Autonomous Vehicle Following System - A Virtual Trailer Link Approach

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***Abstract* – Through the use of a virtual tractor-trailer link model, vehicle following capabilities have been implemented without the need of communications links between the two vehicles or the installation of special road infrastructure. The principle is based on the modeling of an off-hooked trailer system as a software link between the lead and led vehicles. The leader vehicle is modeled as the tractor (towing vehicle) whilst the follower vehicle as the trailer (towed vehicle). The conventional approach is for the led vehicle to follow a focus point in the leader vehicle, in the approach presented in this paper, following the leader vehicle is done by following the estimated trajectory of the virtual trailer, which is predicted from observations of the lead vehicle behavior. The system response of this configuration is much smoother. A series of simulations and experiments conducted has shown the validity of the proposed approach.**

Index Terms – Vehicle following, Virtual trailer system.

I. INTRODUCTION

Research in vehicle following has attracted the attention of several research centres in the past decades, particularly in the USA and Europe where safety, energy consumption and the need to optimise the use of public roads 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]. The Chauffeur project developed an electronic tow-bar system, in which all vehicles in a platoon follow a leader, independent of any road infrastructure, it was based on an inter-vehicle communication system [5]. Swaroop proposed a controller, for a follower vehicle in an emergency lane change manoeuvre, it uses real-time trajectory curvature information generated and transmitted, by the leading vehicle via inter vehicle communications link [6]. Takehiko [7] had implemented a longitudinal control vehicle following system. The follower vehicle uses on-board sensors to acquire its velocity, yaw rate and sideslip angle whilst at the same time locates the position of the lead vehicle. In addition, wayside vehicle communication and inter vehicle communication are used. Wang et al. [8] implemented a vehicle following model by imitating human driving practices. Stefan [9] proposed a trajectory-based approach for vehicle following, by making use of the time history associated with the lead vehicle. Ng [11] [12] has implemented vehicle following with obstacle avoidance capabilities in natural environments where a path planner was used to track the leader vehicle.

The literature review has shown that most research efforts in this domain center on the control of the follower vehicle only. There are very few endeavors on the modeling of the entire vehicle following system. Existing vehicle follower controllers guarantee that the vehicle trails the leader, without attention to the trajectory of the lead vehicle. They are based on the longitudinal control to maintain a set distance between the two vehicles, and lateral control to minimize the alignment angles between the vehicles. A combination of both controllers achieves only a “towing” effect [4].

Techniques that use wayside or inter-vehicle communications, or embedded markers on road networks to achieve vehicle following have various disadvantages. These add cost and limit the application areas. 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 vehicle.

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 model” has been inspired from the tracking capability demonstrated in actual vehicle-trailer systems [17]. The remainder of this paper presents details of this novel approach. Section II formulates the performance of the physical trailer system. It determines the design of the link parameters, for the trailer to follow the trajectory determined by the towing vehicle. Section III models the leader vehicle as a tractor (towing vehicle) and the follower vehicle as a trailer (towed vehicle). The Kinematic modeling for vehicle following using this virtual trailer link will be discussed. Section IV provides simulation and experimental results to evaluate the feasibility of implementing the virtual trailer link model for vehicle following. To the authors’ knowledge the virtual trailer link concept has not been implemented. Section V discusses the results and examines in detail future research directions to improve the results. Finally, Section VI concludes the paper presenting a critique of this novel approach and the expected results.

II. EVALUATION OF TRACTOR-TRAILER LINK SYSTEM

A trailer system is an articulated vehicle composed of two or more bodies connected by a king-pin hinge. Passive trailers are widely used in industry and airport luggage transportation such as the one designed by Yamamiya [12] and Nakamura [17]. For the past decade, mobile robots with trailers show examples which support research on control of non-holonomic systems. [12] [13] [17]. 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 figures 1 and 2.

In order to apply the concept of the trailer system in vehicle following, the trajectory following capability of the trailer in following the towing vehicle has to be studied. The trailer system will be evaluated under the steady state condition in which the towing vehicle is moving at a constant speed with a constant angular velocity, that is, to test the system under circular movement. An optimized trailer system will then be proposed to be 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*

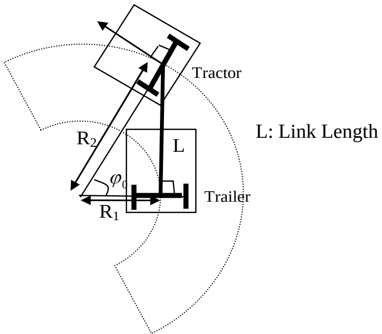


Figure 1. Direct Hooked Trailer system under steady state configuration. Both the tractor and trailer are moving on respective circular path with radii R_2 and R_1 respectively.

The steady state configuration of the direct hooked trailer system is as shown in Figure 1. As can be seen in figure 1, the trailer is not actually following the path of the tractor under 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 obtained as:

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

On the other hand, unlike the direct-hooked trailer, the trailer, in the off-hooked system, is not directly attached at the centre of the previous axle but at a distance D from this point. Figure 2 shows the steady state configuration of an off-hooked, single-trailer system.

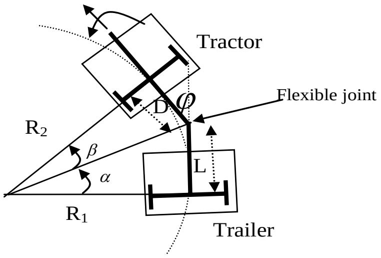


Figure 2. Off-hooked trailer system under steady state configuration. Both tractor and trailer are moving on the same circular path if D=L.

For both the tractor and the trailer to be maneuvering on the same curve, ie, $R_1=R_2$, the condition, $L=D$, must apply. It can be shown that:

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

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 the trailer. Hence, it is possible for the rear trailer to follow the reference trajectory, dictated by the tractor, without an error, as shown in Figure 2. This fact implies that the tracking error converges to zero in the steady state. Therefore, theoretically, if the tractor moves along the path consisting of lines and circles, there is no steady state tracking error. This makes it a very attractive solution for vehicle following, where minimum tracking following error is desired.

B. *Virtual Trailer Link Design*

Two parameters, the number of virtual trailers required and the length of the virtual links, have to be determined. As discussed in section II.A, the off-hooked model with single-trailer configuration theoretically has zero steady state tracking error if D=L, as shown in figure 2. This result can easily be extended to a more general case, of a n-trailer system. However, measurement uncertainties and other external disturbances will affect the performance of the system. The existence of errors, such as steady state tracking errors or measurement errors, in the (i+1)-th link will propagate down to the (i+2)-th link. This error propagation will affect the “string stability” [15] of the connected trailer system. Hence, it can be concluded that the optimized trailer systems should have a single-trailer with the length of the front and rear connection links being equal.

III. VIRTUAL TRAILER LINK MODELING FOR VEHICLE FOLLOWING

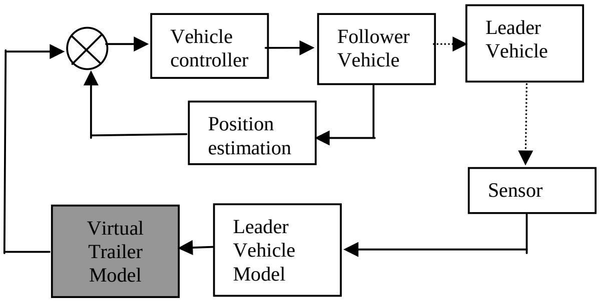


Figure 3. Control block diagram of the proposed vehicle following system.

A simple block diagram of the proposed vehicle following system consists of two main feedback loops as shown in figure 3. The inner loop is a motion controller to maintain stable traction speed and steering angle. The outer loop is the feedback loop to guide the follower vehicle to follow the estimated trajectory of the leader vehicle. This paper concentrates mainly on the modelling and performance analysis of the virtual trailer link. The function of the virtual trailer model is to estimate the pose of the leader vehicle with respect to the follower vehicle. The kinematics, of the trailer under the influence of the tractor's motion, are used to form the virtual trailer concept. The task of the follower vehicle will then be confined to behave as this virtual trailer.

As there are no physical links involved in the virtual trailer model, the dynamics of the trailer can be ignored, thus simplifying the modelling process. The fact that the vehicles travelling on the road are either moving straight or occasionally making turns makes the off-hooked system a very attractive solution to the vehicle following system. Nevertheless, clothoids [14] or road transitions, between the straight road and the turn should also be studied. The performance evaluations of the model under these conditions are discussed in section IV.

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

a. **Updating the vehicle poses**: to acquire the relative pose of the leader vehicle with respect to the follower vehicle
b. **Modelling the virtual trailer**: for every updated position of the leader vehicle, it is necessary to model and predict the maneuver of the virtual trailer. The previous and current poses of the leader vehicle is important in the modelling of the virtual trailer system.
c. **Commanding** the follower vehicle to pursue the virtual position of the trailer

Figure 4 shows a typical configuration of the positions of the leader and the follower vehicles and the estimated pose of the virtual link. At any time step t, the follower perceives the position of the leader with the on board sensor to obtain the relative pose of the leader vehicle. The position of the leader vehicle, with respect to the position of the follower vehicle, can be obtained as:

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

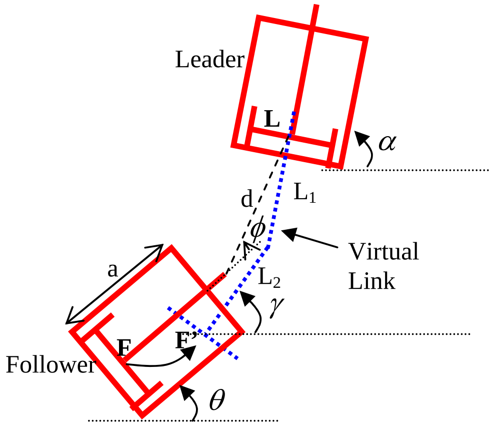


Figure 4. At any time instance, the follower perceives the pose of the leader with the onboard sensor. The pose, **F'**, of the virtual trailer link is then estimated. The follower will be commanded to the new position, F'. The whole process will be repeated at the next time instance.

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

$$\begin{bmatrix} F_x' \\ F_y' \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} a + d\cos\phi \\ d\sin\phi \end{bmatrix} - L_1 \begin{bmatrix} \cos\alpha \\ \sin\alpha \end{bmatrix} - L_2 \begin{bmatrix} \cos\gamma \\ \sin\gamma \end{bmatrix} \qquad (4)$$

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 link is directly related to the motion of the leader as shown in figure 5. The pose of the virtual trailer at position **T'**, can be formulated as in [18], and will not be discussed in here.

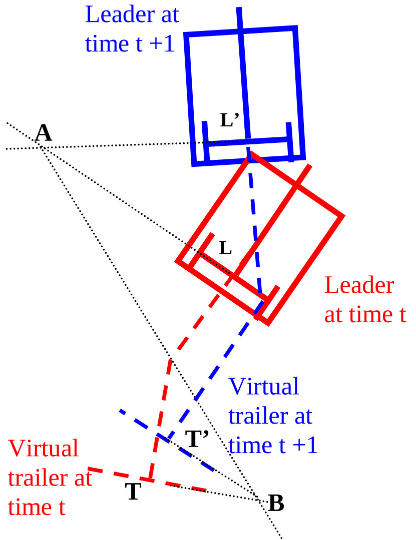


Figure 5. The leader vehicle moves from L to L' (from time step t to time step t+1), with an instantaneous centre of rotation, A. In response, the virtual trailer would have travelled from T to T', with an instantaneous centre of rotation B.

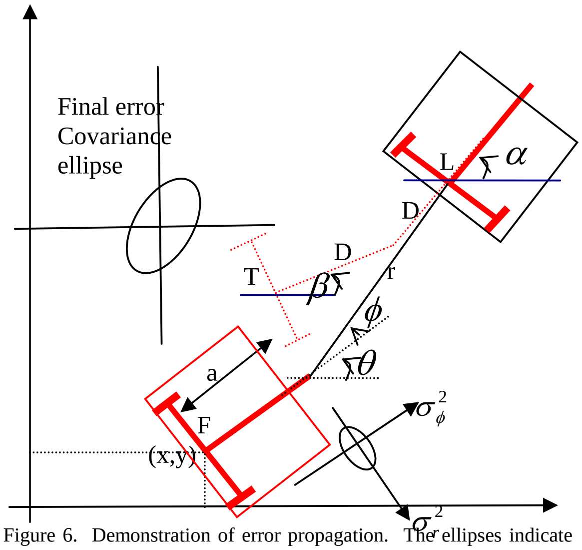


Figure 6. Demonstration of error propagation. The ellipses indicate the errors covariance caused by the perception noise. The error in estimating the virtual trailer point is compounded.

Effect of measurement errors: Processing of observations involves the conversion of the measurement into a Cartesian observation, referenced to the follower vehicle's coordinate system. These conversions are highly non-linear and the error is compounded as shown in figure 6. Thus, the error covariance matrix is significant in estimating the pose of the virtual trailer. The covariance for observation from the follower vehicle can be written as:

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

where σ_r^2 and σ_θ^2, are the variances in range and bearing from the sensor. It can be shown [18] that the position of the virtual trailer point is given as

$$Z_T = \begin{bmatrix} z_{Tx} \\ z_{Ty} \end{bmatrix} = \begin{bmatrix} z_{Lx} \\ z_{Ly} \end{bmatrix} - D\begin{bmatrix} \cos\alpha \\ \sin\alpha \end{bmatrix} - D\begin{bmatrix} \cos\beta \\ \sin\beta \end{bmatrix} \tag{6}$$

The final observation variance of interest at point T is

$$\Sigma_T = \Sigma_L + R_T Q R_T^T \tag{7}$$

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

$$R_T = \begin{bmatrix} \dfrac{\partial z_{Tx}}{\partial\alpha} & \dfrac{\partial z_{Tx}}{\partial\beta} \\ \dfrac{\partial z_{Ly}}{\partial\alpha} & \dfrac{\partial z_{Ly}}{\partial\beta} \end{bmatrix} \tag{8}$$

The extended kalman filter (EKF) can be implemented in this case for pose prediction and error estimation.

IV. TEST RESULTS

To prepare the system for on-the-road implementation, simulation tests on straight, circular and transition paths [14] are carried out. For the simulation and experimental tests, both the length of the virtual link and the length of the virtual trailer link are set to 3m. The relative angle between the leader vehicle and the virtual trailer was set to 20 degrees initially. Also, the initial condition is to assume that the pose of the follower vehicle is aligned with that of the virtual trailer. A commonly used controller, known as the pure pursuit controller [16], 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, on the follower vehicle, hence some tracking errors are expected. For circular path tracking, the difference in radius of the original path and the tracked path is the best choice for computing the tracking errors. However, for other types of maneuver, it is difficult to have a good performance index for tracking errors.

Figure 7 shows an original path traced by the leader vehicle and the tracked path traced out by the follower vehicle, enlarged for illustration purposes.

Area of triangle =

$$O_{i-1}O_iT_i = \frac{1}{2}\begin{vmatrix} T_{i,x} & O_{i-1,x} & O_{i,x} & T_{i,x} \\ T_{i,y} & O_{i-1,y} & O_{i,y} & T_{i,y} \end{vmatrix} \tag{9}$$

Assuming that the sampling time is small enough such that the consecutively acquired positions of the leader vehicle 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 in equation (9). If the area is zero, this implies 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

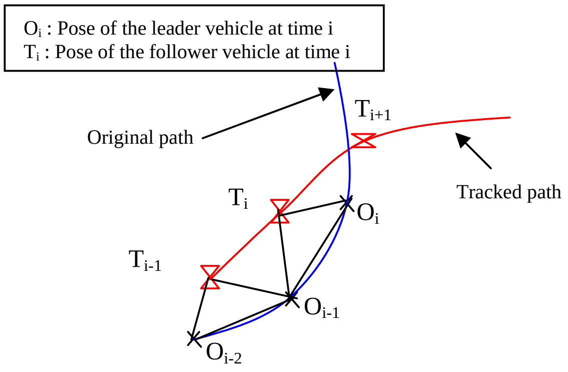


Figure 7. Computation of tracking errors.

A. Simulation results

Under simulation tests, the direct-hooked and off-hooked trailer link models were both tested in the circular path with radius of 10m, 20m and 40m. The initial pose of the leader vehicle was placed at (0,R), where R is the radius of the circular path under test. The leader vehicle was orientated to align with the vertical axis. For simulation purposes, the circular path is divided into 180 sub-divisions, each at an increment of 2 degrees. It was observed that the tracking errors eventually converge to some steady values.

Table 1 Steady state error performance for both direct-hooked and off-hooked models

Radius of Path (m)	**Virtual Trailer Model**	
	Direct-hooked model	**Off-hooked model**
10	~0.5m	~0.25m
20	~0.25m	~0.18m
40	~0.18m	~0.18m

Table 1 summarized the steady state tracking performance for both models. From the table, the steady-state tracking errors for the off-hooked model is quite consistence throughout the three tests. However, for the direct-hooked model, the steady state tracking error, when tracking the leader vehicle under the curvature radius of 10m, is quite substantial as compared to the error for the off-hooked trailer model. The steady state error for the direct-hooked model, when following the leader vehicle under curvature radius at 40m, is comparable to that of the off-hooked trailer model.

Table 2 summarized the performance of both trailer models when following a clothoid. The length of clothoid is as indicated by L. R indicates 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. This is expected as both the models are maneuvering on a smooth transition path, which is the main characteristic of clothoid roads

Table 2 Performance comparison between direct-hook 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	2.15	-0.31	1.8

B. Experimental Results

The simulation results have verified that the virtual off-hooked trailer link model performed better than the virtual direct-hooked trailer link model in terms of tracking errors performance. To evaluate the performance of off-hooked virtual trailer link model under real environment and to prepare the model for implementation, two different sets of experimental data, one on urban roads and the other on sub-urban roads, are collected. Throughout the experimental tests that follow, the mean error and standard deviation of tracking will be used as metrics to measure the robustness of the proposed virtual trailer model. The mean error is computed by taking the average of the "error area" calculation, as shown in equation9, over the entire tracking points. The standard deviation measures the spread of the tracking error. A confident level of 3 sigma is chosen in order to ensure the follower vehicle stay within the tracking trajectory.

Urban Road: Figure 8 shows the setup of the vehicles for this experiment. A goods vehicle is used as the leader vehicle. Neither GPS nor inter-vehicle communication links are installed in this vehicle. An in-house built autonomous vehicle (AGV) equipped with laser scanner is used as the follower vehicle. There are on-board odometry sensors on the AGV. The data acquired by the on-board computer in the AGV includes its orientation, steering and speed. The position of the leader is computed by using the measurement data from the laser scanner.

Figure 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 turnings are gradual. The result in Figure 9 shows that the off-hooked trailer model has a relatively small standard deviation (0.6) in the trajectory tracking error. This implies that the follower is actually closely trailing the leader.

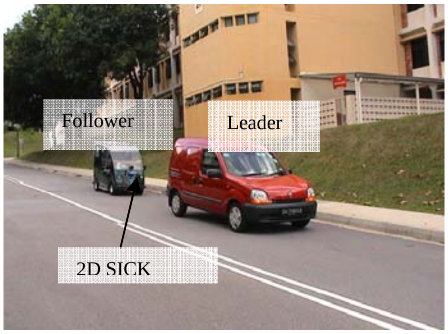
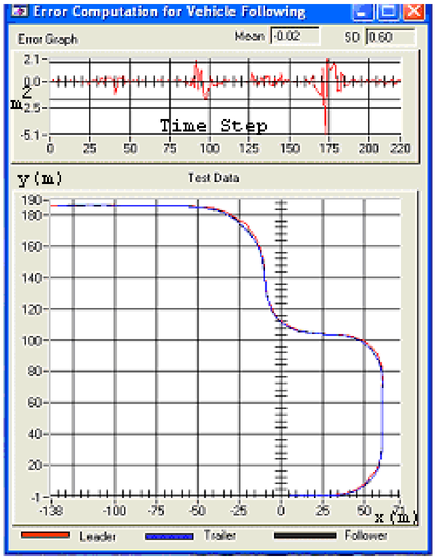


Figure 8. Experimental setup for vehicle following in urban environment



Mean -0.02

SD 0.60

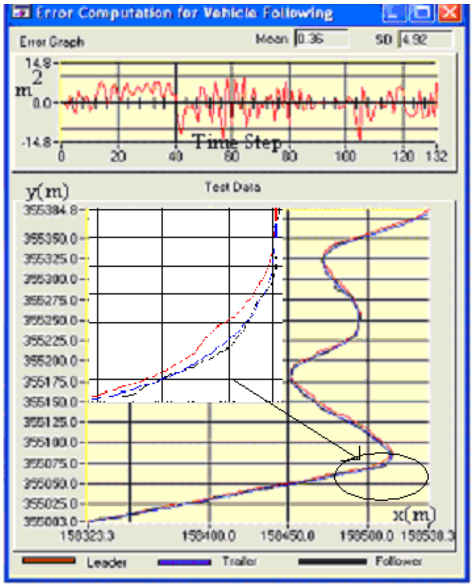
Figure9. Test result for vehicle following in urban area.

Sub-Urban Road: Two vehicles were equipped with on board sensors for data collection as shown in Figure 10. The leader vehicle is a multi purpose vehicle (MPV). The follower vehicle is an 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 information.

Figure 10. Experimental setup for vehicle following in sub-urban

Figure 11 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 maneuvering in an unstructured environment where there exist non-paved roads.

The leader vehicle is free to make turns at any time. It can be seen from Figure 11 that the leader vehicle had made several sharp left and right turns. From figure 10, overall, the off-hooked virtual trailer is able to follow the trajectory of the leader closely. The mean error in tracking is about 0.36 m^2 and the tracking errors falls well within 3σ error bound. The virtual trailer model (off-hooked model) has no problem in following the trajectory of the leader vehicle under steep turning. However, there are some tracking errors along the path. This is mainly due to the noisy measurement from GPS and laser scanner. Both the vehicles are moving in a rough terrain in the "jungle" environment, where there are trees blocking the GPS signal. Furthermore, the pitching effect of the vehicle also affects the reliability and accuracy of the sensor readings, thus affecting the performance of the model.



Mean 0.36

SD 4.92

Figure 11. Experimental result for vehicle following in sub-urban area. The inset image is a zoomed in view of the error.

V. FUTURE WORK

The challenges for autonomous vehicle following are the prediction and estimation of the leader's pose while the follower vehicle is in motion. Also, the uncertainties in the data acquisition processes had played an important role in the accurate and reliable prediction and estimation process.

As discussed in the experimental results, perception is the only means of estimating the pose and trajectory of the leader vehicle. Typical sensors used for this purpose are the laser scanner and vision. However, there are measurement uncertainties [19] in the raw data. Improvement on the perception sensing is thus needed.

Accurate estimation of the position of the leader vehicle is crucial in system modelling. In the real application, it is difficult to perform system modelling for the leader vehicle as the vehicle to be followed can be of any type. However, the maneuver of the leader vehicle can be estimated through the on board sensors mounted in the follower vehicle. The motion of the leader vehicle can be modelled as constant velocity, constant acceleration and turning mode models. For this purpose, the Interactive Multiple Model (IMM) algorithm will be studied.

VI. CONCLUSION

The trajectory following of the leader vehicle by the follower vehicle is the main focus of this paper. It has been shown that the overall system modelling for vehicle following is very important to ensure the performance of vehicle following system. This is particularly important due to the limitation on the sensors used for tracking when the system is to be deployed in urban environments.

The use of the virtual-trailer model based on the off-hooked, single-trailer configuration had been identified as having the most potential to perform close following of the trajectory traced by the leader vehicle rather than the conventional approach that track the lead vehicle directly. By making the length of the virtual link and virtual trailer to be of the same size, the virtual off-hooked trailer model has been implemented successfully for vehicle following operations. Simulation tests and field experiments have been performed to evaluate and understand the issues encountered by vehicle following in a real environment. They have showed theoretically and experimentally the feasibility of the proposed virtual off-hooked trailer link model has resulted in low tracking errors. In order for the proposed system to be deployable in a robust manner, further work on the perception issues, error propagation problems, multiple modelling, and prediction plus sensor fusion are to be carried out for successful deployment.

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