Minimization of the effect of wireless communication on the distance control between vehicles

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Abstract—Previous work demonstrated that adding a wireless link to a distance control between vehicles has effect on its performance. This paper presents an algorithm that minimizes the effect of the transmission delay and the packet losses of said wireless link. The extrapolation algorithm is implemented by a block added just after the link, so that it is transparent to the control system and it does not reduce the efficiency of the link. The results demonstrate that choosing an appropriate extrapolation order makes the performance equal to the case in which the communication is hardwired.

Index Terms— Wireless control, Bluetooth, delay compensation, extrapolation

I. INTRODUCTION

Cooperative driving is generally regarded as a potential solution to increase the capacity of roads [3]. Distance control between vehicles in a platoon is a basic feature of cooperative driving. The performance of distance control is crucial for the efficiency of platoon driving: a too long distance will decrease the capacity of the road, while too short distances might result in potential collisions. If information (e.g. position) has to be transmitted between vehicles, this has to be done with a wireless connection. Previous work demonstrated that the intermittent packet losses and the delays introduced by the wireless connection have major impact on the performance of the distance control, increasing the distance error with an order of magnitude. This is especially critical when speed changes are required [1]. In those moments the delays make the following vehicle change its speed some instants later than the leading vehicle, what can deteriorate the performance of the system.

The objective of this paper is to present a method to compensate the transmission delay inherent to the wireless communication and minimize the effect of packet losses. The simulation results reveal that this is possible using simple extrapolation algorithms without reducing the efficiency of the wireless link.

The paper is outlined as follows. In Section II, the simulation system is presented. Section III is divided in two sub-sections: first, the transmission delay compensation algorithm is explained and some results are presented; second, the extrapolation algorithm is added to the simulation set-up and its effect simulated. Finally Section IV summarizes the conclusions.

II. SYSTEM

Distance control with inter-vehicle position communication is a nice example of a wireless control system where the control loop is closed via a wireless link. The control system (Figure 1) consists of two vehicles, the leader and the follower, with the same speed and acceleration limitations. A discrete-time PID controller, placed inside the follower vehicle, controls the distance between both vehicles by changing the acceleration profile of the follower [4] and [5]. Each vehicle has a position sensor. The distance between the two vehicles is obtained as the difference between the two position sensors. The position of the leader is sent every 20ms over a Bluetooth link to the controller in the follower. The sampling interval of the controller has been synchronized with the communication interval of 20ms. The behavior of the following vehicle is modeled as a continuous time process. As input, it uses the last acceleration value passed by the controller. Its position output is sampled synchronously with the execution of the controller. The Bluetooth link is modeled as a communication link with a constant delay of 20ms per transmission and up to 7 retransmissions per packet. As a consequence, the maximum considered delay is 160ms. To this control system we added a block (called “extrapolation” block) just before the controller that will implement the error minimization algorithms presented in the paper.
III. ERROR MINIMIZATION

A. Transmission delay

In previous works it was demonstrated that the distance error is affected not only by packet losses but also by the transmission delay inherent to any wireless communication. Even in the case of an ideal link, without retransmissions, the constant communication delay doubles the distance error between the vehicles [1]. However, the actual distance error is not only determined by the communication delay which causes it but it also depends on the speed and acceleration of the leader in that instant. To tackle this problem we assume an ideal Bluetooth link, whose transmission delay is known or can be estimated, and we use the Richardson extrapolation [7] method: Periodically, every Ts, the leader sends a message to the follower with its position at this very instant. It takes the message a time Td to arrive to the receiver in the follower. This means that, when a packet arrives to the follower vehicle at instant t, this was sent by the leader at (t-Td) and contains its position at the instant (t-Td); to know the actual position of the leader at the instant t, it is necessary to know its speed. For that we will calculate the average speed during the last Ts period (Figure 2) and we will assume it as constant during the complete period. With these data it is possible to know the distance that the leader traversed during the transmission delay time, Td. In consequence, adding said distance to the received position value, p, we obtain a good estimation of the leader’s position at the very instant t, \( p' \)

\[
p' = p + \text{speed}_{\text{leader}} \times T_d
\]

Equation 1

Notice that, to calculate the average speed, the values of the last sample and the last but one sample are necessary; some kind of short memory is required in the error minimization block to store that value.

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**Figure 1** Wireless control system

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As mentioned before the most critical scenario is the one in which the leader runs at a certain speed and suddenly it stops. In this case, due to the transmission delay, the follower will start to reduce its speed some milliseconds later than the leader and consequently its speed will be higher, running the risk of colliding with the leader. In the selected scenario the leader runs at a constant speed of 5 m/s and at the instant \( t=10 \) s starts to decelerate till it stops. Initially, only the transmission delay is considered and not packet losses. Figure 3 shows the leader position versus time and the input to the controller. The red curve is the input to the controller when the transmission delay compensation block is not added. During the time the leader is running at constant speed the distance between the two positions is also constant and is not reduced until both vehicles stop. When the compensation block is added, the constant distance between the leader’s position and the input to the controller is reduced, becoming negligible.

**Figure 2** Temporal axis of the packet generation at the leader packet arrival to the follower

**Figure 3** Leader position and input to the controller using an ideal wireless before and after the compensation block

**Figure 4** shows the performance of the system for the two inputs that have just been presented. When the transmission delay is considered and not packet losses.
delay is not compensated we can see that the constant distance between the leader and the controller’s input becomes a constant distance between leader and follower (0.1m in this case). As expected, when the compensation block is added, that distance disappears till the leader starts to decelerate, $t=10s$. At this moment the distance between both vehicles becomes negative, what means that the follower overtakes the leader. The absolute value of this negative overshoot is higher when the compensation block is present. However, the difference between the deviation at constant speed and the maximum overshoot is shorter in the second case. This means that in this case the necessary safety distance to avoid collisions can be shorter. Finally, some packet loses have been simulated for the same scenario and the same two cases (blue and cyan curves). They show that packet loses are still a problem for the system performance; it will be necessary to tackle this second problem.

$$p(t) = \sum_{k=0}^{N} l_k(t)p(t_k)$$

$$l_k = \frac{(t - t_0) \cdots (t - t_{k-1})(t - t_{k+1}) \cdots (t - t_N)}{(t_k - t_0) \cdots (t_k - t_{k-1})(t_k - t_{k+1}) \cdots (t_k - t_N)}$$

Equation 2

As only received information is used for the extrapolation, when a sample $p_t$ is lost and a previous one, for instance $p_{t-2Ts}$, was also lost, then, the N-order extrapolation algorithm will use the following N samples: $p_{t-Ts}, p_{t-3Ts}, \ldots, p_{t-(N+1)Ts}$.

This algorithm is implemented together with the transmission delay compensation algorithm in the extrapolation block. When a sample is received the delay compensation term $(\Delta t)_{est} = \Delta t$ is added to it to get the actual one. In case the packet is lost and doesn’t arrive, its value is extrapolated using previously received positions and the compensation factor estimated for the previous sample is added to the extrapolation. To test the algorithm, the same scenario as before has been simulated but now a retransmission pattern is included just at the moment in which the leader starts to decelerate, 9.9 seconds. A pattern is an Nx1 array where N is the number of samples that may need retransmissions. Each element of the array represents the number of times the sample in that position has to be retransmitted. An element equal to 0 means that the sample arrived to the controller the first time it was transmitted, no retransmissions are needed. In previous work [2] the best and worst case regarding the number of retransmission were obtained for a 10-sample pattern. These are [0 0 0 0 4 6 0 0 0 0] for the best case and [1 1 1 1 1 1 1 1 1 1] for the worst case. We start with the worst case. Figure 5 compares the deviation of the follower for different extrapolation orders with the deviation when the extrapolation block is not added to the controller and when there are not packet losses.

B. Packet losses

When considering packet losses, it should be taken into account that multiple consecutive packets can be lost and each of them may be retransmitted different number of times. Every time this happens, the extrapolation block will estimate the position of the leader at the instant the new packet should arrive. For that, different extrapolation techniques have been considered and the Lagrange’s method has been selected [Equation 2]. This method is simple but optimal for the cases in which the samples are non-equidistant. It allows to estimate the current position from previously received positions. These positions are stored together with their times of arrivals to be used in case next packets are lost and have to be extrapolated.

Figure 4 Deviation of the follower with respect to the leader when packet losses occur with and without compensation block; and for an ideal wireless link with and without compensation block.

Figure 5 Deviation of the follower with respect to the leader when the extrapolation block is not used, ideal wireless link and link with packet losses, and when the extrapolation block is added for different orders.
The figure shows that the initial offset, due to the transmission delay compensation, becomes negligible. Once packet losses occur, some negative overshoot appear meaning that the follower vehicle overtakes or collides against the reference vehicle. This overshoot is reduced by increasing the extrapolation order till 3; for higher orders the performance does not improve anymore. Comparing the performance of the system with no extrapolation block for an ideal wireless link with the performance when packet losses occur and a 3rd order extrapolation is applied we see that both of them describe the same curve but shifted. The first one presents an initial constant delay; in the second one this delay is reduced to zero.

Figure 6 shows the same curves as previously but for the best case. One can observe that communication delays when the reference vehicle is starting to break can even improve the performance of the system. In this case the effect of the delays is cancelled by the new block. Again, the curve for a 3rd order extrapolation is equal to the curve of an ideal wireless link whose constant deviation, due to the constant transmission delay, is shifted to the level zero. The optimal system performance is obtained for an extrapolation order equal to 3; and, opposite to the previous case, a higher order diminishes the performance. That is explained by Figure 7. It shows the reference signal before and after the wireless link and the input to the controller for different extrapolation orders. The more adjusted the extrapolation order is to the order of the reference signal, the closer the extrapolated samples will be to its real value. When no consecutive packets are lost the effect is negligible, because the extrapolated value is very close to the last value received. When, on the contrary, multiple consecutive packets are lost, the extrapolation block will tend to reproduce a curve which follows its order, and as the extrapolated sample is further in time from the last received value, the deviation with respect to its real value will be higher.

Figure 7 Leader’s position, reference signal after the wireless link without and with packet losses. Input to the controller after different orders of extrapolation

IV. CONCLUSION

As shown in this paper, it is possible to minimize the effect of wireless communication on real-time distance control between vehicles. In the case of an ideal link, without retransmissions, the constant communication delay doubles the distance errors between the vehicles. When a real Bluetooth link with probabilistic retransmissions is considered, the maximum distance error can be up to an order of magnitude higher. Both problems can be solved with simple real-time extrapolation methods that do not affect the efficiency of the wireless link. What is more, it is not necessary to increase the communication bandwidth. However, to have a good performance results it is convenient to adapt the extrapolation order to the order of our reference signal. To do so, efficient methods are still under development and must be further explored.

REFERENCES


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