Journal of Power Sources 186 (2009) 478–484

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Short communication

Bluetooth wireless monitoring, diagnosis and calibration interface for control system of fuel cell bus in Olympic demonstration

Jianfeng Hua, Xinfan Lin, Liangfei Xu, Jianqiu Li, Minggao Ouyang*

Tsinghua University, State Key Laboratory of Automotive Safety and Energy, Beijing100084, China

ARTICLE INFO

Article history:
Received 18 August 2008
Received in revised form 1 October 2008
Accepted 2 October 2008
Available online 17 October 2008

Keywords:
Fuel cell bus
Bluetooth
Universal data interface
Control system
Wireless calibration and monitoring
In-system programming

ABSTRACT

With the worldwide deterioration of the natural environment and the fossil fuel crisis, the possible commercialization of fuel cell vehicles has become a hot topic. In July 2008, Beijing started a clean public transportation plan for the 29th Olympic games. Three fuel cell city buses and 497 other low-emission vehicles are now serving the Olympic core area and Beijing urban areas. The fuel cell buses will operate along a fixed bus line for 1 year as a public demonstration of green energy vehicles. Due to the specialized nature of fuel cell engines and electrified power-train systems, measurement, monitoring and calibration devices are indispensable. Based on the latest Bluetooth wireless technology, a novel Bluetooth universal data interface was developed for the control system of the fuel cell city bus. On this platform, a series of wireless portable control auxiliary systems have been implemented, including wireless calibration, a monitoring system and an in-system programming platform, all of which are ensuring normal operation of the fuel cell buses used in the demonstration.

1. Introduction

Against the background of the increasingly serious global energy crisis and environmental problems, governments and enterprises around the world have paid more attention to the development of green energy. The fuel cell city bus has become a favorite among new energy vehicles due to its being free of emissions, its high energy conversion efficiency and its long driving endurance. Proton exchange membrane fuel cells (PEMFC) feature simple compact stacks without complex requirements with respect to fuel, oxidant and coolant supplies. PEMFCs deliver high power density and offer the advantages of low weight and volume, compared with other fuel cells. PEMFCs operate at relatively low temperatures—around 80 °C. Low temperature operation allows them to start quickly and results in less wear on system components and better durability. Therefore, PEMFCs are one of the most popular fuel cell types for automotive applications [1].

In the last decade a variety of demonstration vehicles have been developed by the major car manufactures. Ford, GM. Toyota Nissan Honda and many others have made considerable progress toward mass production of fuel cell cars in the near future [2].

The State Key Lab of Automotive Safety and Energy at Tsinghua University initiated research on the fuel cell vehicle as early as 2002, mainly focusing on commercial vehicles. With the support of the China National 863 Hi-tech Research Program, the first Chinese fuel cell city bus was developed in 2004 by Tsinghua University and its partners. It is a hybrid vehicle combining a PEMFC as its main source power and a battery as the auxiliary power unit. To date, a fleet of fuel cell buses has been developed in sequence [3].

In July 2008, three fuel cell city buses using third generation technology began operating as part of a 1-year-long Olympic demonstration in Beijing. The buses were produced cooperatively by Tsinghua University and its partner, the commercial vehicle manufacturer Foton Motors. Theses buses serve an ordinary bus line around north-west Beijing and operate 5 days a week. During the Beijing 2008 Olympic and Paralympic Games, the buses served the marathon races as a pick-up vehicle, providing a pure zero-emission environment for athletes. The vehicles are shown in Fig. 1.

The buses are equipped with dual 40 kW rated fuel cell stacks and a special electrified power train system. The power train is controlled and monitored by a distributed control system, which consists of fuel cell engine management system (MS), electric motor

Abbreviations: BDM, background debug mode; CAN, control area network; CRC, cyclic redundancy check; DCS, diagnosis center service; ECU, electronic control unit; EDR, enhanced data rate; EEPROM, electrically erasable programmable read-only memory; EMC, electro magnetic compatibility; GPRS, general packet radio service; ISP, in-system programming; J2ME, Java 2nd micro edition; MS, management system; PC, personal computer; PDA, personal digital assistant; PEMFC, proton exchange membrane fuel cell; RAM, random access memory; SCI, serial communication interface; SoC, state of charge; SPI, serial peripheral interface; VCU, vehicle control unit.

* Corresponding author. Tel.: +86 10 62785706; fax: +86 10 62785708.
E-mail address: ouymg@tsinghua.edu.cn (M. Ouyang).

0378-7753/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2008.10.013

Fig. 1. Fuel cell vehicles at the Beijing 2008 Olympic games.

MS, DC–DC MS, power-battery MS and hydrogen supply MS. Different types of microprocessors are embedded into each control node according to the complexity of control tasks, enabling nodes to manage their own components and system independently. These control sub-systems are connected by control area networks (CAN) bus and centrally governed by a Vehicle Control Unit (VCU), as shown in Fig. 2.

Due to the complexity of the power train configuration, and the potential dangers in hydrogen systems some working parameters are important when it comes to diagnosis and safety. Calibration and an in-system programming (ISP) interface are also necessary for control system optimization during road tests. Normally, a solution is achieved by the CAN bus interface [7] because all significant data supervised by each sub-control node can be gathered in this way. For the Beijing public demonstration, however, the CAN-based solution is inconvenient for the following reasons:

(1) The placement of monitoring devices is restricted into a limited bound because the connection must be created through a twisted-pair cable to in-vehicle CAN networks. During the public demonstration, all internal development interfaces have to be removed for security reasons.

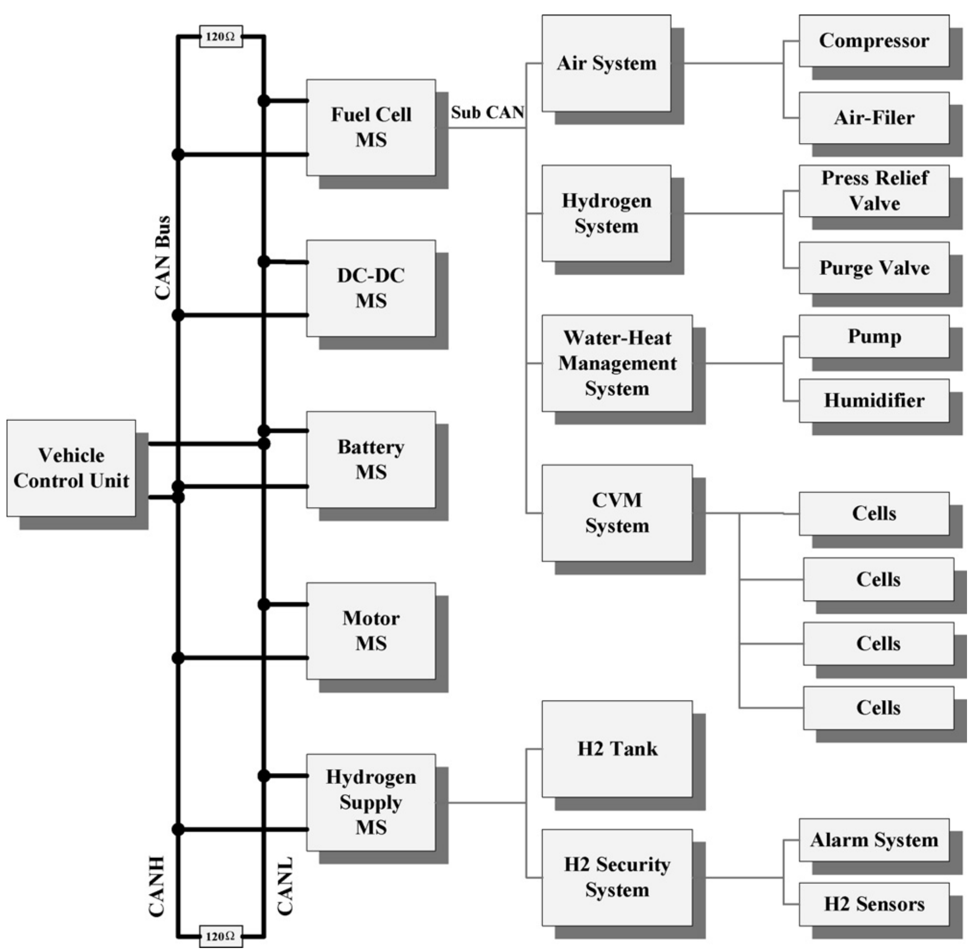

Fig. 2. Power train control system configuration of the fuel cell city bus.

Table 1
Bluetooth transmission data rate [5].

Version	Data rate
Version 1.2	723 Kbps
Version 2.0 + EDR	3 Mbps
WiMedia Alliance (proposed)	53–480 Mbps

(2) For monitoring via CAN bus, a PC or laptop is necessary because almost all of the CAN interface applications run only on Windows or Linux platforms. It is very inconvenient to setup a PC environment inside a vehicle during road tests.
(3) Remote monitoring and diagnosis is difficult due to the lack of common network for PCs or laptops in most urban and suburb area.

Based on the latest Bluetooth wireless technology, a novel Bluetooth universal data interface was developed for the control system of the fuel cell city bus.

2. Bluetooth universal data interface

Bluetooth is a universal short-range low-power radio protocol operating in the unlicensed industrial, automotive, scientific, and medical frequency band. Bluetooth technology was designed primarily to support simple wireless networking of personal consumer devices and peripherals, including cell phones, PDAs and laptops. Wireless signals transmitted with Bluetooth cover short distances, typically up to 10 m for Bluetooth class 2 and 100 m for Bluetooth class 1. It allows both data and voice connections, with a nominal maximum data of 723 kbps by Bluetooth 1.2 version and 3 Mbps by Bluetooth 2.0 + enhanced data rate (EDR version), as shown in Table 1. The modulation for Bluetooth technique is Gaussian frequency-shift keying, with transmission at a rate of 1 M symbol/s on one of 79 channels with 1 MHz spacing in the 2.402–2.480 GHz band. Bluetooth uses a spread-spectrum frequency hopping connection with a rate of 1600 hops s^{-1} and its radio transceivers are categorized in three power classes, as shown in Table 2 [4].

The Bluetooth universal data interface is implemented with a mature Bluetooth 2.0 + EDR module. The system structure is shown in Fig. 3. All significant data from the vehicle, such as fuel cell output voltage and current, minimal cell voltage, hydrogen pressure, motor speed, state of charge (SoC) of the power battery, working state of each device, and error code, can be measured by each distributed control sub-system and gathered to the VCU via CAN bus.

Table 2
Bluetooth communication coverage [5].

Class	Maximum permitted power	Range (approximate)
Class 1	100 mW (200 dBm)	~100 m
Class 2	2.5 mW (4 dBm)	~10 m
Class 3	1 mW (0 dBm)	~1 m

As a gateway between CAN and Bluetooth networks, VCU transmits the data over a secure Bluetooth connection according to the predefined protocol. Any Bluetooth device, such as a cell phone, can communicate with VCU through the Bluetooth interface. The data can, for example, be monitored in real-time with a J2ME application running on a smart cell phone. The data exchange between the cell phone and VCU is highly secure given the guarantee of the Bluetooth pairing and authentication mechanism.

Researchers can obtain vehicle information easily with either a PC or a laptop with standard Bluetooth interface. The physical signal is transmitted and received through an antenna outside the VCU metal case, as shown in Fig. 4. In the Beijing trial, a series of Bluetooth universal data interface-based wireless calibration, monitoring and control applications working on different platforms was successfully developed.

3. Bluetooth-based calibration platform with on-line monitoring

Operational data monitoring and control parameter calibration constitute a major part of the work involved in implementing

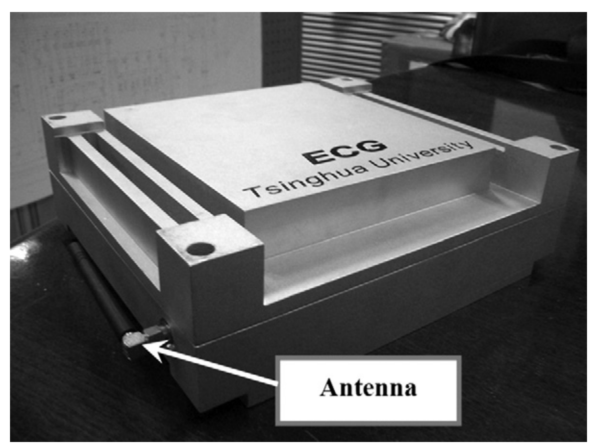

Fig. 4. The VCU of the fuel cell city bus with antenna.

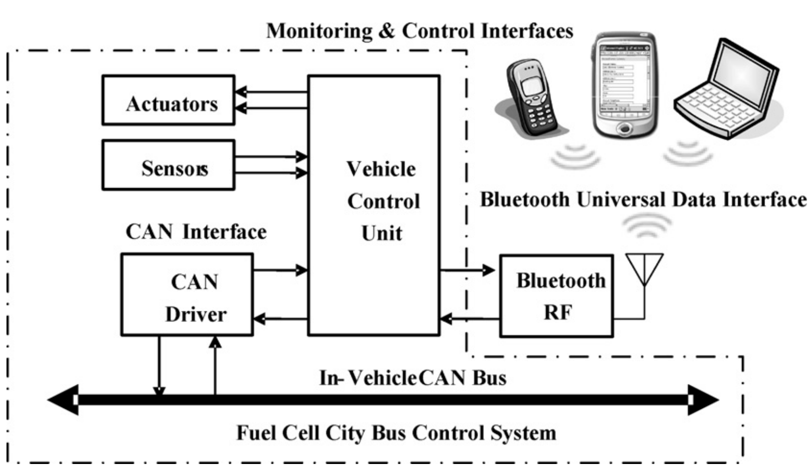

Fig. 3. Bluetooth universal data interface system structure.

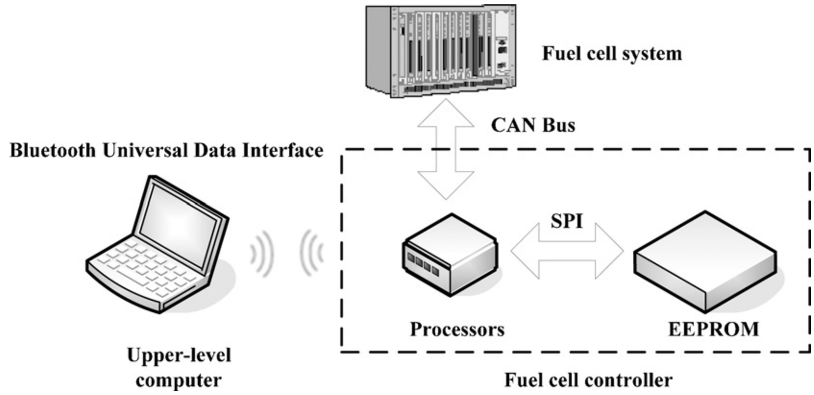

Fig. 5. Bluetooth-based calibration system for the fuel cell city bus.

an automotive power train control system, especially in the early stages of development. In fuel cell bus applications, on-line calibration and monitoring is desirable because repetitive start-ups and shutdowns of the fuel cell in off-line parameter tuning experiments can be inefficient. They can also shorten the life of the fuel cell system. Therefore, an on-line calibration and monitoring platform based on instant parameter modification interface and non-volatile data record and access mechanism is implemented in the fuel cell control system.

The calibration and monitoring platform is composed of three major components: an upper-level computer, the fuel cell system controller and non-volatile memory media, as shown in Fig. 5.

The upper-level computer provides a visual parameter access and modification interface based on Freescale FreeMaster (Freescale Inc., USA), a real-time monitor, control panel and demonstration software. The upper-level computer acquires real-time data from the fuel cell controller through a Bluetooth universal data interface and users are capable of modifying all operation parameters on computer and having them transferred back to the fuel cell controller to achieve on-line calibration. It is worth noting that the CAN calibration package widely used in automotive engine calibration was not adopted here because the volume of parameters in fuel cell systems is not as large as that in engine systems. Therefore, a Bluetooth-based solution was preferred for simplicity and convenience. The fuel cell controller exchanges measurement signals and control instructions with the fuel cell system through the CAN network to perform control and monitoring. In order to retain parameter values after calibration, non-volatile memory media electrically erasable programmable read-only memory (EEPROM) is applied to store data in power-off conditions. This can be programmed to read and write data by fuel cell controller through serial peripheral interface (SPI). Human–computer interface of the platform is shown in Fig. 6.

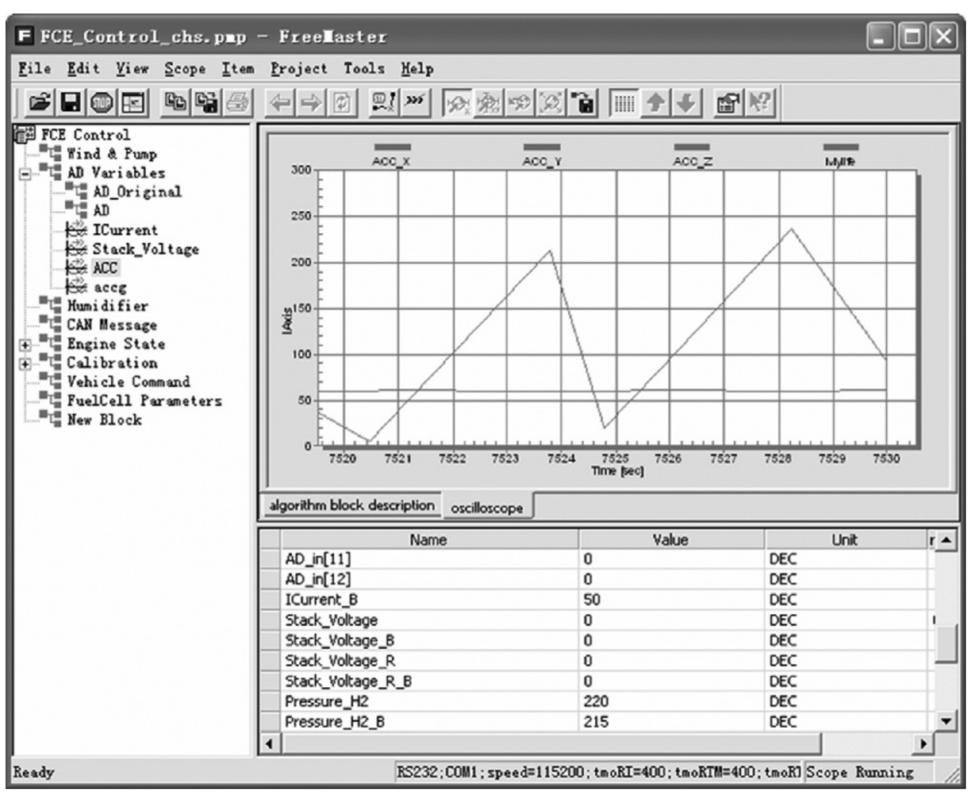

Fig. 6. Human–machine interface of the calibration system.

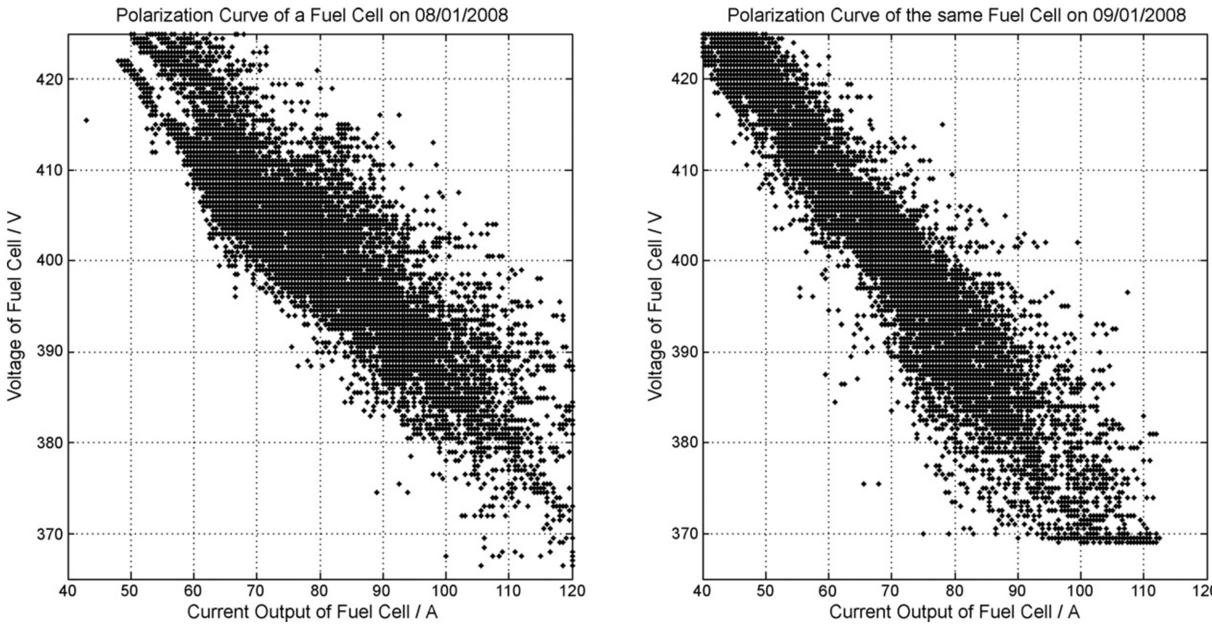

Fig. 7. Fuel cell performance degradation during the Olympic games.

The platform software consists of two main parts: the Bluetooth-based tool-kit FreeMaster and the embedded EEPROM data access program in fuel cell controller.

FreeMaster is a real-time monitor, control panel and demonstration software based on serial communication interface (SCI). It was developed by Freescale as a support tool for the embedded electronic control system implementation of Freescale series microcontrollers. FreeMaster provides both a graphical data display and modification interface at computer level and an embedded memory access and SCI transfer drivers kit at microcontroller level. The SCI of FreeMaster is compatible with the Bluetooth universal data interface. None of original code should need to be modified to work along with the Bluetooth universal data interface. During the coding process of software on Codewarrior (Metrowerks Inc., Germany), the integrated software development environment for Freescale microcontrollers, users should include relevant functions of the FreeMaster embedded variable access and SCI transfer drivers kit. These take care of variable reading and writing as well as data packaging and device settings for communication with the user's interface on computer through the Bluetooth universal data interface. On completion of coding, an *.elf file will be generated by Codewarrior as a symbol list for each software project, in which all the variables are labeled with their locations in the internal memory of the microcontroller. By decoding this *.elf file, FreeMaster automatically associates each variable on the computer user's interface with its counterpart in microcontrollers. This means that during the whole process of calibration and monitoring the fuel cell controller retrieves measurement signals from fuel cell system and transfers them to up-level computer along with control parameters to display on graphical interface for monitoring. At the same time, users perform control parameters tuning on upper-level computer and sends them back to the fuel cell controller for controlling. At the same time, users modify constant control parameters on the upper-level computer and send them back to the fuel cell controller.

As mentioned, non-volatile memory media are indispensable when it comes to storing calibrated parameters in power-off conditions in the middle of, and after, calibration experiments. EEPROM is preferred here for convenient data access and automotive-compliant performance. Since the speed of accessing EEPROM is considerably slower than that of control algorithm execution, it is more practical that parameters for calibration should be read from EEPROM for their latest value all at once before every calibration experiment and be written into EEPROM in the same way afterwards. In order to facilitate the process of large-scale parameter accessing, parameter variables are managed so that they are allocated in a successive area of internal memory in the microcontroller. They are also assigned with successive memory area in EEPROM. Consequently, every time parameters are updated between EEPROM and a microcontroller, a simple C loop structure should be applied to achieve mass memory copy. A symbol variable defined as the first parameter variable is introduced so that before each data access, the absolute address of the symbol variable can be acquired first to locate the absolute memory region for parameter variables and thus ensure the accuracy of memory copy between EEPROM and the microcontroller.

Fig. 7 is a record data example of the system. It shows fuel cell degradation [9] of one bus during more than 2000 km on-road operation during the Olympic Games. Under the small and high current condition, degradation is more pronounced.

4. Wireless in-system programming establishment

In-system programming (ISP) is the ability on the part of some programmable logic devices, microcontrollers, and other programmable electronic chips to be programmed while installed in a complete system, rather than requiring the chip to be programmed prior to installing it into the system. A large number of ISP devices are implemented with bootloader mechanism. Embedded systems, especially in automotive applications rely heavily on Flash Bootloaders to ensure that the Electronic Control Unit (ECU) is programmable either in production or in service. A Flash Bootloader resides in Flash memory, and is always the first code segment to run after a reset. The Flash Bootloader decides whether an application is ready and thereby either stays in the ECU or jumps to the application to start execution. The benefit of having a Flash Bootloader on an ECU is mainly to allow the erasing and programming of new applications on a single ECU in case of application updates, a recall, or change in configuration due to the downloading of new calibration files. The most popular Flash Bootloaders are CAN-based.

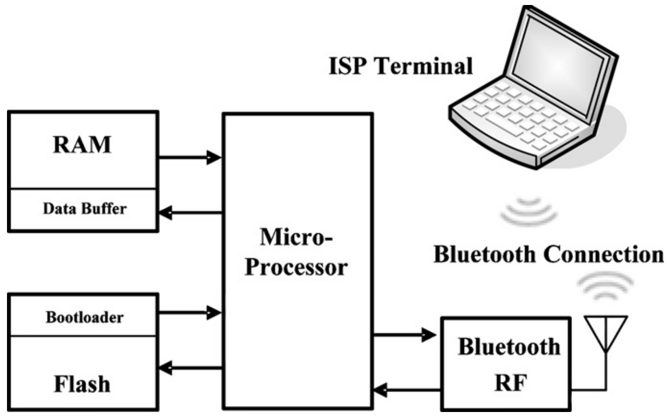

Fig. 8. Bluetooth wireless in-system programming system.

These bootloaders use a particular protocol to communicate and download to an ECU [5].

In the development process, and in the demonstration period, an on-line in-system programming system with the capacity to self-update is indispensable for the fuel cell city bus due to the following reasons:

(1) This is the first demonstration of homemade fuel cell buses in Beijing. The buses serve as ordinary buses on the streets of Beijing. Some control strategies are not yet mature during the complex transient city cycle and still needed to be optimized using the updated experiment data collected with day-to-day operation.
(2) Although Freescale has provided standard background debugging mode (BDM) protocol to update the application in the VCU of fuel cell city bus, it can lead to unanticipated results under the rugged automotive EMC environment. For this reason some field area networks such as CAN are preferred means of communication.
(3) The security of the control application has to be taken into account, in order to avoid non-deliberate and/or illegal update. The BDM interface is strictly forbidden in the fuel cell bus control system.

Based on the Bluetooth universal data interface, a wireless ISP system is implemented. This possesses the following advantages:

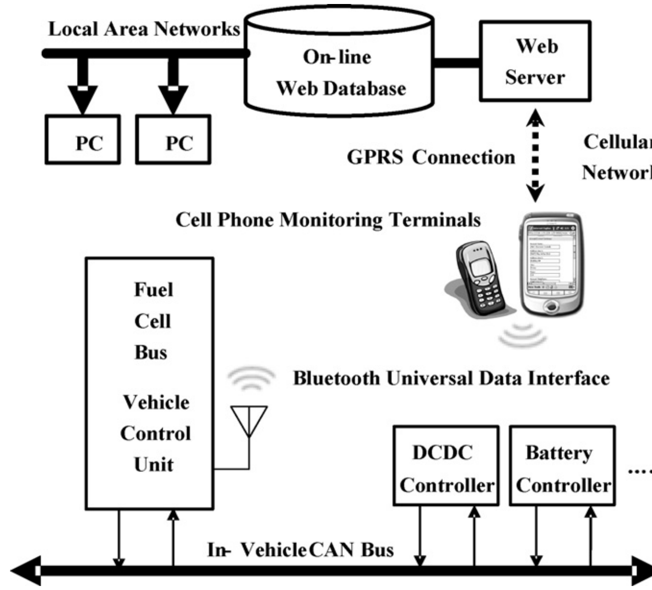

Fig. 10. J2ME-based monitoring and diagnosis system.

(1) Wireless operation: updating can be done without any cable connection to ECU, which is very convenient and also suitable for long-term public demonstration.
(2) The capacity for on-line updating: special reset and other similar operation is not necessary when using an ISP system. A friendly human–machine interface is established.
(3) High data security: is guaranteed with the pairing of Bluetooth and an authentication mechanism. Only authorized devices can connect with an ISP interface.

The hardware configuration of the ISP system is shown in Fig. 8. A Bootloader routine for ISP is resident in a Flash segment. A dedicated section of RAM is utilized as ISP data buffer. In cases where the ISP terminal communicates with the ECU via a secure Bluetooth connection (paired), a start ISP command can be sent to ECU via Bluetooth with the previously established protocol. The ECU then ceases the normal control program, and the Bootloader routine residing in the Flash is duplicated to the RAM data buffer. The entire updating binary file is downloaded into the data buffer then burned into the Flash memory permanently. The data file transmission is achieved through the XMODEM protocol via Bluetooth

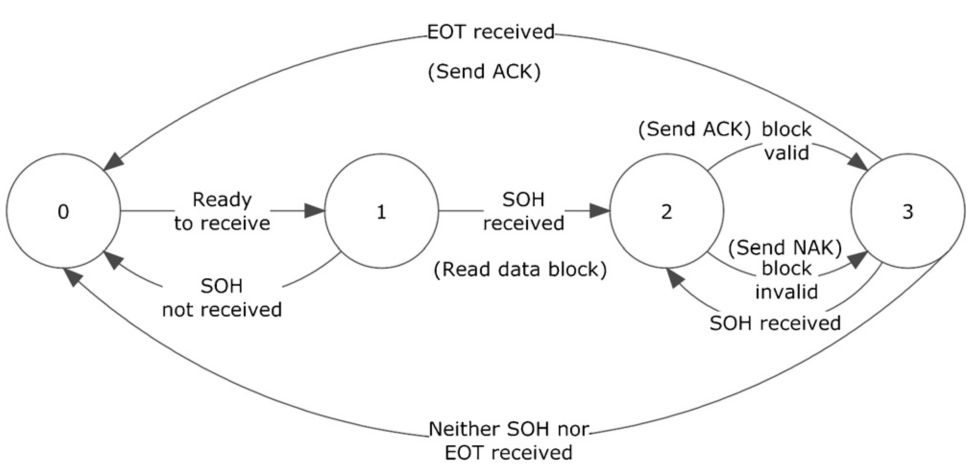

Fig. 9. Xmodem protocol state machine chart.

Fig. 11. Fuel cell bus status on-line monitoring on cell phone.

universal data interface. XMODEM, like most file transfer protocols, breaks up the original data into a series of packets sent to the receiver, along with additional information allowing the receiver to determine whether that packet was correctly received. Statistically, the chance of detecting an error is less than 16 bytes long 99.9969% with 16-bit CRC XMODEM protocol, and even higher for longer data. An XMODEM protocol state-machine diagram is shown in Fig. 9.

During the Olympics, the control strategy of the fuel cell buses was updated several times with different fuel cell engine status for each bus. With help of the Bluetooth wireless ISP system, the reloading process was dramatically simplified and the fuel cell buses maintained zero-failure operation during whole service period.

5. J2ME-based monitoring and diagnosis system

In order to procure the status of the vehicle power train, and especially the fuel cell engine, rapidly and conveniently, a novel wireless portable on-line monitoring system based on Java 2nd micro edition (J2ME) and Bluetooth technology was implemented for the fuel cell city bus. The monitoring terminal can be a cell phone, PDA or any other smart mobile device.

This cell phone monitoring system features a real-time, multichannel and auto-scaled monitor canvass. Data received can be stored as files in specific data format, which can be sent to the Diagnosis Center Server via GPRS later, as shown in Fig. 10. The implementation of this J2ME-based Bluetooth monitoring and diagnosis system has been thoroughly described in the reference paper [6]. Please consult this paper if more detailed information is required.

As shown in Fig. 11, the status inquiry of the fuel cell bus based on the system is very convenient. The fuel cell output current data sent from the VCU can be illustrated on the screen of a cell phone for on-line monitoring, meaning that some pre-failures can be quickly recognized.

6. Conclusions

Based on Bluetooth technologies, a series of novel wireless portable control auxiliary systems including calibration, monitoring and ISP systems have been successfully implemented for fuel cell city buses. These systems can be operated using any cell phone, PDA or laptop equipped with Bluetooth communication devices. For J2ME monitoring system, an additional Java virtual machine environment is also required. These systems have been utilized in the Olympic fuel cell bus demonstration project in Beijing since July 2008, and have improved the development environment of the fuel cell city bus, establishing an open platform for vehicle remote diagnosis, parameter calibration and control strategy optimization.

Acknowledgments

This work is part of the project of “Research and development of Fuel Cell City Bus” in China. The authors appreciate the financial support sponsored by the National 863 Hi-tech Research Program during the 11th 5-year plan of China.

References

[1] Larry Frisch, PEMFC Stack Sealing Using Silicone Elastomers, SAE paper 2003-01-0801.
[2] Felix Buechi, Martin Baertschi, Akinori Tsukada, Philipp Dietrich, Ruediger Koetz, Guenther Scherer and Alexander Wokaun, Performance and Operational Characteristics of a Hybrid Vehicle Powered by Fuel Cells and Supercapacitors, SAE paper 2003-01-0418.
[3] Y.Q. Jia, H.W. Wang, M.G. Ouyang, J. Power Sources 155 (2006) 319–324.
[4] M.F.A. Rasid, B. Woodward, “Bluetooth telemedicine processor for multichannel biomedical signal transmission via mobile cellular networks,” IEEE Transactions on Information Technology in Biomedicine 9 (1) (2005) 35–43.
[5] http://www.wikipedia.org, a free encyclopedia on the internet.
[6] Jianfeng Hua, Ping Guo, Jianqiu Li and Minggao Ouyang, J2ME-Based Bluetooth Portable Monitoring & Diagnosis System for Fuel Cell City Bus, 2008 SAE International Power Trains, Fuels and Lubricants Congress, SAE paper 2008-01-1517.
[7] K.W. Tindell, H. Hansson, A.J. Wellings, Analysing real-time communications: controller area network (CAN), Real-Time Systems Symposium 7-9 Dec 1994, 1994, pp. 259–263.
[9] J. Larminie, A. Dicks, Fuel Cell Systems Explained, Wiley, New York, 2001.