Experimental evaluation of a co-operative driving setup based on inter-vehicle communication.

EXPERIMENTAL EVALUATION OF A CO-OPERATIVE DRIVING SETUP BASED ON INTER-VEHICLE COMMUNICATION

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Abstract: This paper presents the design and evaluation of a co-operative longitudinal controller for a cluster of vehicles with inter-vehicle communication (IVC). By applying IVC a smooth traffic flow can be realized. The proposed controller can actively control the throttle, the brake and the gears of the used vehicles in order to do so. The longitudinal controller uses two loops; the outer loop computes a desired acceleration, which the inner loop uses as a reference. The outer loop uses acceleration, velocity and position information from the own vehicle and preceding vehicles. These three states first have to be estimated from various sensors in the vehicle. An Extended Kalman Filter (EKF) has been used for fusing the signals from the different sensors. The used signals are available from DGPS and from inertial sensors on the test-vehicles. Real-life experiments with the proposed algorithm for a cluster of three vehicles will be evaluated.

Keywords: Kalman filter, sensor fusion, throttle/brake control, longitudinal control, Co-operative driving.

1. INTRODUCTION

Different strategies have been proposed to address the problem of traffic congestion and passenger safety and comfort. Advanced Driver Assistance Systems(ADAS) have been designed to decrease the workload of drivers. An example of such a system is Adaptive Cruise Control (ACC). ACC does not only perform the same function as the "ordinary" Cruise Control, which is to keep the velocity of the vehicle at a desired value, but it can also control the distance to the predecessor by application of both throttle and brake. In Prestl et al. (2000) the ACC system in the BMW 7-series is explained. These ACC systems for commercial use in vehicles are based on radar or LIDAR for determining the distance to the predecessor. ACC systems mostly function only above a certain speed because of sensor limitations. Therefore Stop & Go controllers have been introduced more recently (Yamamura et al., 2001). These controllers can automatically follow the preceding vehicle throughout the whole speed range of the vehicle by using sophisticated distance sensors.

Although Stop & Go systems can reduce workload and increase safety and comfort, they do this by only regarding the direct predecessor. The application of IVC however can expand this functionality by taking into account more vehicles beyond the direct predecessor. This is known as Co-operative driving. For this application the distance to the predecessors (headway) has to be known. In this paper a method is proposed to determine the headway by IVC. An accurate real-time estimation by each vehicle is required for this purpose. This position is communicated to the vehicles behind along with the velocity and acceleration, which are necessary for the longitudinal control algorithm. Already some projects exist in which communication between vehicles is used for platooning. In these platoons very little space is allowed between vehicles in order to increase the throughput of vehicles travelling on the road. The time headways can be as small as 0.25s (PATH, 1998). The available communication link is used only to communicate the velocity and acceleration of the predecessors. The headway is still being obtained by using optical sensors. However, using IVC for this purpose as is a cost-efficient method because no distance sensor has to be used. Furthermore these sensors are only capable of determining the distance to the direct predecessor, while the distance to more than one predecessor is desired for Co-operative driving.

The Differential Global Position System (DGPS) has been used for providing the global position. DGPS only however is not sufficient for providing the position for real-time purposes because a DGPS update is received with 1Hz. For real-time control a higher frequency is needed, which can be achieved by using inertial sensors. Navigation systems using accelerometers or gyroscopes are known as Inertial Navigation Systems (INS). These additional sensors have much higher update rates and can therefore be used to complement the DGPS signals. In this project signals from an accelerometer and an odometer are fused by using an EKF. The Kalman Filter (KF) is a well known method for fusing signals with different properties and for state estimation. In the automotive industry the Kalman Filter has been used by several researchers for state estimation. Examples hereof can be found in Carlson et al. (2002); Gustafson et al. (2001). Other applications of the KF can be found in autonomous vehicles and robots (Thrapp et al., 2001; Kiriy and Buehler, 2002).

This paper is organized as follows: In section 2 the sensor fusion of the different sensors will be explained. Section 3 will focus on the design of the longitudinal control algorithm. Subsequently experimental results will be presented in section 4. Finally, in section 5 the conclusions will be given.

2. SENSOR FUSION AND STATE ESTIMATION

In order to allow Communication Based Longitudinal Control (CBLC) some vehicle states have to be known. Because the desired states can not be directly measured from one sensor they have to be estimated from various sensors. A state estimator that has to be applied for real-time longitudinal vehicle control must be accurate, robust and provide the estimates in real-time with a high enough update rate. The estimator for our purpose has to interpolate the position of the vehicle by adopting inertial measurements when there are no signals available from the DGPS system, furthermore it has to estimate some other desired states. The used estimator is an Extended Kalman Filter (EKF) (Anderson and Moore, 1979), based on a non-linear kinematic model of the vehicle movements. A problem that rises when using DGPS for real-time purposes is its latency. In order to still apply DGPS for the real-time system a latency compensation scheme has been developed. More detailed information about the design of the EKF and the latency compensation can be found in (Hallouzi et al., 2004).

3. LONGITUDINAL CONTROL ALGORITHM

The estimated vehicle parameters by the EKF as described in the previous section are going to be used for longitudinal control of the vehicles in the demo-setup. For longitudinal control of a cluster of vehicles, two hierarchical levels can be used. By using two loops these two loops can be designed separately from each other. This has the advantage that a division of the complexities that can occur during the design is made. Furthermore this approach has the advantage that a separation is made between two aspects that are really present in a driver-vehicle system (Persson et al., 1999). These two aspects are driver behaviour, which corresponds with the outer loop, and vehicle dynamics, which corresponds with the inner loop. The outer loop controller specifies the acceleration that the current vehicle must achieve. This acceleration is based on algorithms using information obtained by communication between vehicles. The inner loop controller must obey the acceleration set-point as fast as possible. An overview of the control structure is given in figure 1.

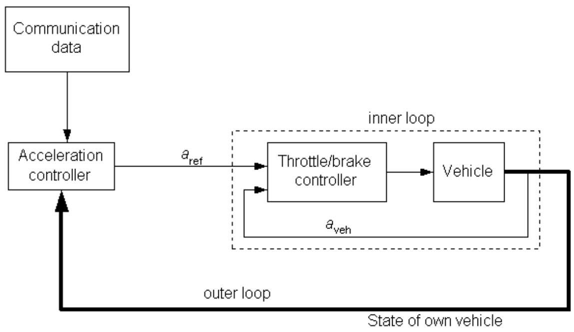

Fig. 1. Graphical representation of the control loops

3.1 *Design of the outer control loop*

The control objective of the outer loop is to keep a certain desired headway relative to the front vehicle. The outer loop however also has the aim to keep a desired headway relative to more vehicles beyond the direct predecessor. The desired headway is based on a variable time headway h, defined by

$$h = h_0 - c\Delta v \tag{1}$$

where $h_0 > 0$ and $c > 0$ are constants and Δv is the relative velocity. This definition of the headway is quite intuitive (Yanakiev and Kanellakopoulos, 2001). A certain vehicle can maintain a time headway h_0 to its predecessor, while both are travelling at the same speed. If the preceding vehicle is travelling faster $(\Delta v > 0)$, it is safe for the following vehicle to reduce the time headway until the velocities are equal again. However, if there is a slower preceding vehicle

$(\Delta v < 0)$, the time headway should be increased. The desired headway (separation) between the vehicles can be calculated by

$$d_{ref} = d_0 + h v_{veh} \quad (2)$$

where d_0 is the minimal headway between vehicles and v_{veh} is the vehicle velocity. The total acceleration value commanded to the lower level controller is calculated according to:

$$\begin{aligned} a_{ref} &= c_1 a_{MND} + c_2(d - d_{ref}) \\ &+ c_3(v_{i-1} - v_i) + c_4(a_{i-1} - a_1) \end{aligned} \quad (3)$$

c_1-c_4 are positive constants and i is the index of the current vehicle, $i-1$ is the index of the preceding vehicle etc. The tuning of the different parameters has to be done in a way that the outer loop behaviour corresponds with "real driver behaviour". In Bengtsson (2001) for example it is concluded from several research works that drivers tend to brake with a rather constant deceleration. Therefore the outer loop should also do so in order to give the driver a natural braking feel. This has been done by adding the term (Morsink et al., 2002)

$$a_{MND} = \frac{-\Delta v^2}{2(d - d_{ref} + dx)} \quad (4)$$

where dx is a positive term used to make sure that a_{MND} does not get too big in situations where $d \approx d_{ref}$ or even become negative when $d_{ref} > d$.

Because the reference acceleration from equation 3 only considers the front vehicle a method has been developed to also consider more vehicles in front, which is the aim of Co-operative driving. In figure 2 different distances between a 3-vehicle setup are depicted. The idea is that vehicle 3 in this setup should

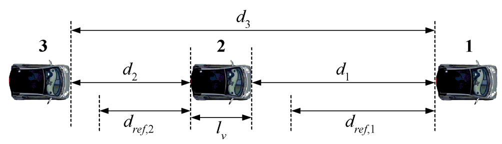

Fig. 2. Distances between vehicles

not only keep a headway of $d_{ref,2}$ to vehicle 2, but is should also keep a headway of $d_{ref,1} + l_v + d_{ref,2}$ to vehicle 1. For this purpose the following relation has been used.

$$a_{ref} = \begin{cases} \min(a_{ref,2}, a_{ref,1}), & \text{if } \min(a_{ref,2}, a_{ref,1}) < 0 \\ \max(a_{ref,2}, \frac{s}{2}), & \text{otherwise} \end{cases} \quad (5)$$

where $a_{ref,2}$ is the acceleration due to vehicle 2, $a_{ref,1}$ is the acceleration due to vehicle 1 and $s = a_{ref,2} + a_{ref,1}$. In this relation positive and negative relations have been considered separately. For negative accelerations the minimal value of the two reference accelerations is taken. For positive accelerations the maximum value of $a_{ref,2}$ and the mean of $a_{ref,1}$ and $a_{ref,2}$ is taken. A smooth transition between these two relations has been used in order to prevent abrupt changes in the acceleration command. Furthermore the direct predecessor always has priority. If for example the direct predecessor is braking and other vehicles in front are accelerating, then the following vehicle will brake in reaction on the direct predecessor.

3.2 Design of the inner control loop

Contrary to the outer loop the design of the inner control loop is specific for each vehicle. In order to achieve a high level of control accuracy for the inner loop, the exact vehicle behaviour must be known. Furthermore the time scope of the design of a very detailed controller based on precise information of vehicle parameters is very large. Because these means were not available, the acceleration (inner loop) controller has been realized by using Sliding Mode Control (SMC) based on a simple vehicle model. SMC has been chosen because it is well known for its robustness to system modelling error and external disturbance (Slotine and Li, 1991).

Because the controller should not apply the throttle and brake at the same time, a switching law is designed that takes into account the residual acceleration. Furthermore a shift algorithm has been developed in order to know the shift moments of the gearbox. More details about the inner loop controller can be found in Hallouzi et al. (2004).

4. EXPERIMENTAL RESULTS OF THE CONTROLLER

4.1 Demonstration set-up

In order to display the functionality of the CBLC system at demonstrator-level a demo-setup with the required hardware has been built at TNO Automotive. The demo set-up, depicted in figure 3, consists of three test vehicles. All three vehicles can communicate via an infrared connection up to a distance of 300m. The front vehicle is a Peugeot 806 and the two vehicles behind it are Smarts. The Smarts have an electronically controlled automatic transmission and electronic throttle as standard equipment. The Peugeot is used as a lead vehicle on which the two Smarts that can be automatically controlled have to anticipate. The throttle and the gears of the Smarts can be controlled by the control computer. The braking system in the Smarts can also be controlled by the control computer by using a brake actuator that mechanically pulls the brake pedal. The control computer is in the PC-104 format and the used operating system is Realtime Linux. Furthermore all vehicles are equipped with DGPS, accelerometers in longitudinal and lateral direction and a velocity sensor. The velocity sensor is actually a pulse counter (odometer) that is mounted at a wheel of the vehicles. The velocity can be computed from the counted pulses.

Fig. 3. The three-car demo setup

4.2 *Experiments*

Experiments have been conducted with the demo-setup to analyze the functionality of the whole CBLC system for different manoeuvres at different speeds. These experiments have been performed on a test track without other traffic that was placed at our disposal by the Dutch ministry of traffic. Two test scenarios have been defined. In the first scenario three steady-state situations are adopted at velocities of respectively 18m/s, 11m/s and 24m/s. By steady-state situation a situation is meant at which all vehicles drive with the same velocity at a distance belonging to that velocity. The vehicles all start from standstill. In the second scenario Stop & Go at different velocities has been performed. In this scenario the front vehicle drove from a standstill position to a steady velocity of about 15m/s, after a while the front vehicle decelerated to stand-still again. The same routine was gone through once again, but the steady velocity was taken to be 17.5m/s the second time and the front vehicle decelerated harder. The first scenario resembles traffic with large variations of the speed without fully stopping (busy freeway traffic). The first scenario resembles typical Stop & Go traffic in which vehicles brake until they stand still and then drive on again (busy urban traffic). The driver of the front vehicle relied on traffic cones placed along the track to start a certain manoeuvre (brake or accelerate). In this way the experiments were reproducible. The two following vehicles automatically followed the front vehicle during the whole test sequence, the drivers only had to steer. A time headway of 1.5s is used for all experiments.

In figure 4 the velocities of the three vehicles in the first test scenario are depicted. In this figure it can be seen that the velocities of the three vehicles become equal at the three steady-state situations and that the braking and accelerating manoeuvres of the front vehicle are followed by the two following vehicles. In figure 5 the accelerations of the three vehicles are depicted. In this figure it can be seen that the two following vehicles react instantaneously on decelerations of the front vehicle at 40s and 90s. This fast reaction is due to the Co-operative driving approach. The second time the front vehicle brakes with maximal deceleration. Furthermore it can be seen that the following vehicles have to brake less hard than the front vehicle because in clusters with a time headway it is allowed to keep a smaller headway at smaller velocities. The sudden variations in the acceleration pattern of the vehicles are due to shifting of the gearbox. In figure 6 the distances between the vehicles are depicted. In the distance figures the steady-state situations can be recognized by a constant value of the distance. These distances are obtained solely from the DGPS-based EKF without the use of other distance sensors. It can be seen that the distance signals are free from discontinuities (due to the EKF) that could be expected from using only DGPS. During the whole test-day the distance estimation from the DGPS did not once cause a dangerous situation in which the following vehicles should be braked manually by the drivers.

In figure 7, 8 and 9 the results for co-operative automatic driving for the second scenario are depicted. In these figures it can also be seen that the two following vehicles anticipate correctly on the front vehicle.

4.3 *Co-operative vs. manual driving*

In order to compare automatic Co-operative driving with manual driving the same two scenarios have also been tested without the help of the Co-operative driving system. The drivers were specifically instructed to keep the same time headway of 1.5s as the automatic system. The results of manual driving for the second scenario are depicted in figure 10. It should be noted that although the drivers were instructed to drive without exaggerated attention to the front vehicle, they knew that the front vehicle would brake at a certain position. This knowledge influences the reaction time significantly. In figure 11 a close up of the second braking manoeuver for both manual and automatic co-operative driving is depicted. It can be seen that for manual driving it takes the two following vehicles respectively 1.1s and 1.9s to react on the front vehicle, while for automatic driving both following vehicles start braking 0.9s later than the front vehicle. Especially the rear vehicle has to brake very hard (-6m/s^2) for manual driving in order to avoid a collision. With automatic co-operative driving the rear vehicle can stop at the right distance by applying only mild decelerations (maximum of -3m/s^2).

5. CONCLUSIONS

A Communication Based Longitudinal Control algorithm has been developed that uses state estimation of individual vehicles combined with inter-vehicle communication. For estimation of the desired states an Extended Kalman Filter has been used with DGPS as input. One of the estimated states was the position, which was used to determine the distance between vehicles. The longitudinal controller was divided into two loops. The inner loop is an acceleration controller and the outer loop calculates the desired acceleration.

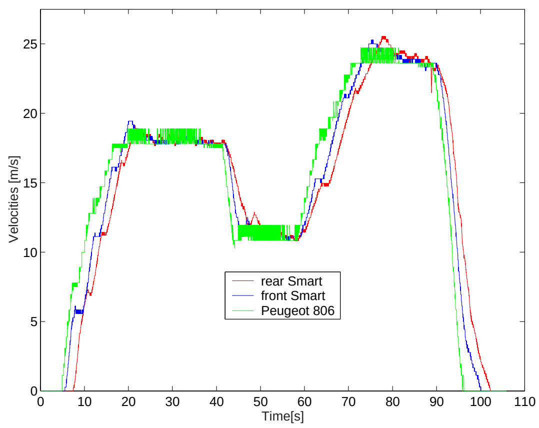

Fig. 4. Velocities of the three vehicles for the second scenario

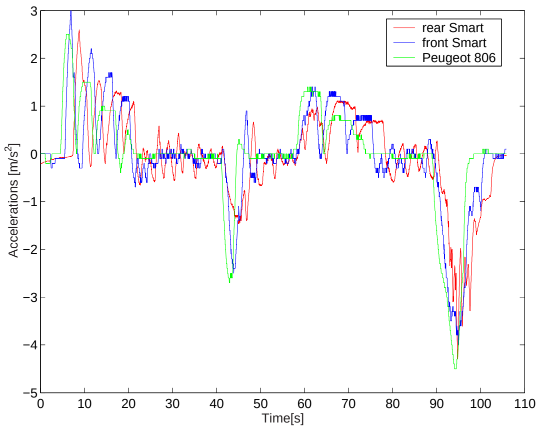

Fig. 5. Accelerations of the three vehicles for the second scenario

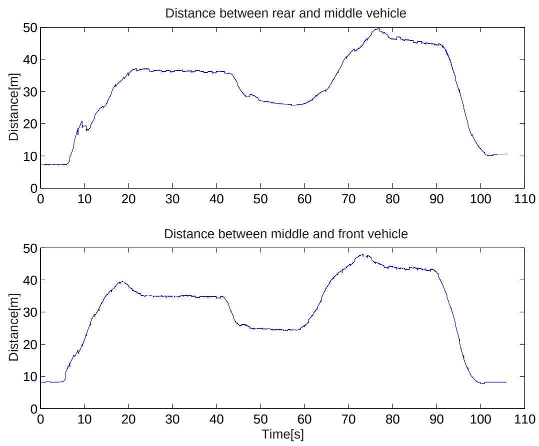

Fig. 6. Distances between the three vehicles for the second scenario

From experiments it can be concluded that the CBLC system functions properly. By only using an DGPS-based EKF the experiments were accomplished successfully. The CBLC functionality shows a decrease in

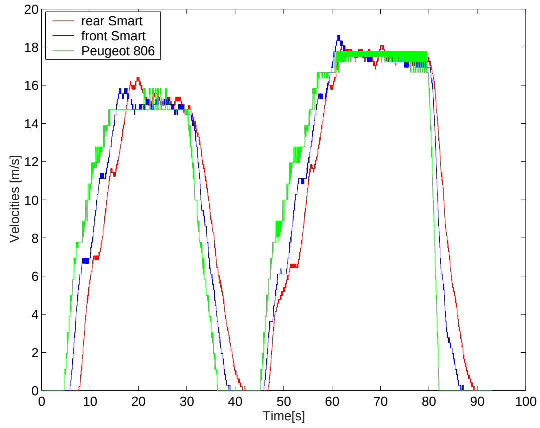

Fig. 7. Velocities of the three vehicles for the first scenario

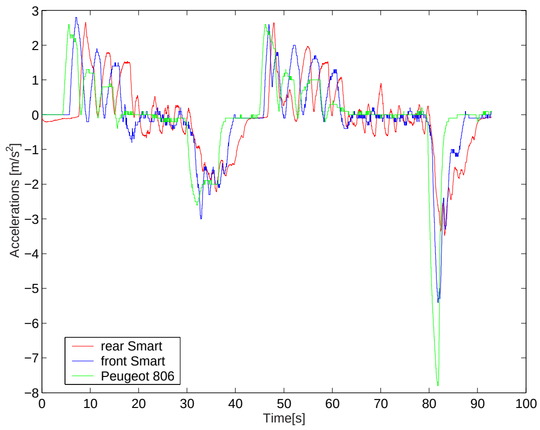

Fig. 8. Accelerations of the three vehicles for the first scenario

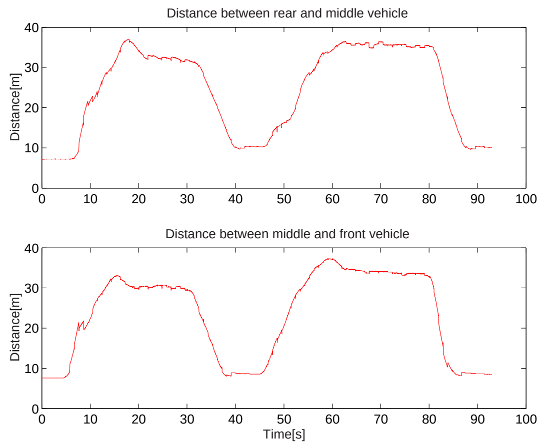

Fig. 9. Distances between the three vehicles for the first scenario

reaction times with respect to human drivers by early anticipation on more than one vehicle in front.

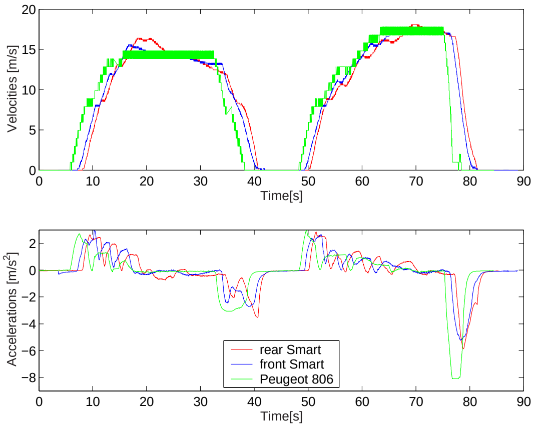

Fig. 10. Velocities and accelerations for manual driving according to the first scenario

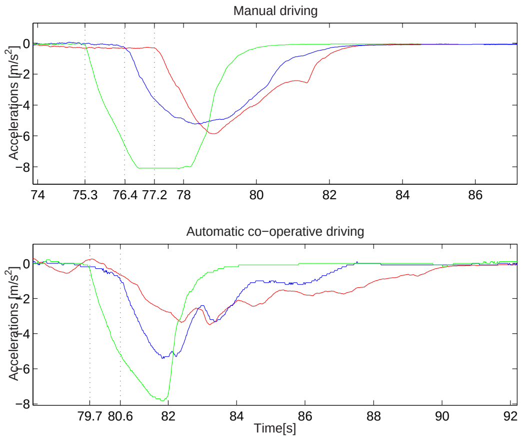

Fig. 11. Comparison of manual and automatic driving during hard braking of the front vehicle

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