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Vehicular platooning experiments with racing slot cars

Dan Martinec and Michael Šebek and Zdeněk Hurák

Abstract— **The paper reports on an affordable platform for indoor experimental verification of algorithms for distributed control of platoons of vehicles. The platform is based on commercially available racing slot cars (by Carrera) equipped with an on-board 32-bit microcontroller-based control system. The assembled PCB board was provided by Freescale Semiconductor, Rožnov pod Radhoštěm, Czech Republic, within their Freescale Race Challenge 2012 competition of individual autonomous slot cars organized for student teams in Czech and Slovak republics. The documentation is freely available online. Some extra components such as an infrared range sensor and a wireless communication module have been added to the original system. The capabilities and potentials of the proposed platform are demonstrated on platooning experiments using two of the most popular platoon control schemes: predecessor following and leader following. Some technical parameters of the platform as well as design experience are shared in the report. It is hoped to encourage other teams to build a similar setup and possibly expose their new distributed control algorithms to an experimental competition.**

I. INTRODUCTION

The objective of the work presented in this paper was to build a cheap and friendly yet realistic platform for indoor experimental verification of advanced control and communication schemes in the domain of vehicular platooning.

The proposed platform is based on commercially available racing slotcars produced by Carrera and equipped by the authors with a specialized control system based to a large extent on the electronics provided kindly by Freescale Semiconductor, Rožnov pod Radhoštěm, Czech Republic. They provided a fully assembled PCB board (see Fig.1) within their *Freescale Race Challenge 2012* competition of individual autonomous slot cars organized for student teams in Czech and Slovak republics. The web page `http://hw.cz/FRC2012` contains not only the race information (unfortunately in Czech only) but also full documentation to the control unit (including standard datasheets in English). The same race has been organized in Romania too and their web page (shortened address) `http://goo.gl/WQkyP` reads English.

Some extra components such as an infrared range sensor and a wireless communication module have been added to the original system.

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D. Martinec is a graduate student at the Faculty of Electrical Engineering, Czech Technical University in Prague, 16627 Prague, Czech Republic `dan.martinec@fel.cvut.cz`.

Z. Hurák and M. Šebek are with the Department of Control Engineering, Faculty of Electrical Engineering, Czech Technical University in Prague, 16627 Prague, Czech Republic `hurak@fel.cvut.cz`, `michael.sebek@fel.cvut.cz`.

The capabilities and potentials of the proposed platform are demonstrated on platooning experiments using two of the most popular platoon control schemes: predecessor following and leader following. Some technical parameters of the platform as well as design experience are shared in the report. The motivation for writing this paper was to share the experience with the chosen technology and encourage other teams to go for the same experimenting and eventually organize some indoor vehicular platooning competition. Real-size competitions in this domain have already been organized, namely *Grand Cooperative Driving Challenge (GCDC)* (`http://www.gcdc.net`) organized by TNO for the first time in May 2011 in the Netherlands.

The work presented in this paper offers yet another experimentation platform in addition to the LEGO Mindstorms NXT vehicular platoons reported by the authors in [1]. An interested reader is also referred to that paper for some more general background in control in vehicular platoons including a richer list of references.

II. TECHNICAL DESCRIPTION

A. Carrera racing slot cars

The experimental platform is based on the the popular commercially available *Carrera Evolution* set. The sets in this series feature the tracks scaled at 1:24 and offer the total track length ranging from 4 m to 6 m, and two cars scaled at 1:32. The cost of the basic sets ranges between USD 150 and 200. Additional cars have been bought separately, each for about USD 50. In total, 5 cars were available for the experiments described in this report but platooning experiments with 10 cars are under way at the time of writing this report.

The particular type of a vehicle is *Ford Capri RS Tuner 3* shown in Fig.2. Since the controller printed circuit board (PCB) provided by Freescale Semiconductor (see below) turned out not to fit into the interior of the chosen car (the car dimensions are not readily available before buying), the plastic corpus of the car had to be adjusted (cut). This leaves the cars a bit ugly with holes on their sides. Certainly different (larger) cars could be bought, but we wanted to use the available cars already purchased. Alternatively, the layout of the PCB board could also be modified so that it fits into the chosen car, but with several assembled PCB boards available for free from Freescale Semiconductor, it was decided to... cut. When purchasing another type of a car, it may be useful to consider the shape of the front fender for easy attachment of the infrared proximity sensor.

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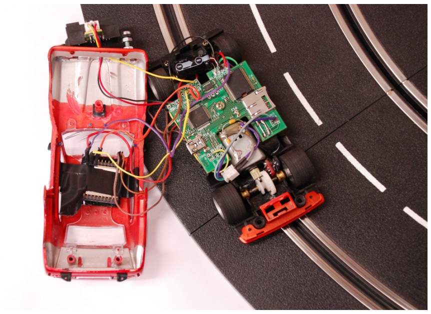

Fig. 1. Assembled PCB board provided by Freescale Semiconductor inserted into a car.

Fig. 2. Carrera Ford Capri RS Tuner 3 with a hole cut in the side revealing the controller PCB inside. IR proximity sensor attached to the front.

B. Electronic circuits

1) Block diagram: The PCB was designed by Freescale Semiconductor, Rožnov pod Radhoštěm, and is offered for free to the student teams participating in the Freescale Race Challenge competition where single autonomous cars compete in driving ten laps as fast as possible with the actual shape of the track unknown before the competition.

The basic block diagram is shown in Fig.3. A detailed documentation of the PCB is available at [2]. The PCB was used as a platform for additional electronic components such as a wireless communication module, a distance measurement sensor and velocity measurement sensor, see Fig.4.

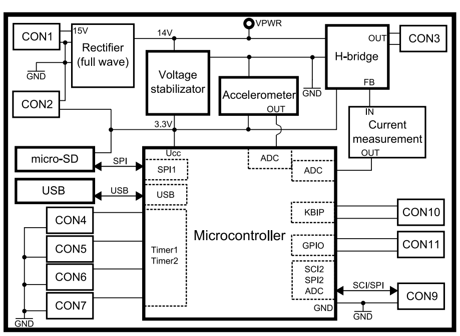

Fig. 3. Block scheme for the provided PCB.

2) Components list: Although the key focus of the research presented in this paper is on platoons, for convenience of readers we briefly describe here design issues related to a single car. The core of the car electronics is 64-pin 32-bit MCF51JM64 microcontroller from their *ColdFire* series, running at 3.3 V and 48 MHz with 64 KB Flash memory and 16 KB RAM. Another key component is MC33931 H-bridge operating at 14 V and 8 kHz. Additionally, two voltage regulators 7805 and LF33CV convert the rectified track voltage 14 V to 5 V and to 3.3 V, respectively. 3M Card Connector provides data logging to a microSD card. This is for the basic equipment as provided by Freescale Semiconductor. The extra hardware added to obtain velocity measurement, distance measurement and wireless communication is enumerated and described in the dedicated sections below.

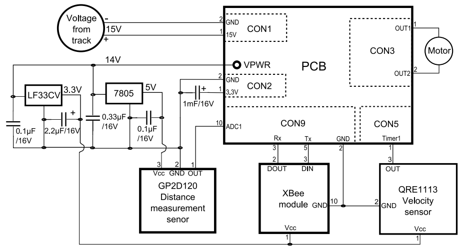

Fig. 4. Scheme with some additional electronic components.

The microcontroller's own 12-bit A/D converters operate at 3.3 V. Voltage (in Volts) measured by the A/D converters in the microcontroller is calculated with $U = \frac{3.3 \cdot N}{2^{12}}$, where N is an integer number returned from the A/D converter. A single-polarity voltage can only be measured.

C. Acceleration measurement

The accelerations in three axes are measured by MMA7361L accelerometer with the output connected to the A/D converter of the microcontroller. This analog accelerometer can be set to high sensitivity mode with s_{high}=800 mV/g or low sensitivity s_{low}=200 mV/g. The high sensitivity was selected for the experiments. The measured acceleration is calculated as $\alpha = 10^3 \cdot \frac{U_{\mathrm{acc}} \cdot g}{s_{\mathrm{high}}} = 9.8795 \cdot N_{\mathrm{acc}}$, where α is in mm/s^2 and U_{acc} is voltage is in Volts and was measured by the A/D converter.

D. Motor current measurement

The motor current is measured with the frequency of 8 kHz on the feedback pin of the H-bridge supplying it with 0.24% of the actual motor current. The current in mA is given by $I = 10^4 \frac{100}{0.24} \frac{U_{\mathrm{IR}}}{R_{\mathrm{IR}}} = 12.413 \cdot N_{\mathrm{IR}}$. The voltage is in Volts and resistance in Ohms. The pin is connected to the analog low-pass RC filter with a bandwidth $f_{\mathrm{bw}} = 590$ Hz which filters the disturbances caused by PWM switching frequency. The resistor with $R_{\mathrm{IR}} = 270\,\Omega$ then converts the current to the voltage U_{IR} measured by the A/D converter of the controller.

An interesting phenomenon appears in the measurement of the motor current. Periodic switching of the rotor poles on the commutator causes oscillations of the current signal. Although these oscillations do not significantly affect car velocity, they can be used to measure the angular rate as suggested in Fig.5, where twelve peaks correspond to one rotation of the motor, i.e. one-third of wheel rotation.

E. Velocity measurement

The chosen car offers a direct access to the drive shaft making it easy to install a velocity sensor to a shaft vicinity.

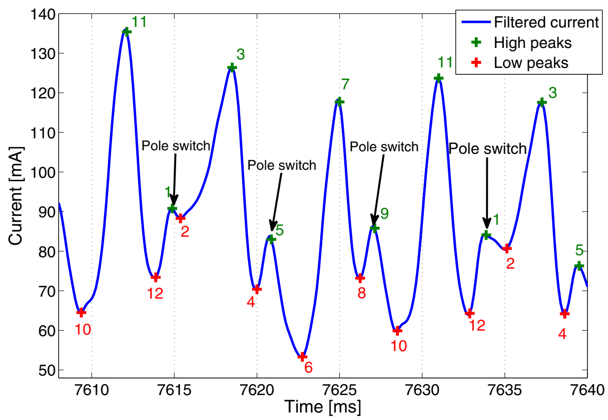

Fig. 5. Periodicity in the filtered current.

The velocity is then measured using an IR reflectance sensor QRE1113 from Fairchild Semiconductor (bought from Sparkfun). The sensor is oriented against a small piece of paper patterned with black and white stripes. This way a simple low resolution rotary encoder was built. The output of the sensor is connected to the Input capture pin of the processors timer making it possible to detect the black-white threshold and to measure the time from the previous threshold detection. There are 4 black and 4 white stripes on the paper, the wheel radius is r=10 mm and the timer runs at the frequency $f_{\text{input capture}}$=3 MHz. The car velocity in mm/s is then

$$v = \frac{2\pi r f_{\text{input capture}}}{8C_n} \approx \frac{23.56 \times 10^6}{C_n}, \quad (1)$$

where C_n is the number of pulses in the timer value. The implemented rate limiter limits the maximum velocity change from the previous measurement to 200 ms. This precaution minimizes velocity measurement errors. Additionally, the velocity is smoothed with a 8-sample moving average filter.

A classical disadvantage of an incremental sensor like this is that its sampling frequency depends on the velocity of the car. The slower the car, the longer the intervals between two pulses arrivals. Assuming the average car velocity of 800 mm/s, the interval between measurements is 9.8 ms.

F. Distance measurement

The distance to the vehicle ahead is measured by the analog infrared Sharp GP2D120 with the measurement range from 5 cm up to 50 cm. The sensor output is connected to the A/D converter of the processor. The measured distance in mm is calculated from voltage as $d = 133/U$, where the measured voltage U is in Volts.

G. Wireless communication

1) Wireless module: The communication between the leader car and the operator, and also among the vehicles is realized by the XBee 802.15.4 OEM RF module from DIGI operating at $3.3\,V$ in the packetized API mode. The structure of the typical XBee packet is in Fig.6 and a more detailed documentation is available at the Digi webpage.

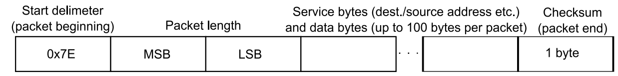

Fig. 6. Structure of the XBee packet.

A packetized communication has several advantages. It contains the packet length, the source address and the packet identifier (used to determine the purpose of the packet). Moreover, the module retries to send the packet if the receiver does not acknowledge reception.

There are two possibilities how to communicate between the cars, either using one-to-one or one-to-all (broadcast) communication. The former way was chosen since the experiment is supposed to simulate conditions where the broadcast communication is not possible (e.g. due to large distances between cars).

2) Wireless configuration: The module is designed to communicate with the processor via the UART serial interface. A converter such as XBee Explorer USB is required to enable the connection between the wireless module and a computer USB port. This device allows an easy configuration of the XBee module.

There are a few configuration settings that have to be in place before the first use of the module. Those are a) a module address which has to be unique for all modules, b) the modules Interface Data Rate and the processors SCI Baud rate have to set to the same value of communication speed, c) API option has to be enabled. Besides of these settings there are several others that keep communication more secure.

H. Programming of the car

The code for the car's onboard microcontroller is created in the C language. In particular, CodeWarrior Development Studio for Microcontrollers v6.3 from Freescale was used. A template for a project is available at [2]. Uploading a compiled code to the microcontroller is via the USB.

III. CONTROL OF A SINGLE CAR

A. Model of dynamics of a single car

Due to spatial constraints, the mathematical model of a single car is not detailed here. One-dimensional translational dynamics is modeled although the cars travel on a curved track. Most parameters of the model can be obtained by direct measurement. Useful guidance on parameters of the motors can be found at `http://slotcarnews.blogspot.com/2007/02/slot-car-news-motor-list.html`.

B. Controller structure of a single car

A cascade controller structure as in Fig.7 was used for controlling a single car. There are three loops: current, velocity and distance, each using a PI controller. The Bode characteristics of all three closed loops with PI controllers are in Fig.8. Closed-loop velocity transfer function of the car is $T_{v_{ref} \to v} = \frac{27.5}{s+27.5}$.

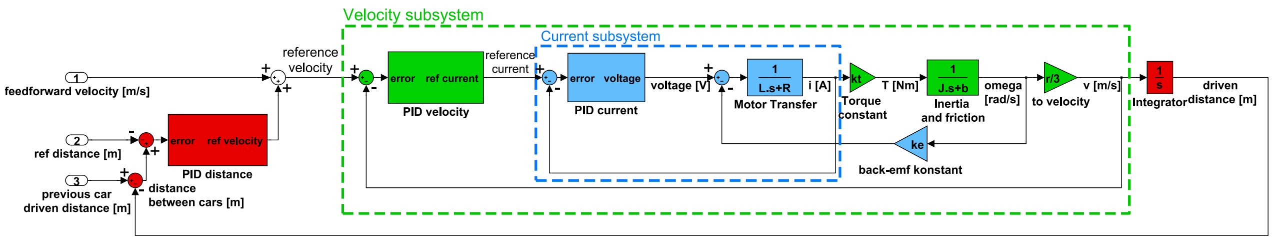

Fig. 7. Cascade structure of the feedback controllers: current, velocity, position/distance.

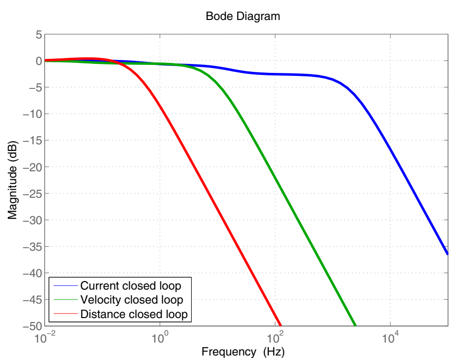

Fig. 8. Bode characteristics of the three complementary sensitivity functions for the current, velocity and distance loops.

IV. CONTROL OF THE PLATOON

A. Model of dynamics of the platoon

One approach for modeling a platoon is the state-space paradigm

$$\frac{d}{dt}\begin{bmatrix} x_0 \\ v_0 \\ \vdots \\ x_4 \\ v_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & & & \\ 0 & -q & & & \\ & & \ddots & & \\ & & & 0 & 1 \\ & & & 0 & -q \end{bmatrix} \begin{bmatrix} x_0 \\ v_0 \\ \vdots \\ x_4 \\ v_4 \end{bmatrix} + \begin{bmatrix} 0 & & \\ p & & \\ & \ddots & \\ & & 0 \\ & & p \end{bmatrix} \begin{bmatrix} v_{ref_0} \\ \vdots \\ v_{ref_4} \end{bmatrix}, \tag{2}$$

where x_n and v_n are the position and velocity of the n-th vehicle, respectively, and index $n = 0$ denotes the platoon leader. Another possibility is to use a joint Laplace and z-transform, which is described in detail and accompanied by references in [3]. The complex variable z represents a shift of the vehicle index in the platoon. Therefore $\mathcal{LZ}$ transforms 2-D signal $x(t,k)$ into $\hat{x}(s,z)$ and shifted (i.e. the next vehicle) signal $x(t,k+1)$ into $z\hat{x}(s,z)$. Using this formalism, the distance between vehicles is described as

$$\hat{d}(s,z) = \hat{x}(s,z)(z^{-1} - 1). \tag{3}$$

Then, the transfer function from the vehicle velocity to the distance between vehicles is

$$G_v(s,z) = \frac{\hat{d}(s,z)}{\hat{v}(s,z)} = T_{\text{vel}}\frac{(z^{-1} - 1)}{s}, \tag{4}$$

where T_{vel} is the complementary sensitivity function for the velocity loop. That is, transfer function from the reference velocity to true (measured velocity).

B. Distributed control of the platoon

A regulation error for a distance controller uses the regulation error defined as

$$e(t,k) = x(t,k) - x_{\text{ref}}. \tag{5}$$

1) Predecessor following algorithm: The *Predecessor following* algorithm regulates a distance to the previous vehicle. The input to the distance controller is described (after $\mathcal{LZ}$ transform) as

$$\hat{e}(s,z) = \hat{d}(s,z) - d_{\text{ref}} = \hat{x}(s,z)(z^{-1} - 1) - d_{ref}, \tag{6}$$

where d_{ref} represents the reference (desired) distances between vehicles. Incorporation of this algorithm into a full cascade structure is depicted in Fig.7.

2) Leader following algorithm: The *Leader following* algorithm works similarly. The difference is that each vehicle regulates its own distance to the platoon leader. Therefore each vehicle requires information about its position in the platoon as well as the distance to the leader of the platoon. Distances to other previous vehicles do not affect an outcome of the algorithm. However, the vehicles in the platoon have to cooperate to deliver a measurement of a distance to the leader to every vehicle. In particular, each vehicle (except for the first one just behind the leader) repeats three steps:

- Receive information about the distance to the leader from the predecessor.
- Increase this value by the measured distance to the predecessor.
- Send this information to the next vehicle.

Since identical vehicles are used in the experiment, the vehicle length is not taken into consideration. The input to the distance controller is

$$e(s,z) = \hat{x}(s,z)(z^{-n} - 1) - nd_{\text{ref}}, \tag{7}$$

where d_{ref} represents the reference distances between vehicles and n is the index of the vehicle in the platoon (e.g. $n = 1$ for the first vehicle behind the leader).

V. SIMULATIONS AND EXPERIMENTS

In the experiment described in this report, cars travel on a circular track with a diameter of 80 cm (R1 in Carrera's notation) built from the basic *Carrera Evolution Set*. The motivation for building a purely circular track was to avoid problems with varying diameters of turnings, which acts as a disturbance to the vehicle control system. Of course, a diameter this small makes the curvature of the track rather high. At the time of writing the report, some extra parts were bough which enable building a circular track of a diameter about 3 m.

Two typical situations were simulated for both control strategies: (i) the reference distance (d_{ref}) is changed for all vehicles via wireless communication, (ii) the reference velocity of the platoon leader ($v_{0_{\text{ref}}}$) is changed without notifying other cars.

A. Predecessor following algorithm (PFA)

Fig.9 shows a change of inter-vehicle distances after receiving a command to get closer to or further from its predecessor. Fig.10 demonstrates that cars located towards the tail of the platoon travel a longer time at a higher velocity. This is a typical phenomenon of the vehicular platooning demonstrating a spatial (not temporal) instability.

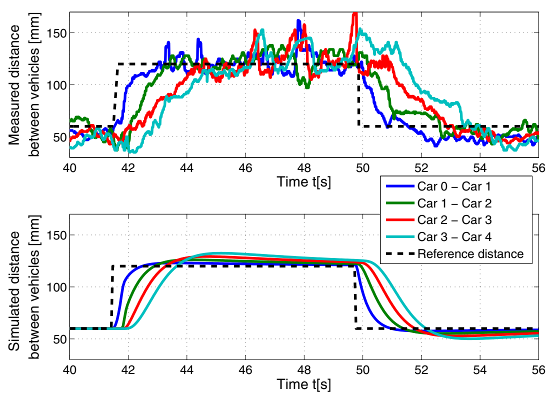

Fig. 9. Inter-vehicle distances in response to the changes in d_{ref} for PFA.

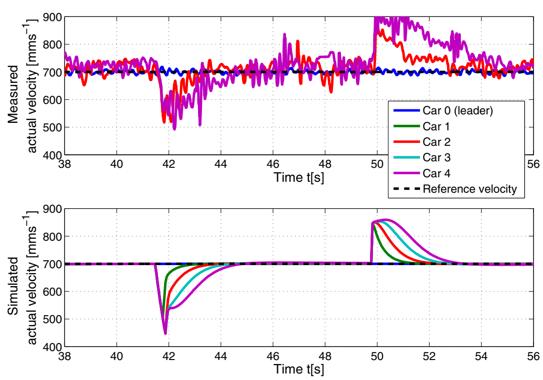

Fig. 10. Velocities of cars in response to changes in d_{ref} for PFA.

The response to the change in the platoon leader velocity is in Fig.11 and Fig.12. They show similar behavior as in d_{ref} change scenario.

B. Leader following algorithm (LFA)

The same experiments and simulations as for PFA were carried out for LFA.

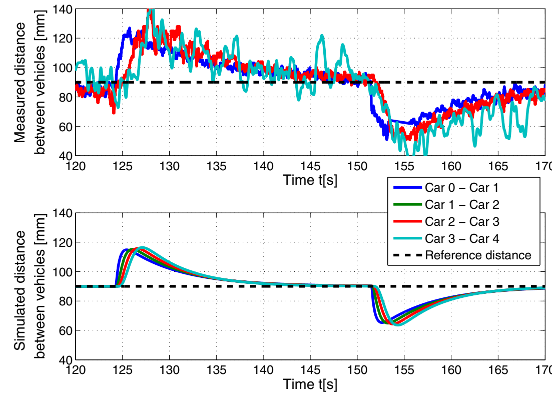

Fig. 11. Inter-car distances in response to $v_{0_{\text{ref}}}$ change for the PFA.

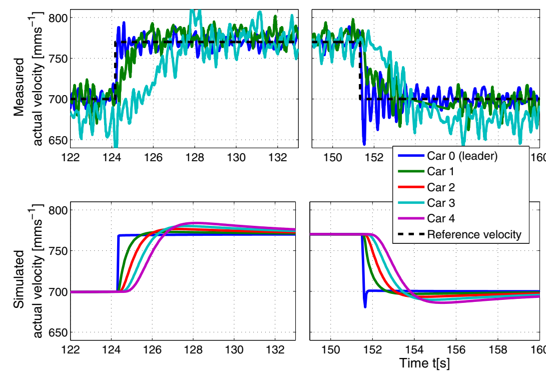

Fig. 12. Velocities of cars in response to the change in $v_{0_{\text{ref}}}$ for the PFA.

Fig. 14 and 15 in comparison with Fig. 9 and 10 show that the reaction of the cars is faster for the Leader following algorithm making the velocity peaks higher but regulating the inter-car distances faster.

Fig.16 shows that in the case of a leader accelerating/decelerating the only changing inter-vehicle distance is the one between the leader and the first follower. The reason for that is explained in Fig.17. All the following cars change their velocities in the same manner, keeping the distances between followers.

VI. SUGGESTIONS FOR IMPROVEMENTS

The major drawback of the platform is a limited measurement range for the distance detection due to small radius of the circular track. At the distance about 15 cm the car gets out of the field of view of the sensor. This limits the operational distance from 5 cm to 15 cm. An immediate solution (already taken but not documented here) is to buy a track with a larger radius. A track with a radius up to 100 cm (R4 in Carrera's notation) is available on market.

A related trouble with the distance sensor is the ambiguity of the output when the measured object is out of the acceptable range. If the object is closer than 5 cm, its false output is the same as for much more distant objects. A

Fig. 13. Platoon of Carrera slotcars speeding on a circular track.

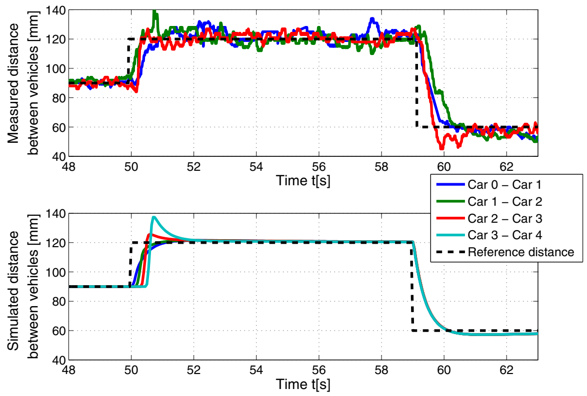

Fig. 14. Inter-car distances in response to the changes in d_{ref} for LFA.

possible solution is to limit the increment of the measured distance between each measurement.

Both can be alleviated with the help of the wireless communication. Each car would periodically send its measured velocity to the next car making it possible to calculate an inter-vehicular distance increment. This would call for some kind of distributed estimation scheme, possibly fusing with the onboard velocity sensors.

Yet another minor inconvenience is caused the PCB not fitting into the car. It required a substantial modifications to the car. Replacement of the Ford Capri RS Tuner 3 by a larger car of the same scale is recommended to anyone who starts from the scratch.

VII. Acknowledgements

Thanks go to M. Brejl from Freescale Semiconductor, Rožnov pod Radhoštěm, Czech Republic, for donation of assembled PCBs. Contribution of other two graduate students — Jaroslav Marek and Karel Němec — is acknowledged.

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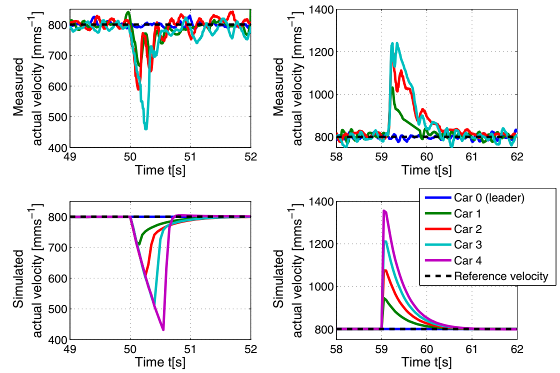

Fig. 15. Velocities of cars in response to the changes in d_{ref} for LFA.

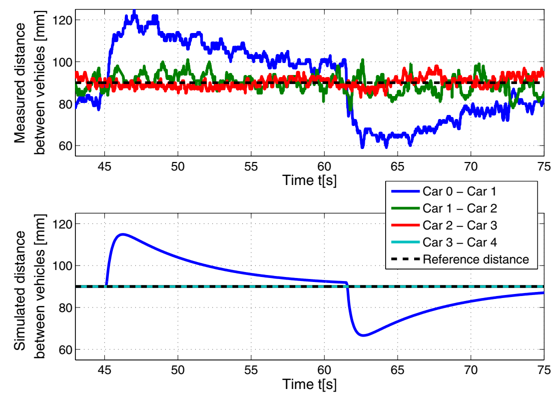

Fig. 16. Inter-car distances in response to the change in $v_{0_{\text{ref}}}$ for LFA.

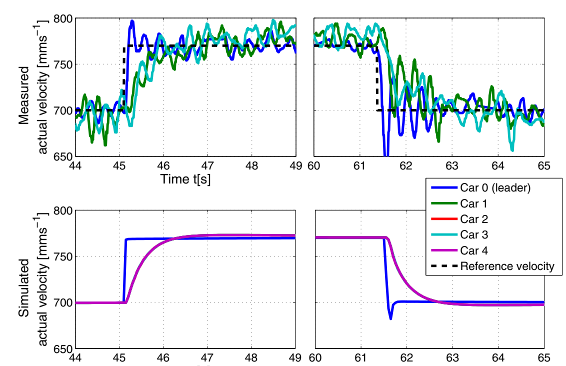

Fig. 17. Velocities of cars in response to the change in $v_{0_{\text{ref}}}$ for LFA.