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Remanufacturing of electronic control units: An RFID based (service) interface

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Abstract

Remanufacturing of electronic control units (ECUs) is a challenging task. Current technology does not allow retrieving the status of installed electronics. In addition, it is not possible to access ECUs wirelessly without power supply. The wireless (service) interface radio-frequency communication (RFCo) has been developed to overcome these challenges. Here we show that by integrating RFCo into ECUs, operating data, general information, and the error log can be obtained without a mechanical connection. Furthermore, it is possible to update the firmware wirelessly. Consequently, the new interface RFCo permits faster and easier remanufacturing of ECUs, with results of superior quality.

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Keywords: remanufacturing; electronic control unit (ECU); radio-frequency identification (RFID); wireless interface

1. Introduction

Electronic control units (ECUs) process information measured with a sensor and in response put out a calculated value to an actuator. The ECU thus enables actuator functions depending on different sensor inputs according to a previously programmed software, see Figure 1. In the last 20 years, ECUs have become an integral part of automotive assemblies, white goods, consumer electronics and industrial machinery. For example, modern vehicles are supplied with up to 70 ECUs, [1] necessary for various functions from braking to infotainment. [2] During maintenance, ECUs are usually connected mechanically. However, problems may occur depending on the device housing and position within the overall machinery. [3] In case of a defective or unpowered device, firmware and status data as well as the error log may not be accessible. [4] The lack of standardized service plugs, especially in older cars, complicates diagnosis even further. [3] It is estimated that because of inadequate ECU diagnosis capabilities during car maintenance, around 50 % of replaced ECUs are still functional. [2]

As the highest form of recycling, remanufacturing aims at maintaining the current added value of a device. Within the six remanufacturing process steps of initial diagnosis, disassembly, cleaning, inspection, reconditioning and reassembly, [5] initial diagnosis of ECUs currently faces the highest challenges due to the above stated reasons of device and data inaccessibility.

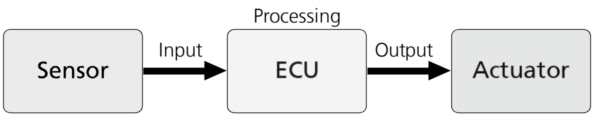

Fig. 1. Schematic functionality of an ECU.

To overcome these challenges, radio frequency identification (RFID) can be utilized. RFID system applications range from ticketing over identification of products and animals to access control. Consequently, RFID systems exist in various configurations tailored to different applications. RFID systems can differ, for example, in the used frequency range (from low frequency up to microwave frequency) or in the realized power supply mode (active or passive). All RFID systems share a common set-up: A tag, also called transponder, a reader and an application, see Figure 2. The RFID tag consists of a microchip, storing and processing the necessary data, and a coupling element. An RFID tag is called passive, when the electric power required for the RFID tag operation is supplied by the

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electromagnetic field of the RFID reader. An RFID tag is called active, when it includes a battery for power supply. [6] However, some RFID tags can be connected to a microcontroller, [7] for example of an ECU. This connection enables power supply of the RFID tag through the ECU. Such RFID tags are passive, but the power supply can be realized in two different ways: Wirelessly via the RFID reader, or non-wirelessly via the ECU. The commonly used term RFID “reader” might be misleading, because RFID readers actually unite reading and writing functions. Major components of an RFID reader are a high frequency module, a control unit and a coupling element in order to access the RFID tag. Most RFID readers can be connected to an application, e.g. a computer, via a wired interface such as RS 232 or Universal Serial Bus (USB). [6] With this set-up, data to be transferred to the RFID tag can be entered into the application. For the reversed case, data obtained from the RFID tag can be read out at the application.

Using the newly developed wireless (service) interface RFCo (radio-frequency communication), we present a solution to diagnose both mechanically and electronically inaccessible ECUs. A prototype module consisting of an ECU with an integrated RFID tag has been developed to demonstrate wireless access to the ECU. Furthermore, firmware and operating data saved onto the memory of the RFID tag can be read out while the ECU is unpowered. We will show that RFID has advantages over other wireless interfaces for this purpose. In addition, integrating the wireless (service) interface RFCo into ECUs is expected to facilitate remanufacturing in order to save costs and avoid waste.

The structure of this paper is as follows: In section 2, we will introduce materials and methods necessary for the development of the wireless (service) interface RFCo. After comparing and evaluating the wireless (service) interfaces Infrared, Wireless Local Area Network (WLAN), Bluetooth and RFID, we present the procedure followed in the development of a prototype module. Technical requirements for the prototype module are defined and the used hardware and software components are explained. The results are presented in section 3. With the previously defined components, a prototype ECU has been developed. The application has been demonstrated within an experimental set-up. It could be shown that bidirectional communication between the microcontroller of the ECU and the RFID tag is possible, facilitating initial diagnosis significantly. This is because error log and general data such as the firmware version can be saved onto the RFID tag regularly. In a service and maintenance scenario, this information is available wirelessly, even with an unpowered ECU. In section 4, the results are discussed and future development steps for the wireless (service) interface RFCo are introduced.

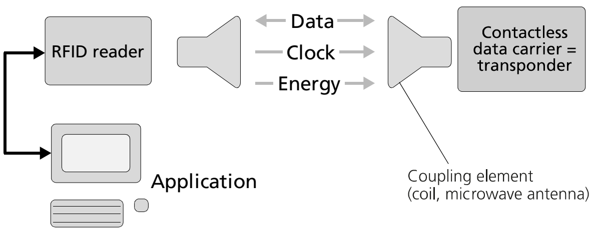

Fig. 2. Schematic set-up of an RFID system (adapted from [6]).

Nomenclature

CAN	Controller Area Network
DC	Direct Current
ECU	Electronic Control Unit
I²C	Inter-Integrated Circuit
LED	Light Emitting Diode
PCB	Printed Circuit Board
RFCo	Radio-Frequency Communication
RFID	Radio-Frequency Identification
RGB	Red Green Blue
SPI	Serial Peripheral Interface
UHF	Ultra-High Frequency
USB	Universal Serial Bus
WLAN	Wireless Local Area Network

2. Materials and Methods

Commonly available wireless interfaces include Infrared, WLAN, Bluetooth and RFID. As shown in Table 1, not all of them are suitable for initial diagnosis of ECUs. Infrared can only operate at a direct line of sight between two Infrared enabled devices. This is disadvantageous because ECUs can be obstructed from view by other components. Both WLAN and Bluetooth systems can cover wide distances with high data rates, but an external power supply is necessary for communication. In contrast, a passive RFID tag allows powerless access of the ECU during initial diagnosis. Consequently, the wireless (service) interface RFCo has been developed with RFID technology.

The wireless (service) interface RFCo has been developed in three major steps: Hardware development, software development and validation. During hardware development, a general hardware set-up has been designed, see Figure 3, and the technical requirements have been defined, see Table 2. Hardware components were chosen according to the technical requirements, allowing the set-up of a prototype module.

The wireless (service) interface RFCo consists of an RFCo tag including an RFID tag and an antenna, connected via an interface such as Serial Peripheral Interface (SPI) or Inter-Integrated Circuit (I²C) to a microcontroller. Data can be exchanged bidirectionally via the interface between the RFCo tag and the microcontroller. The RFID interface between the RFID reader and the RFCo tag allows for transferring data to the microcontroller.

Table 1. Comparison of wireless (service) interfaces.

Interface	Nominal range [m]	Direct line of sight	Max. data transfer rate [Mbit/s]	External power supply for ECU diagnosis
Infrared [8]	1	Necessary	1000	necessary
WLAN [9]	300	Not necessary	600	necessary
Bluetooth [10]	100	Not necessary	1	necessary
RFID [6, 11]	15[1]	Not necessary	0.64[2]	Not necessary

[1]With active RFID tags [2]With passive RFID tags

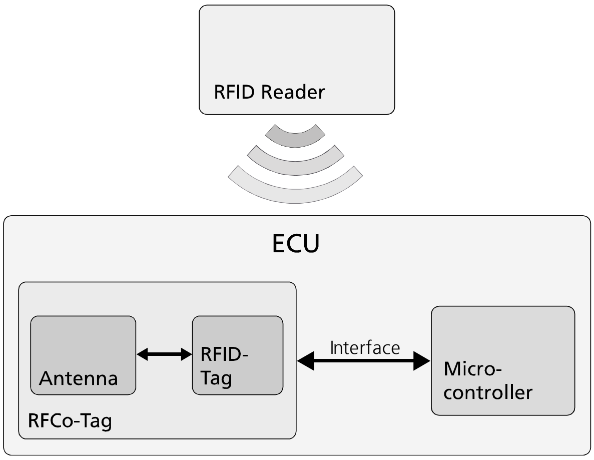

Fig. 3. Schematic set-up of the wireless (service) interface RFCo.

For hardware component selection, the following technical requirements have been defined: The range of the wireless (service) interface RFCo, namely the maximum distance between the ECU (including the RFCo tag) and the RFID reader, should be at least 1 m. While the data transfer between the ECU and an external diagnosis device is realized wirelessly over the RFID interface, energy transfer can be wireless or non-wireless. This is because both wireless energy transfer by the RFID reader and non-wireless energy transfer by the ECU should be possible. In consequence, a flexible data transfer in two steps is possible: In a first step, data is transferred from the RFID reader to the RFID tag. The microcontroller is unpowered. Energy for writing data onto the RFID tag is transferred by the RFID reader. In a second step, the microcontroller is powered. The data saved onto the RFID tag is transferred to the ECU. Power supply for reading out the data is transferred by the ECU. This does not require the presence of an RFID reader for wireless energy transfer. The minimum data transfer rate was set to 100 kbit/s. The operating frequency of 868 MHz has been chosen from available frequency bands. In Germany, four frequency bands can be used for RFID applications: 125 KHz, 13.56 MHz, 868 MHz, and 2.4 GHz. [12] The former two have been disregarded due to insufficient data rates. The microwave band at 2.4 GHz has not been selected due to significant reflections, limiting application possibilities for encased devices. The most important technical specifications of 868 MHz are: a maximum range of 4 m and a maximum allowed power of 2 W. [6] Three operation modes should be possible with RFCo. In a first operation mode, the ECU is not connected to a power supply. Data sent by the RFID reader are buffered on the RFCo tag and transferred to the microcontroller once it is powered. Energy required by the RFCo tag for buffering is transferred wirelessly from the RFID reader. In a second operation mode, operation mode one is extended with an external energy harvesting unit. The energy harvesting unit allows for supplying both the RFCo tag and the microcontroller with power, transferred wirelessly by the RFID reader. In a third operation mode, the ECU is connected to a power supply. Data can be transferred between the ECU and the RFCo tag at all times. The combination of the first operation mode and the third operation mode has been described further above as an example for flexible data transfer.

Table 2. Technical requirements for the wireless (service) interface RFCo.

parameter	value
Minimal range [m]	1
Data transfer	wireless
Energy transfer	Non wireless and wireless
Data transfer rate [kbit/s]	100
Frequency [MHz]	868

In accordance with the technical requirements, the passive RFID tag NXP SL34011 [7], hereinafter referred to as RFID tag, has been selected. The RFID tag can be operated at frequencies between 860 and 960 MHz, is equipped with an I²C interface and a user memory of 3.3 kbit. Both wireless energy transfer by the RFID reader, and non-wireless energy transfer by the ECU is possible. Two connections for the I²C bus to the microcontroller are necessary for operation of the RFID tag. Additionally, two ultra-high frequency (UHF) interfaces can be connected to the RFID tag. A radio frequency – I²C bridge function allows for direct bidirectional communication between the RFID reader and the microcontroller. Data transferred between the radio frequency and the I²C interface is buffered, permitting the exchange of data beyond the size of the RFID tag user memory. A block diagram of the RFID tag is shown in figure 4.

Several printed circuit board (PCB) antennas have been developed for different applications. The PCB antennas have been adjusted to the RFID tag and to the RFID reader Kathrein RRU4-ETG-E6, hereinafter referred to as RFID reader. The RFID reader is designed for UHF frequencies between 865 and 868 MHz, with an output power of 2 W and four antenna ports. The connection to a computer is realized via Ethernet. As the RFID reader antenna, the Kathrein MiRa ETSI, a UHF mid-range antenna with a range of 0.2 to 2 m, has been used. Basic read and write functions can be implemented by using the Kathrein reader software. However, further user-specific applications can be realized with an individual software.

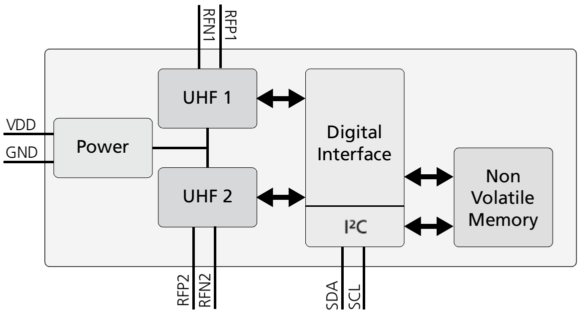

Fig. 4. Block diagram of the RFID tag NXP SL34011 (adapted from [7]).

During software development, a software including a communication protocol specific for the wireless (service) interface RFCo has been developed. As a requirement, two functionalities should be realized: To control the actuator via RFID and to read out ECU status as well as general data via RFID. The software can be separated into three layers: The physical, link and application layer. The physical layer has been implemented for the I²C interface between the microcontroller and the RFID tag. The link layer, comprising the communication protocol, has been developed in accordance with currently available automotive and white goods communication protocols. The communication protocol of the wireless (service) interface RFCo should be as close to existing communication protocols to ease a later market acceptance. The application layer has been designed in a way to facilitate the demonstration of different applications.

During validation, a demonstrator has been developed, including a prototype of the wireless (service) interface RFCo based on an existing automotive ECU. The resulting RFCo CAN LED module incorporates the chosen hardware, implementing the software described above.

3. Results

Within the prototype RFCo CAN LED module, the selected hardware has been combined with the developed software. In accordance with an existing automotive ECU, the RFCo CAN LED module is based on an AT90CAN128 microcontroller controlling a red, green and blue (RGB) light emitting diode (LED). Further components are an RFCo tag connected to the microcontroller via I²C, and external Controller Area Network (CAN), SPI and I²C interfaces. CAN is the most commonly used bus system in automotive applications. [13] Consequently, the CAN interface can be used to simulate the integration into an automotive environment. The SPI interface has been implemented for programming the microcontroller. The I²C interface can be used additionally for data transfer to and from the microcontroller. The microcontroller power supply is realized with a direct current (DC)/DC converter, converting the vehicle power of 12 V to supply voltage (VDD). The RFCo tag consists of the RFID tag and a PCB antenna. A block diagram of the RFCo CAN LED module is shown in Figure 5.

In Figure 6, the experimental set-up as a demonstrator for the RFCo CAN LED module is illustrated. Simulating power supply with a car battery, the RFCo CAN LED module is connected to a power source of 12 V. The bus interface VN 1630 is integrated into the experimental set-up to mimic a connection to other ECUs. The RFID reader is connected to the computer via Ethernet. The RFID reader antenna Kathrein MiRa ETSI complements the experimental set-up.

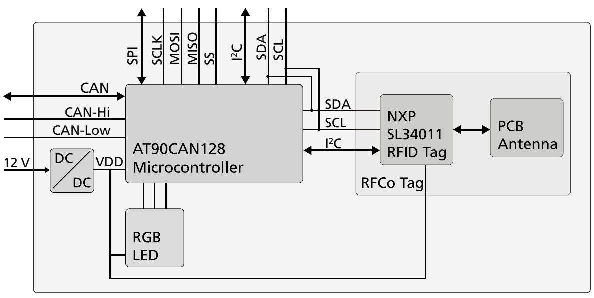

Fig. 5. Block diagram of the RFCo CAN LED module.

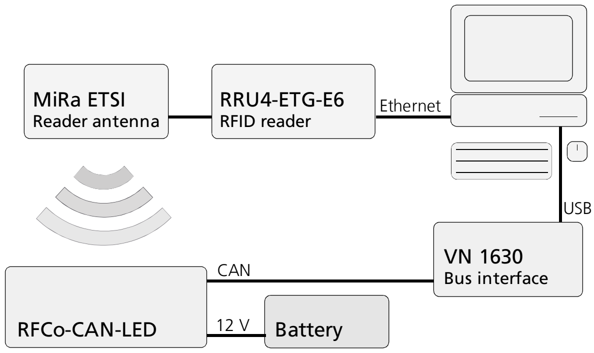

Fig. 6. Experimental set-up for the RFCo CAN LED module.

The user interface of the RFCo software allows for controling LED color and brightness via RFID. The information for these LED settings is entered by the user at the computer. It is transferred wirelessly by the RFID reader to the RFCo tag. Subsequently, the information is transferred via I²C to the microcontroller, which processes the information to finally output a signal to the LED. However, it is also possible to transfer the same information from the computer to the RFCo CAN LED module through the wired USB-CAN connection, simulating the integration into an automotive environment. During both control scenarios, general data, for example the RFCo CAN LED module name, the microcontroller and RFID tag status, as well as process data like the current LED settings can be read out via the RFID interface. These data are transferred from the microcontroller to the RFID tag, except for the RFID tag status data, which is generated directly on the RFID tag. All data can be transferred via RFID to the RFID reader and on to the computer. The data is then processed and displayed within the user interface. When disconnecting the power supply from the RFCo CAN LED module, the general data can still be read out via RFID. This is because general data is transferred from the microcontroller to the RFID tag in regular intervals. Thus, the latest transferred and saved information can be read out. In return, LED settings information communicated via RFID is saved onto the RFID tag and processed by the microcontroller as soon as the power supply is available.

Two out of three operation modes have been realized within the experimental set-up. The first operation mode with an unpowered ECU, where data for the microcontroller transferred via RFID is buffered on the RFCo tag until power supply of the ECU is available, can be carried out. Additionally, the third operation mode with external power supply for the ECU, where data between the RFCo tag and the microcontroller can be transferred at all times, has been realized.

4. Discussion and Conclusion

Integrating the RFCo CAN LED module into the experimental set-up, we have demonstrated the main advantage of using RFID over other wireless (service) interfaces, namely the possibility to read out ECU information while the ECU is unpowered. Consequently, initial diagnosis of ECUs as the first step of remanufacturing is facilitated significantly with the integration of the wireless (service) interface RFCo into the ECU. This is because the ECU can be analyzed wirelessly and in an unpowered state. As a requirement, the ECU has to be programmed to save general data, such as the firmware version as well as the error log, in regular intervals onto the RFID tag. It will be possible to read the logged data and to interpret them. With this interpretation initial diagnosis, become much easier. Additionally, wireless access to an ECU saves time because the ECU does not have to be connected mechanically. Opening the device comprising the ECU and connecting the ECU with a wired interface are maintenance and service steps becoming redundant with the wireless (service) interface RFCo.

Apart from an application in remanufacturing, the wireless (service) interface RFCo can also be beneficial in earlier stages of the supply chain. For example, firmware is currently installed onto ECUs during production due to the mechanical accessibility. This procedure has two major drawbacks: Firstly, by the time of delivery to the customer, the installed firmware might not be at the current version. In consequence, customers have to update the firmware upon first usage. Secondly, installing country-specific firmware during production leads to country-specific stocks of packed ECUs. An adaption of the stocked ECUs to applications in other countries due to changed demand is thus not possible. With an integrated wireless (service) interface RFCo into ECUs, the most up-to-date and country-specific firmware can be installed wirelessly onto the packed ECUs directly before delivery. This allows for more flexible stocks and facilitates customer usage of the ECU.

In a next step, one more operation mode of the wireless (service) interface RFCo will be implemented in order to power both the RFCo tag and the microcontroller using the energy transferred by the RFID reader. For this purpose, an energy harvesting unit will be used to expand the current set-up. Apart from this hardware adaptation, the application layer as the third software layer should be developed to facilitate different applications even further.

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