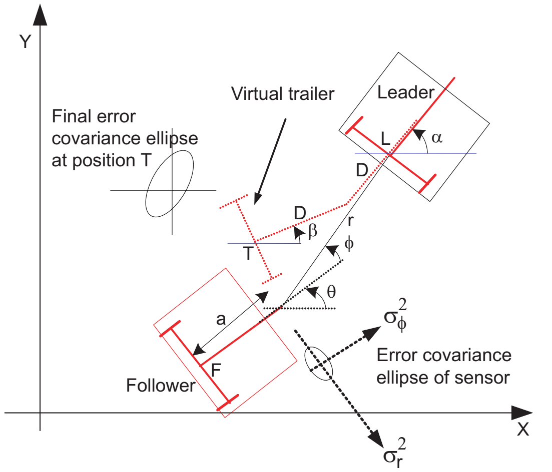

Fig. 6. Demonstration of error propagation. The ellipses indicate the error covariances caused by perception noise. The estimation error of the virtual trailer point is compounded

IV. Performance of Virtual Trailer Link Model

Prior to on-the-road implementation of the proposed method, simulation tests on straight, circular and transition paths were made. The length of the virtual link and length of the virtual trailer are set to 3m for the simulations and experimentation tests . The relative angle between the leader vehicle and the virtual trailer was set initially to 20 degrees (i.e, set $L = D = 3m$ and $\varphi = 20^o$ in Fig. 2). Another initial condition is to assume that the the follower vehicle pose is aligned with that of the virtual trailer. A frequent used controller, the pure pursuit controller [14], is being implemented in the follower vehicle. In the experiment, the Ackerman model was applied together with non-honolomic constraints, which assume rolling without slipping on the wheels, of the follower vehicle, hence some tracking errors will be expected. For circular path tracking, the difference in radius of the original path and the tracked path is the best choice for computing tracking errors. Whilst, for other types of manoeuvres, it is difficult to have a good quantitative performance index for tracking errors.

For illustration purposes, Fig. 7 shows an original path traced by the leader vehicle plus the tracked path traced by the follower vehicle. This assumes that the sampling time is small enough such that the consecutively acquired displacement between the leader vehicle poses can be considered as a straight line. Two consecutive positions of the leader vehicle and the current position of the follower vehicle will be used to form a virtual triangle, whose area can be used to represent the tracking error of the follower vehicle with respect to the leader vehicle as:

$$Areaof\Delta O_{i-1}O_iT_i = \frac{1}{2}\begin{vmatrix} T_{i,x} & T_{i,y} & 1 \\ O_{i-1,x} & O_{i-1,y} & 1 \\ O_{i,x} & O_{i,y} & 1 \end{vmatrix} \quad (9)$$

If the area is zero, this means that the three vertices are co-linear. The sign of the result, in area, indicates that the position of the follower vehicle is either on the left or right hand side of the leader vehicle.

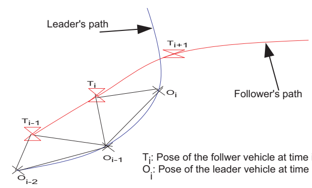

Fig. 7. Computation of tracking errors

A. Simulation results

The direct-hooked and off-hooked trailer link models were tested on a circular path with radius R being, 10m, 20m and 40m. The leader vehicle was placed at Rm away from the origin of the circular path under test. The leader vehicle was aligned with the vertical axis. For simulation purposes, the circular path is divided into 180 segments, each is an arc of 2 degrees. It was observed that the tracking errors eventually converge to some steady values during simulations.

TABLE I

Steady State error performance for both direct-hooked and off-hooked models

Radius of Path (m)	Direct-hooked model	off-hooked model
10	0.5m	0.25m
20	0.25m	0.18m
40	0.18m	0.18m

Table I summarizes the steady state tracking error for both models. It shows that the steady-state tracking errors for the off-hooked model are consistent throughout the three tests. By contrast, for the direct-hooked model, the steady state tracking error for a curvature radius of 10m, is substantially larger than the error for the off-hooked trailer model. Now, this error for test run under curvature radius of 40m is similar for both models.

Table II summarizes the performance of both trailer models when following a clothoid. The length of which is given by L. R labels the final radius of the clothoid at the end of the transition path. The results show that both models have small mean errors and standard deviations in trajectory tracking. As both the models are manoeuvering on a smooth transition path, which is the main characteristic of clothoid roads, the results are as expected.

TABLE II

Performance comparison between direct-hooked and off-hooked models moving on clothoids

	Direct-hooked Model		off-hooked Model	
Clothoids	**Mean**	**SD**	**Mean**	**SD**
R=60,L=98	-0.03	0.45	-0.03	0.45
R=70,L=161	-0.01	1.02	-0.12	0.92
R=80,L=240	0.00	2.15	-0.31	1.80

B. Experimental Results

The simulation results demonstrated that the virtual off-hooked trailer link model outperformed the virtual direct-hooked trailer link model in terms of tracking error performance.

To evaluate the performance of off-hooked virtual trailer link model in real environment and to prepare the system for implementation, two different sets of experimental data were acquired: on urban roads and on sub-urban roads. Throughout the experiments, the mean and standard deviation of the error tracking are used as metrics, to measure the robustness of the virtual trailer link model. The mean error is computed by taking the average of the "error area" calculation, as shown in equation (9), over all the tracking points. The standard deviation measures the spread of the tracking error. A confidence level of 3σ is chosen to ensure the follower vehicle stay within the tracking trajectory.

Urban Road: Fig. 8(a) shows the experimental setup of the vehicles. Neither GPS nor inter-vehicle communication links are installed in the lead vehicle. A custom build electrical autonomous vehicle (AGV) is used as the follower vehicle. It has an on-board laser scanner and odometry sensors. The AGV on board computer acquires data in real-time, these includes the vehicle orientation, steering and speed. The leader position is estimated using the measurement data from the laser scanner.

Fig. 9 shows the test results of the off-hooked trailer link model in an urban environment. Both the leader and follower vehicles are travelling in a well-paved road. The vehicle speeds are smooth and turning are steady. The results shown in Fig. 9 indicate that the off-hooked trailer model has a relatively small standard deviation ($0.6m^2$) in the trajectory tracking error. This implies that the follower vehicle is closely trailing the leader.

Fig. 8. Experimental setups of vehicle following system in (a)urban and (b) sub-urban environment. Both leader vehicles are travelling at a speed of around 25 km/h (a) along a well paved road and (b)in a jungle. The follower is equipped with on board odometry sensors and a laser scanner.

Sub-Urban Road: Two different vehicles were equipped with on board sensors for data collection as shown in Fig. 8(b). The leader vehicle is a multi purpose vehicle (MPV). The follower vehicle is a utility truck equipped with a laser scanner and a GPS receiver. The scan data from the laser scanner on board the follower are collected at a rate of 10 Hz. The on-board computer is installed in the follower and is responsible for synchronizing and storing the laser and GPS data. The operating environment is a sparsely built area in the middle of tropical forest.

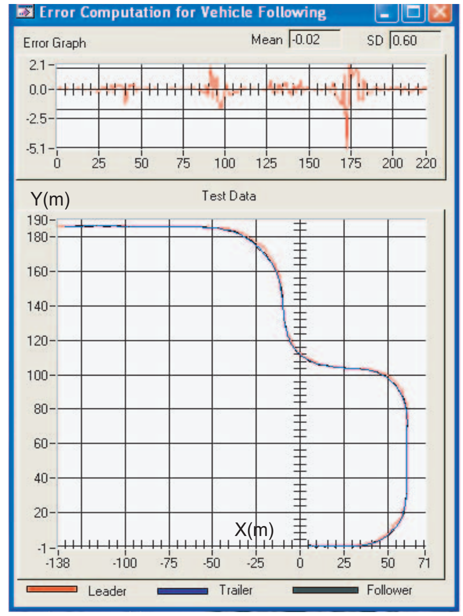

Fig. 9. Test result for vehicle following in urban area. Top graph indicates the tracking error of the follower. Bottom graph shows the trajectories of the leader and follower

Fig. 10 shows the experimental results for sub-urban vehicle following. The trajectory of the leader vehicle is obtained by manipulating the laser range data and GPS information as ground truth. During the data collection phase, both the leader and follower vehicles are manoeuvering at the speed of about 25km/h in an unstructured environment where there are non-paved roads. The leader vehicle wonders randomly and thus

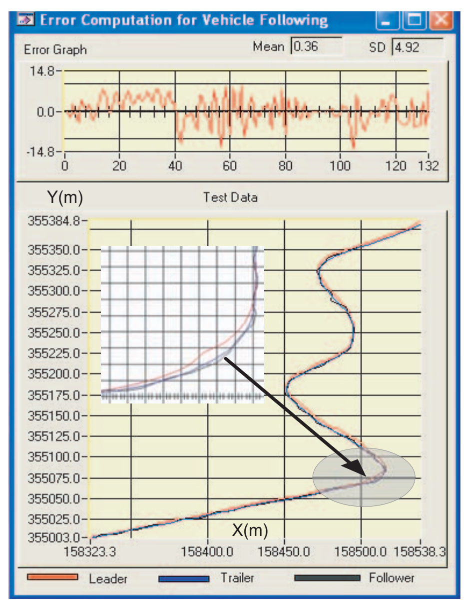

Fig. 10. Experimental result for vehicle following in sub-urban area. The inset image is a zoomed view of the error. Top graph indicates the tracking error of the follower. Bottom graph shows the trajectories of the leader and follower

it is free to make turns at any time. Fig. 10 indicated that the leader vehicle had made several sharp left and right turns. It shows that the off-hooked virtual trailer is able to follow the trajectory of the leader closely despite the random motion of the lead vehicle. The mean tracking error is about 0.36 m^2 and the tracking errors falls well within 3σ error bound. There are no difficulties for the virtual trailer model (off-hooked model) in following the trajectory of the leader vehicle during sharp turns. Though, some tracking errors exists along the path. This is mainly due to measurement from the GPS and laser scanner. Both vehicles are moving on a rough terrain in a jungle environment, where tree canopies block the GPS signals and introduces position information uncertainty. Furthermore, vehicle pitching also affect the reliability and accuracy of the sensor readings, thus affecting the performance of the system.

V. FUTURE WORK

The main challenges for autonomous vehicle following are the prediction and estimation of the leader's pose while the follower vehicle is in motion. The uncertainties in the sensing processes [16] play an important part in the accurate and reliable prediction and estimation process.

As discussed in the previous section, perception is the key to estimate the pose and the trajectory of the leader vehicle. Laser range scanner and vision are typically used for this purpose. Sensor resolution, vehicle motion and the environment are major constraints for the sensing process. These are linked to the sensor characteristics but also to cost.

An accurate estimation of the leader vehicle is crucial in system modelling. Upon system implementation, it is difficult to model the leader vehicle as this can be of any type. However, manoeuvres of the leader vehicle can be estimated and even predicted through the on board sensors in the follower vehicle. The leader vehicle motion can be modelled as having constant velocity, constant acceleration and turning mode models. For this purpose, we are currently investigating the effectiveness of the Interactive Multiple Model (IMM) algorithm. Another method is to use the estimations together with road information from a navigation system to predict the possible manoeuvres of the lead vehicle and thus to anticipate any changes in the path of the follower vehicle.

VI. CONCLUSION

The trajectory following function of an autonomous vehicle using only on board sensors in urban and sub-urban environments is the focus of this paper. We have demonstrated that entire system modelling for vehicle following is important to ensure the performance of a vehicle following system. The limitations on the sensors used for tracking the leader vehicle, when the system is to be deployed in urban environments, make system modelling an important consideration.

The use of the virtual trailer model based on the off-hooked, single trailer configuration has been identified as having potential to perform close following of the trajectory traced by the leader vehicle. Unlike conventional methods, our model did not track the leader vehicle directly. By designing the length of the virtual link and virtual trailer to be of the same size, the virtual off-hooked trailer link model has been evaluated for vehicle following operations. Simulation test and field experiments have been performed to evaluate and to understand further the issues encountered when operating in real conditions. The results have showed theoretically and experimentally the feasibility of the proposed virtual off-hooked trailer link model which has resulted in low tracking errors. In order to deploy the proposed model in a robust manner, further work on the perception issues, error propagation problems, multiple modelling and prediction plus sensor fusion are to be performed to enhance this method.

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