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Energy-autonomous wireless sensor nodes for automotive applications, powered by thermoelectric energy harvesting

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Abstract. In this paper we will first present the measurement of temperatures on different positions at a diesel-powered car. As a result, several locations are identified as suitable to implement a wireless sensor node powered by thermal energy harvesting. Based on the data gained a thermoelectric generator (TEG) has been selected, and measurements of energy generation have been performed. Further, a complete energy-autonomous wireless sensor node was designed, including the TEG with its mounting bracket, an electronic power management, and a Bluetooth Low Energy (BLE) sensor node. Based on temperature differences from -10 K up to 75.3 K occurring in test drives, a low power set up was chosen to achieve a system start-up time below 10 minutes and to ensure service even under difficult ambient conditions, like high ambient temperatures or a slow movement of the car in stocking traffic. 2 minutes after starting the engine a power about of 10 mW is available from the chosen TEG, and in peak the power exceeds 1 W. In a 50 minute test drive it was possible to generate 650 J of energy. This information was used to develop the complete system, demonstrating the opportunity to deploy energy-autonomous wireless sensor nodes in a car, e.g. for exhaust gas monitoring. The system is used to gather sensor data, like temperature and humidity, and transmits data successfully via BLE to a prepared main node based on a Raspberry Pi.

1. Introduction

Owing to a growing number of sensors and electronic control units (ECUs) [1], there is a motivation for the application of wireless sensor nodes (WSN) in cars to replace wired sensors with all their drawbacks. A modern mid-size passenger car carries 20 to 40 ECUs with, in total, approximately 3 km of wires for the supply of electric components and communication [2]. This requires complicated and error-prone power/data grids, fabricated and installed by hand, not easily maintained, and providing a substantial cost factor.

Even highly efficient combustion engines are exhausting more than 60 % of fuel energy by heat dissipation. This leads to the opportunity to save wires, therefore space and weight in cars, and to add some flexibility through the integration of waste heat-powered WSNs at different parts of the car, which is shown in this paper. This work differs from other experiments, as all systems presented are deployed on-site in a car, and not tested in a laboratory setup [3]. Thermal measurement data gathered from test drives show several positions, where thermal energy can be harvested. Based on these data, a thermoelectric generator has been selected and power measurements were performed. In the most promising application targeted here, a peak power of 1 W is harvested from heat losses. The development of the WSN is ongoing, and will demonstrate the potential of retrofitting a car with, e.g., sensors for exhaust gas monitoring.
2. Temperature measurement set up

Figure 1 shows the measurement setup in the motor compartment of a Citroen C3 Picasso BlueHDI 100: There are five PT1000 1/3 DIN sensors at the (A) oil-level dip stick, (B) manifold, (C) radiator support panel top and bottom (D) as well as a sensor for ambient temperature (E) in the motor compartment next to the battery. In (F) a data logger is placed (LETE LE-LOG_S0), prepared with a four wire sensing interface. A second setup is used to record data at the bottom back of the car, with sensors mounted at the exhaust pipe [G] and the crossbar [H]. The test drive track (see Fig. 2 [6]) contains sections of highway, country road, and city traffic to determine differences in the thermal conditions at the selected positions. The positions were selected based on their basic thermal behaviour and expected temperature difference. All track sections are logged with an external GPS Logger (ASUS K013), giving precise information about velocity and position.

3. Temperature measurements

Three test drives are realized to measure and compare temperature behavior, one is exemplary shown in Figure 3. The measured results are depending of the ambient temperature, especially with respect to the maximum temperature difference between exhaust pipe and crossbar temperature, the latter representing ambient temperature the closest (no direct sunlight and forced convection). With an ambient temperature around 22 °C, an average $\Delta T$ of 18.7 K can be reached at the exhaust pipe, while at approximately 11 °C ambient temperature an average $\Delta T$ of 41.4 K is found. In particular when the car is on the highway, the influence of the vehicle speed is clearly visible. This is related to higher forced convection at the mounted cooler, as well as the higher heat generation that comes with higher exhaust gas flow.

Figure 1. Motor compartment of a Citroen C3 Picasso Blue HDI 100 with five installed temperature sensors [A]-[E], and the data logger [F]. Sensors [B] and [D] are not directly visible, as hidden behind engine parts.

Figure 2. Temperature sensors at the end of the exhaust pipe [G] and crossbar [H]. The right picture shows the drive test track on a map [6], with the start and stop position indicated by the mark.

Figure 3. Measurements on May, 20th. 2016. The top plot shows the car’s speed. The middle plot shows the temperatures at manifold [B] and radiator support panel [C] as the most promising positions for heat extraction in the motor compartment. The bottom plot shows the temperature at the end of the exhaust pipe [G] at the back of the car and at the crossbar [H]. The grey field is highlighting the highway section of the route.
4. TEG system design and power management

A suitable TEG (TEG-071-150-22, Thermalforce [4]) has been chosen and mounted at the exhaust pipe with a custom-made retainer (Figure 5, Top). Thermal coupling of the generator to the air is realized with a passive heat sink (Fischer Elektronik ICK S, 50x50x40 mm, [5]). Figure 4 shows measurements performed on the same test track as used for the temperature measurements. At the beginning of a drive the TEG delivers only a power output around 10 mW. Figure 5 bottom shows the increase of power dependent from the temperature difference between exhaust pipe and ambient temperature and in Figure 6 the system with main parts is displayed. The middle of the test drive shows the highway section, where a maximum power above 1 W is available. Nevertheless a low voltage DC/DC converter has been selected (enOcean ECT310) to enable a short power-up time after engine start.

4.1. Power Management

Harvested energy is stored on a large 4 mF tantalum capacitor to ensure the start-up of a microcontroller (MSP430F5529) and the connected Bluetooth Low Energy (BLE) module (Bluegiga BLE112). A start-up switch is designed based on a comparator MIC833 (Microchip, [7]) with a supply current of 1 µA. It controls the activation of both modules, microcontroller and BLE, depending on the voltage level present at the capacitor. The chosen voltage level for start-up is 4 V. This relatively high value is required to ensure a complete start-up of the BLE module from stored charge during the first initialization, with an associated high power drain of appr. 8 mA over 500 ms. After startup, the microcontroller and the initialized BLE module continue operation in a timed sleep mode, with short wake-up periods for sensing and data transmission. The start-up circuit does also ensure deactivation of the microcontroller and the BLE module as soon as the capacitor voltage drops to a threshold of 1.8 V, thus resulting in a voltage hysteresis for operation in a predefined range between 4V and 1.8 V.

The complete set up was tested with the engine running in idle state. The power management circuit and the radio module are connected to the TEG at the exhaust pipe. The harvested energy is sufficient to power the system. As seen in Figure 4 the output power during driving is much higher, thus giving the potential to perform tasks like data transmission with short sending intervals and powering of various sensors, e.g. a CO2 or NOx sensor.
4.2. Wireless communication
BLE provides a broad availability in modern systems combined with a frequently advertised low power functionality. However, this argument has to be discussed critically in an application that requires frequent reconnection of a synchronized wireless BLE link. The current consumption of the BLE module used here (Bluegiga BLE112) is about 8.4 mA base current and 25 mA peak current per telegram over a period of 1 ms to 10 ms during the transmission of 21 data packets with a payload of 4 byte each. As measured, approximately 1.5 mJ are needed for the transmission of such a single data packet with a payload of 4 byte in bi-directional communication, plus 3 mJ for the establishment of the synchronized wireless connection. Average power consumption is therefore 4.5 mW for 1 telegram per second. Using advertisement mode with a reduced data overhead would decrease the power consumption a lot. However, in automotive applications a bidirectional communication is desirable. From that reason the more power-hungry synchronized communication mode was kept as a realistic scenario. In comparison to that the microcontroller draws negligible power in the range of several µW.

In a laboratory setup using the designed system consisting of a low voltage step-up converter, the developed start up switch, the microcontroller and the BLE module, successful transmission of collected temperature data to a receiver station (Raspberry Pi) was achieved. In its current implementation the capacitor voltage is read by the microcontroller in a predefined interval, simultaneously with the aggregation of measurement data.

5. Conclusions and Outlook
The applicability of a thermally powered wireless sensor node at the exhaust pipe of a passenger car has been demonstrated successfully. The TEG applied for this purpose is working stable since its installation, and has shown stable output over several 1000 km of driving distance, proving again the robustness of the thermoelectric energy harvesting principle. Its functionality will be tested further on with respect to long-term stability and mechanical defects. The WSN will typically turn on within 15 minutes after the start of the car engine. This relatively long period is solely caused by the high energy demand of the BLE module in use, and could be significantly reduced by more sophisticated and low-power wireless communication.

This project shows further possibilities to investigate different places in a car to deploy TEGs, for example in the motor compartment. As well the power management has to be improved, to store excessive energy in times of high power generation, e.g. with a super capacitor. This will allow a faster start up time of the sensor node in the next driving cycle.

6. Acknowledgement
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