Implementation of Inter-vehicle Communication System and Experiments of Longitudinal Vehicle Platoon Control via a Testbed

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Abstract: This study considers the implementation issues of the inter-vehicle communication system for the vehicle platoon experiments via a testbed. The testbed, which consists of three scale vehicles and one RCS(remote control station), is developed as a tool for functions evaluation between simulation studies and full-sized vehicle researches in the previous study. The cooperative communication of the vehicle-to-vehicle or the vehicle-to-roadside plays a key role for keeping the relative spacing of vehicles small in a vehicle platoon. The static platoon control, where the number of vehicles remains constant, is sufficient for the information to be transmitted in the suitably fixed interval, while the dynamic platoon control such as merge or split requires more flexible network architecture for the dynamical coordination of the communication sequence. In this study, the wireless communication device and the reliable protocol of the flexible network architecture are implemented for our testbed, using the low-cost, ISM band transceiver and the 8-bit microcontroller.

Keywords: wireless communication system, inter-vehicle communication, longitudinal vehicle platoon, testbed

1. Introduction

Urban road in most major cities becomes congested more and more because the demand of travel exceeds highway capacity. The congestion problem causes many other problems: the waste of time and energy, the traffic accident, the pollution, and so on. ITS (Intelligent Transportation System) is developed actively as a solution of these problems. Especially, IVHS (Intelligent Vehicle and Highway System) is the major subject in ITS. The purpose of IVHS is to improve safety as well as to increase a highway capacity through automated vehicles and automated highways[1]. In IVHS, a exemplary method of efficient vehicle control by grouping in platoons has been proposed in PATH program[2]. The vehicle platoon is a group of vehicles traveling together at a high speed with relatively small spacing. Vehicles in close-formation platoons are dynamically coupled by feedback control laws. Depending on the information available for feedback and depending on how such an information is processed in the synthesis of an automatic vehicle following control law, dynamic interactions between vehicles can cause instability in a vehicle string. The control with the mixed information of the lead vehicle which is the first vehicle in a platoon and the preceding vehicle can only guarantee the stability in a vehicle string[3].

The information of the preceding vehicle can be obtained relatively by the range radar. But the information of the lead vehicle is not available to all vehicles in a platoon. The wireless communication only enables all vehicles to obtain the information of the lead vehicle. For the static platoon control, where the number of vehicles remains constant, it is sufficient for the information to be transmitted in the suitably fixed interval since each vehicle dose not require the frequent update of the control input. This scheme guarantees that each vehicle in the platoon has an opportunity to transmit its information every one cycle. For the dynamic platoon control, such as merge or split, the more flexible network architecture is required. In this case, since the maneuvering vehicle for merge or split requires the frequent update of the control input, the more information should be transmitted to the maneuvering vehicle than others. Therefore, the more opportunity to transmit the information is given to the lead vehicle and the maneuvering vehicle. In this scheme, the communication sequence should be coordinated effectively. The coordination of the communication sequence may be achieved easily by the RCS(remote control station).

In this study, the wireless communication system, which can coordinate the communication sequence by the RCS, is implemented for the vehicle longitudinal platoon experiments. Then, the performance of the wireless communication system is verified by the help of easy experiments.

2. System Requirements

Traffic flow capacities are affected directly by vehicle platoon control strategies. The effectiveness of a platoon control strategy can be gauged by the maximum traffic flow capacity, the attenuation of spacing errors that it can guarantee, and the amount of information that is needed to implement the strategy in real-time. There are two main methods of control that have been studied in IVHS: constant spacing and constant headway[3]. In constant spacing control, the desired spacing between vehicles is tracked whereas in constant headway control, a desired headway which is the time it takes a vehicle to cover the distance between itself and the preceding vehicle is maintained. The advantages of using constant spacing over constant headway control is to increase the throughput of vehicles on the highway, although constant headway control is more favorable since no external information is required. In constant spacing control, exter-

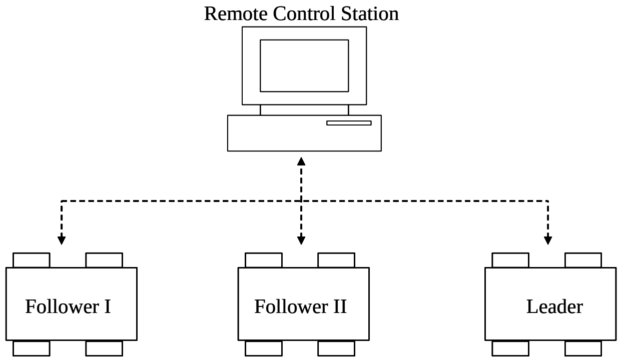

Fig. 1. The configuration of the testbed

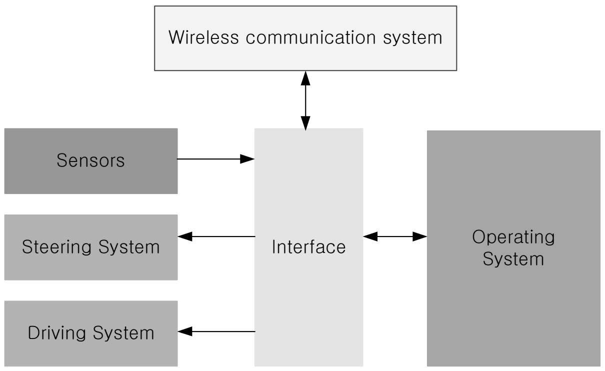

Fig. 2. The configuration of a scale vehicle of the testbed

nal information is required for string stability. A wireless communication system must be used to transfer this external information.

In vehicle platoon system with constant spacing strategy, the following vehicle needs the mixed information of the preceding vehicle and the lead vehicle. The information includes the position, the velocity, the acceleration, and the particular command of the preceding or the lead vehicle. At the same time, each vehicle may need the command of a RCS due to a specified event such as emergency.

In the previous study[4], the testbed for vehicle longitudinal platoon experiments is developed. The testbed shown in Fig. 1 consists of three scale vehicle and a RCS. Each vehicle includes, as shown in Fig. 2, the sensors for the data acquisition of available information, the operating system for the computation of the control command, the automated actuators for the driving and steering for the most effective maneuvering, the wireless communication system for the exchange of external information, and the interface for the synthesis of basic functions.

In the previous study[4], the 433MHz RF-module, BIM-433, is used for the implementation of the wireless communication system of which the architecture is the TDMA (Time Division Multiple Access) with token passing. The data transfer rate of this RF-module is 38Kbps and the carrier sense algorithm is not supported. Therefore, the performance of the communication system is not sufficient for the sequence scheduling algorithm[5], [6] and the control synchronization with vehicles. For stable movement of each vehicle, the sampling period of a vehicle should be less than

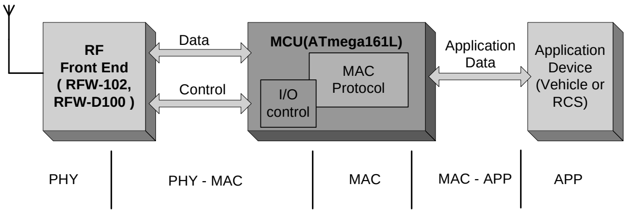

Fig. 3. The configuration of the wireless communication system

40ms. Sensors used in testbed can be satisfied with the sampling period of 30ms. It takes above 5ms to transmit the data (12bytes) and the preamble (above 3ms) at 38Kbps. To improve the performance and robustness of the communication system, more time is needed because the overhead of packet is increased. In addition, the verification with a variety of network sequence scheduling algorithm wants more flexible network architecture. The wireless communication system is composed of both the hardware part and the software part. The hardware part provides the means to connect various nodes (vehicles or RCS) in the network while the software part provides smart control over the hardware components. The software part will also provide a flexible and reliable protocol for the exchange of communication data.

3. Hardware Implementation

The hardware of the wireless communication system is composed of the following components: the RF front-end module, the interface chipset reserved for RF front-end module, and the MCU(microcontroller unit). The Fig. 3 illustrates the configuration of the wireless communication system. The architecture of the hardware is classified into four layers as follows:

- PHY layer (Physical layer)
- PHY-MAC layer (Physical-to-MAC layer)
- MAC layer (Medium Access Control layer)
- MAC-APP layer (MAC-to-Application layer)

The PHY layer is achieved by the RF front-end module, RFW-102 transceiver (transmitter/receiver) chipset which is developed by RFWaves Ltd.[7]. The PHY-MAC layer is constructed by the interface chipset, the I/O (input/output) ports of MCU, and the I/O driver in MCU. The exclusive interface chipset, the RFW-D100 developed by RFWaves Ltd., is used for the interface of the RFW-102[8]. The MAC layer, which is a set of protocols for maintaining order in the use of a shared medium, is the software in MCU. The MAC layer is discussed in later chapter because it is the software component. The MAC-APP layer is the interface part between the wireless communication system and the vehicle or RCS.

3.1. PHY layer

The PHY layer actually handles the transmission of data between the wireless communication system. In this layer, RFW-102 transceiver chipset is used as the RF front-end module. The motivation for the RFW-102 is its high data transfer rate, the ease in interfacing to an external device, the availability for carrier sense algorithm, and the inexpensiveness. Table. 1 shows the specification of the RFW-102.

Table 1. The specification of the RFW-102

Physical Media	DSSS, ISM Band (2.4GHz)
Transfer rate	up to 1Mbps
Bandwidth	30Mhz at -20dB
Peak output power	2dBm
BER	10^{-4} at -80dBm

Table 2. The specification of the ATmega161L

Operationg frequency	3.6864MHz
Serial UART	2EA(up to 1Mbps)
Memory	16Kbyte-flash, 1Kbyte-SRAM
External Interrupts	3EA
Timer/Counter	8-bit(2EA), 16-bit(1EA)

Since the transceiver chipset provides a peak output power of 2dBm and the sensitivity is -80dBm when BER (Bit Error Rate) is 10^{-4}, the transmission is available up to 30m in open. This range is suitable for the testbed using scale vehicles of which the size is about 0.35m.

3.2. PHY-MAC layer

PHY-MAC layer is the interface between the RF front-end module and MAC protocol. The layer is constructed with the following components: the interface chipset reserved for RF front-end module, the I/O ports of the microcontroller unit, the driver for I/O ports.

The RFW-D100, developed by the RFWaves Ltd., is used as the interface chip. The RFW-D100 is a complimentary chip to the RFW-102 chipset. It provides a parallel interface to the RFW-102, and other features which make it easy to implement a protocol suitable for wireless communication. For this study, the MCU is in charge of the MAC layer protocol and the driver for I/O control. The interface chip reduces the real-time demands of the MCU handling the MAC protocol. The interface chip gives the MCU an easy parallel interface with the RF front-end module, similar to memory access. The interface chip converts the fast serial input from the RF front-end chipset to 8-bit words, which are suitable for an 8-bit MCU to work with. In addition, the interface chip requires a lower rate oscillator for idle mode. In the idle mode, the power consumption of the RFW-102 and the RFW-D100 is greatly decreased. The interface chip buffers the data through a 16-byte FIFO (First In First Out buffer), which is giving the MCU access to the RFW- D100 more efficiently. Instead of reading 1 byte per interrupt, the MCU can read up to 16bytes in each interrupt. In cases where each incoming byte causes an interrupt, this reduces the overhead of the MCU in reading incoming words, insofar as stack stuffing and pipeline emptying are concerned. When using the FIFO, the MCU pays the same overhead for all the FIFO bytes, as it paid for only one byte without a FIFO.

The MCU handles actually the RFW-D100 by MAC protocol and application. The ATmega161L, developed by ATMEL Corp., is used as the MCU[9]. Table 2 shows the specification of the ATmega161L.

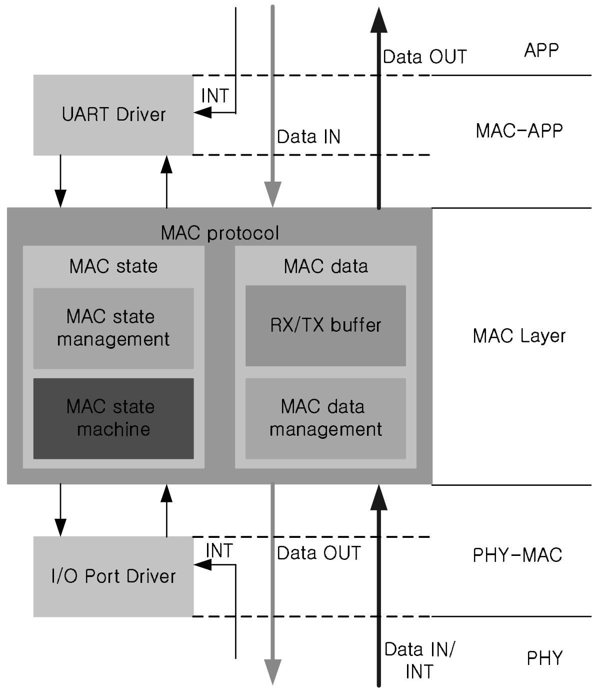

Fig. 4. The scheme of software configuration

In this study, the ATmega161L allows two external interrupts to be invoked by the RFW-D100. The state of MAC layer is changed by the interrupts invoked by the event of the RFW-D100. According to the change of the state, MAC layer executes particular functions, such as receiving, transmitting, error check, acknowledgement, and other handling of data.

3.3. MAC-APP layer

MAC-APP layer is the interface between MAC layer and APP(application) layer. In this study, the application layer is the control loop of each vehicle. The APP layer is connected to the programmable serial UART, which has one interrupt vector. Therefore, the interrupt invoked by the application layer also coordinates the state of MAC layer and the particular functions are achieved. In addition, the redundancy of internal SRAM is allocated for the receiving and transmitting buffer, which extends the FIFO in RFW-D100. Then, it becomes possible to transmit and receive longer size of data than FIFO in RFW- D100 continually.

4. Software Implementation

Fig. 4 illustrates the scheme of software configuration in this study. Software configuration is classified into three layers as follows:

- PHY-MAC layer
- MAC-APP layer
- MAC layer

The MAC layer is also divided into MAC state and MAC data. The general procedure of the MAC protocol is as follows:

1. The external interrupt invoked by the PHY layer or the UART interrupt invoked by the APP layer activates the

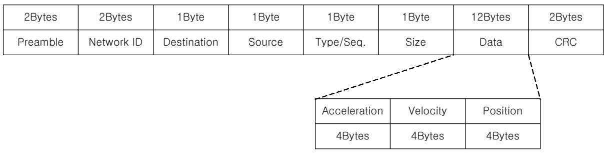

Fig. 5. The configuration of a data packet for vehicle to vehicle

MAC state management.
2. The MAC state management checks the status of the PHY layer or the APP and changes the MAC state in accordance with the result of that.
3. According to the newly changed MAC state, the MAC data management controls the data stream and the RX/TX buffer.
4. And then, in accordance with the result of the MAC data management, the MAC state management sets the new MAC state.

Two external interrupts of the MCU are allocated for the PHY layer and one UART interrupt is allocated for the APP layer. The transition of the MAC state is driven by these interrupts and the 8-bit timer controls the execution time. Therefore, the configuration of the protocol logic is improved effectively and the real-time execution is guaranteed. In addition, RX buffer and TX buffer in the MAC layer have 64bytes of SRAM, respectively, in order to avoid the constraint of the FIFO size in the RFW-D100.

4.1. Reliable protocol

In general, the communication is done by the exchange of the packet which is a set of data for efficiency and convenience. In this study, a packet, as shown Fig. 5, consists of the following fields:

- Preamble: to synchronize the receiver side
- Network ID: to filter a packet from other network
- Destination: Destination ID
- Source: source ID
- Type/Seq: Type of packet/Number of sequence
- Size: Size of the whole packet
- DATA: Actual data to transfer
- CRC: 16bit-CRC to check the validity of the packet

The data field includes the position, the velocity, the acceleration, for the transmission of each vehicle's data. For the command packet of the RCS, the data field includes the command of the RCS.

In this study, the ISM band RF transceiver is used. Since ISM band is a shared resource between many wireless applications such as IEEE 802.11 and Bluetooth, an overlap in time, frequency and space domain must occur and the network may experience interference from other network. Each of the standards such as IEEE 802.11 and Bluetooth uses a packet-oriented protocol and utilizes the shared channel only for fragments of time. A protocol for an ISM band application will have to use the time intervals for which the channel is free or relatively free (the interference is weaker) in order to transfer the required data. When a node wants to transmit, the node listens to the channel and checks if the channel is free. This is done by CS (Carrier Sense) mechanism supported by RFW-D100[8].

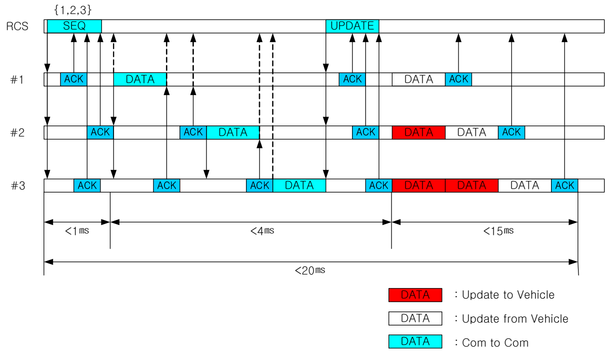

Fig. 6. The example of the protocol behavior

In order to make sure that a data packet arrives successfully at the destination (receiver), the source (transmitter) needs to get some verification from the receiver side within a certain fixed time. The transmitter will get this verification, by getting an acknowledge packet from the receiver side. If the transmitter does not get an acknowledge packet, the transmitter tries to retransmit the data packet.

4.2. Protocol behavior

For the static platoon control, since each vehicle dose not need the frequent update of the control input, the chance of the transmission of the data packet is allocated uniformly in each vehicle. For the dynamic platoon control, since the maneuvering vehicle for merge or split requires the frequent update of the control input, the more information should be transmitted to the maneuvering vehicle than others. This is the reason why the communication sequence is coordinated dynamically. The algorithm of finding the communication sequence was worked in Choi and Fang's work[5], [6]. The coordination of the communication sequence is achieved by the RCS.

Fig. 6 shows the example of the protocol behavior in one cycle between wireless communication systems of this study. The communication sequence is {#1, #2, #3}. The major feature is that the RCS broadcasts the communication sequence command packet and the data update command packet every one cycle. At first, the RCS broadcasts the communication sequence command packet. Then, each vehicle tries to transmit the data packet according to the communication sequence command. For the synchronization of the vehicle control, after last vehicle (the third vehicle in this study) transmits its data packet, the RCS broadcasts the data update command packet. The communication system of each vehicle which has received the data update command sends the received data of other vehicle to its vehicle and gets the new data from its vehicle. The interval of the exchange of the data packet and the acknowledgment is less than 1ms. In the phase of the development, since the transfer rate of UART is set to be 115.2Kbps, more time is exhausted than the communication among the wireless communication system. Since the sampling time of each vehicle is 40ms, the period of one cycle of the communication is less than 20ms and two cycles of the communication are exhausted within the sampling time of each vehicle.

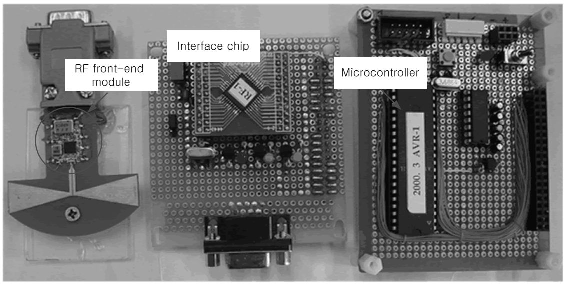

Fig. 7. The implemented communication system

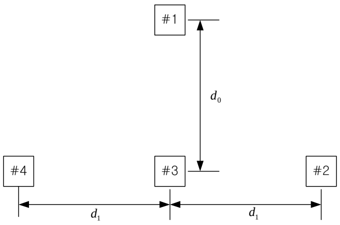

Fig. 8. The setup for the verification

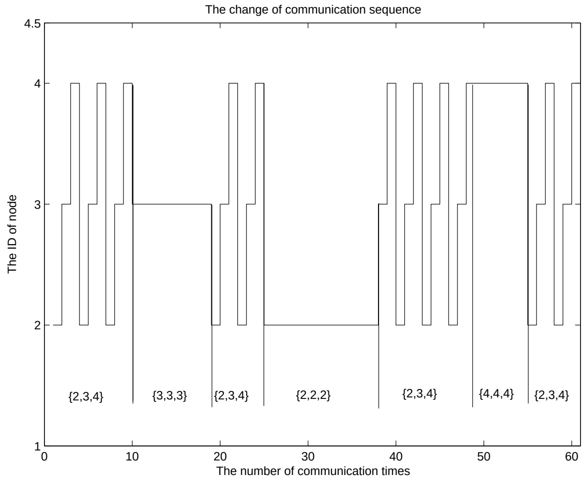

Fig. 9. The result for the sequence change command

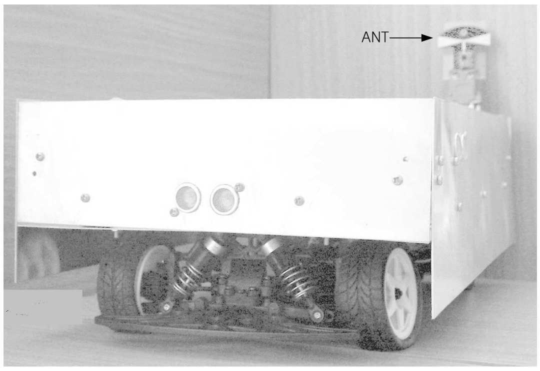

Fig. 10. One scale vehicle of the testbed

5. Experiments

5.1. Performance of protocol

Fig. 7 shows the wireless communication system implemented in this study. The wireless communication is installed in each scale vehicle and the RCS of a testbed.

Fig. 8 illustrates the setup for the verification of the performance of the wireless communication system. As d_0 or d_1, the 32bytes of packet is transmitted at each node in the fixed sequence. When d_0 is up to 30m and d_1 is up to 15m, the packet error is not detected in case of the fixed communication sequence. Since the size of a scale vehicle is 0.35m, the desired distance between two scale vehicles is less than 1.0m, the result is reasonable. In addition, for the command of the communication sequence change given at arbitrary time, it is verified for the communication sequence to be exactly changed. The result of the communication sequence change, as shown Fig. 9, is checked from the source field of the packet received in RCS. It shows that the communication sequence is changed without a error.

5.2. Longitudinal Control Experiment

Fig. 10 shows one scale vehicle of the testbed which is developed in the previous work[4]. Using Sheikholeslam's control algorithm[10], the experiment considers only the performance of the first following vehicle in a platoon. Because the alogrithm of the steering control has not yet been implemented, the experiment in this study uses an expedient: the scale vehicle is supported by a box-shaped block so that four wheels of the scale vehicle can rotate freely.

The available information is only the revolutions of the wheel. The controller of the following vehicle uses the position, the velocity, and the acceleration, which are estimated from the revolutions of the actuator. The desired spacing between two vehicle is assumed as 0.2m. Gains of the controller are determined from the simulation which uses parameters of the tesbed.

The velocities of two sacle vehicles are shown in Fig. 11. The velocity of the following vehicle tracks well the velocity of the lead vehicle. Fig. 12 shows the estimated spacing error between two scale vehicle. But these results under no load will be different from actual driving experiments under load. In Fig. 12, becasue of the computation error and the condition under no load, the estiamed spacing error increases cumulatively and is different from the simulation.

6. Concolusions

In this study, using the low-cost ISM band RF transceiver and the 8-bit microcontroller, the wireless communication system, which is suitable to the condition of experiments, is implemented and the performance has been verified by the help of experiments. Using the interrupts and the timer of the MCU, the real-time operation of the wireless communication system is guaranteed effectively.

Although some expedient experiments are achieved because of the absence of the steering control, experiments in this study are suitable enough to verify the performance of the wireless communication system for longitudinal platoon control experiments using a testbed. The longitudial control experiment has been acheived under no load, but parameters which are used are determined from the simulation under load. Therefore, the control algorithm should be improved through actual driving experiments after the steering contol is added. In addition, the command of the communication sequence change should be transmitted according to

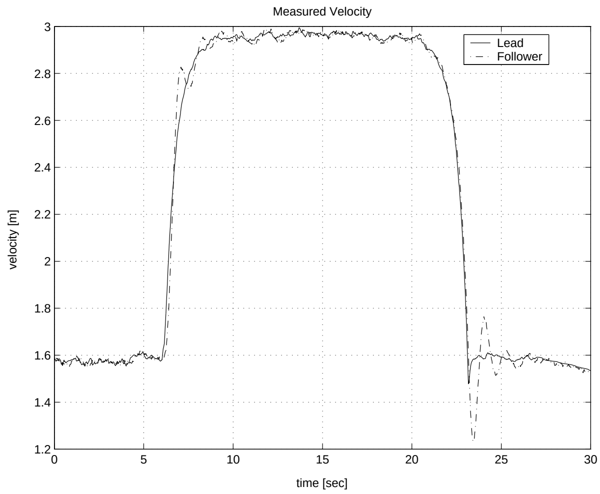

Fig. 11. The measured velocities

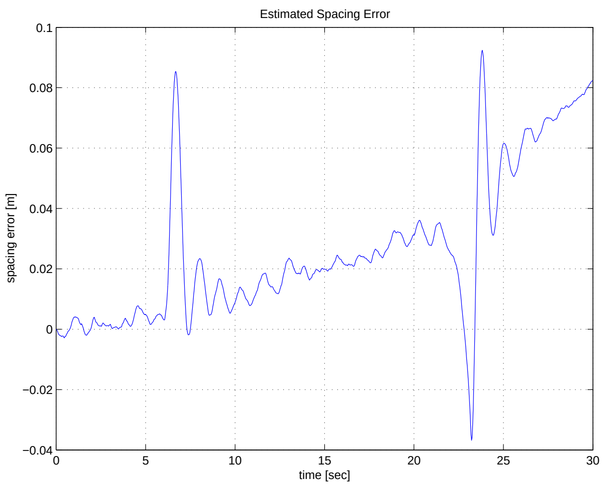

Fig. 12. The estimated spacing error

the status of the vehicles. Additional functions of the RCS to monitor the status of the vehicles remain as future works.

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