Sensors & Transducers, Vol. 212, Issue 5, May 2017, pp. 15-22

Sensors & Transducers

Published by IFSA Publishing, S. L., 2017
http://www.sensorsportal.com

Ultra-Low Power Sensor System for Disaster Event Detection in Metro Tunnel Systems

Jonah VINCKE, Scott KEMPF, Niklas SCHNELLE, Clemens HORCH, and Frank SCHÄFER

Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut, EMI,
Eckerstrasse 4, Freiburg, Germany
E-mail: jonah.vincke@emi.fraunhofer.de, scott.kempf@emi.fraunhofer.de,
niklas.schnelle@emi.fraunhofer.de, clemens.horch@emi.fraunhofer.de,
frank.schaefer@emi.fraunhofer.de

Received: 10 April 2017 /Accepted: 29 May 2017 /Published: 31 May 2017

Abstract: In this extended paper (see [1]), the concept for an ultra-low power wireless sensor network (WSN) for underground tunnel systems is presented highlighting the chosen sensors. Its objectives are the detection of emergency events either from natural disasters, such as flooding or fire, or from terrorist attacks using explosives. Earlier works have demonstrated that the power consumption for the communication can be reduced such that the data acquisition (i.e. sensor sub-system) becomes the most significant energy consumer. By using ultra-low power components for the smoke detector, a hydrostatic pressure sensor for water ingress detection and a passive acoustic emission sensor for explosion detection, all considered threats are covered while the energy consumption can be kept very low in relation to the data acquisition. In addition to [1] the sensor system is integrated into a sensor board. The total average power consumption for operating the sensor sub-system is measured to be 35.9 µW for lower and 7.8 µW for upper nodes.

Keywords: Ultra-low power, Wireless sensor network, Energy harvesting, Tunnel system, Natural disaster management.

1. Introduction

More than half of the planet's population now lives in urban areas. This creates the need for various mass rapid transport systems including metro systems. New vulnerabilities for society that arise due to disaster events, such as terrorist attacks, flooding or fire are increased by a higher population density and current political processes. To address these challenges – in particular for underground metro systems – as part of the bi-national research project SenSE4Metro (Sensor-based Security and Emergency management system for underground Metro systems during disaster events) [2], a concept for a wireless sensor system is introduced that can detect the most significant threats and which provides rescue forces with the relevant and necessary information in the case of an emergency. The particular operation site leads to the requirement for the WSN that each node must be energy autarkic, which in turn necessitates the application of ultra-low power (ULP) components. The focus in this work lies on the needed sensors to achieve these goals and to fulfill the project requirements.

First, the state-of-the-art of wireless sensor networks for different kind of tunnels is presented. After that, an overview of the proposed wireless sensor network is given, taking the special linear topology for a tunnel system into account. Finally, a concept for the needed sensors that can cover all addressed threats is presented that focuses on the power consumption and takes the applicability for a metro tunnel system into account. This includes the integration of the sensor subsystem into the sensor node and the test of the system. At the end, the presented results are discussed and a conclusion is taken.

2. State-of-the-Art

The use of wireless sensor networks for tunnel systems has been investigated in several works. Of the systems described, most are designed primarily for road tunnels [3-5] or mine tunnels [6-7]. Of the latter, some focus on the radio transmission in tunnels (e.g. D. Wu and H. Jiang) and others on special protocols designed to increase robustness against underground collapses [8]. Of the former, Ceriotti, |*et al.* present a WSN consisting of 40 nodes to monitor the light conditions of a 260 m long tunnel. Mottola, *et al.* compared the data of a traffic tunnel (here, railroad tunnels are proposed as analogous with the assessed road tunnel) with a WSN for a vineyard to make suggestions for the communication in road tunnels.

For underground rail tunnels, only a few works exist. Wischke, *et al.* [9] discuss the generation side of the energy autarkic nodes by proposing a vibration energy harvesting solution for maintaining the wireless sensor nodes in rail tunnels. Bennett, *et al.* [10] used MICAz boards as wireless sensor nodes to monitor cracks in a 170 m long part of the Prague Metro and in a 115 m long section of the London Metro. Sivaram Cheekiralla [11] used a WSN to monitor the deformation of a train tunnel during construction using 18 nodes using only a star topology.

Raza, *et al.* introduced a combination of an ULP wake-up receiver with model-based sensing to reduce the power consumption of the rail tunnel WSN by Ceriotti, *et al.* [3]. They simulated an increased lifetime of the nodes by a factor of over 2000 due to their method, which demonstrated the influence of a data model to reduce necessary data transmission and the use of a wake-up receiver.

The optimization of wireless communication in tunnel systems has been widely discussed. Especially Raza, *et al.* [12] showed that the power consumption of the data acquisition is of high interest as they reduced the power consumption of the communication drastically using a wake up receiver. Therefore, the focus of this paper lies on the conception of the sensor system that is based on an initial layout and requirement specification for the WSN.

3. Wireless Sensor Network

For the purposes of defining the requirements of the WSN, an assessment of past terrorist attacks on underground, tunnel and rail infrastructure was performed [13]. The assessment results highlighted several distinct differences between attacks on underground systems as compared to above-ground networks, with respect to tactics and effectiveness (in terms of casualties). Ultimately, event scenarios were defined based on explosive and arson attacks targeting the trains and tunnels themselves. While the assessment also highlighted the threat of biological/chemical attacks, due to previous studies [14], these were explicitly omitted from the scope of the project.

Adding recent historical flooding in underground networks [Prague 2002, New York 2012] and accidents [Valencia 2006, Moscow 2014] the following events should be detected and the corresponding data acquired by the WSN:

- Train passage (positioning and movement);
- Fire (temperature and smoke presence);
- Explosion (impact peak pressure and specific impulse);
- Flooding (water presence and depth).

The combined data will be applied to determine danger levels and traversability of tunnel segments and to coordinate paths of access (rescue forces) and escape (passengers).

In order to acquire the necessary data above, sensors are positioned both at ground and ceiling level and all along the tunnel segment. It was decided that the implementation would be performed as a parallel linear topology (as shown in Fig. 1) with cable wired master nodes at each metro station that work as a gateway to the control center. The topology provides added robustness via path redundancy, as both nodes can be used to forward messages. Using two parallel strings of nodes the upper nodes can be used to measure smoke and impact pressure using a wind energy harvester as their power source. The lower nodes on the other hand measure water ingress and ambient temperature and they are powered using a piezoelectric vibration energy harvester attached to a rail.

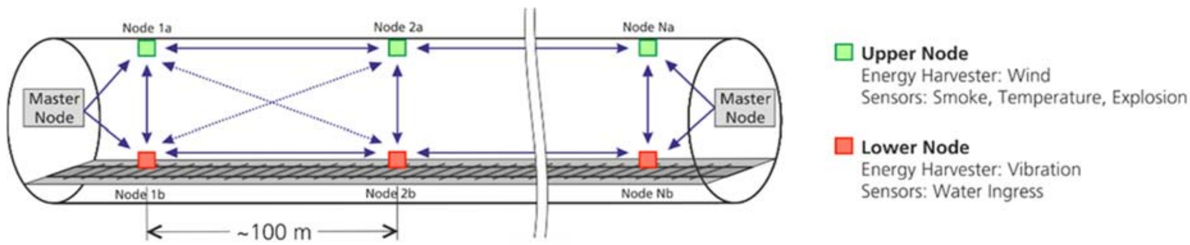

Fig. 1. Applied WSN topology in underground tunnel.

In standard (non-emergency) operation, situational status messages are transmitted during train passage events, which means the energy required for data acquisition and transmission is provided directly via energy harvesting processes. For emergency event detection, an energy storage system is provided to ensure a constant power supply.

Its relatively long path lengths however require special tuning and adaptation of routing algorithms. While classic tree based routing protocols, such as Contiki Collect or CTP [15], can in principle be applied directly, nodes at the end of long paths would have to forward all the messages generated by preceding nodes in the path thus creating significant load and using disproportionally more energy. To counter this, modifications are applied to the Contiki Collect protocol. One modification allows data from different nodes to be combined or filtered so as to only forward messages for significant changes instead of simply forwarding all generated data towards the nearest gateway. This also allows nodes to detect when upstream nodes detect an event allowing the network to increase its measurement and forwarding frequencies on demand. Additionally changes are implemented enabling longer paths and passive non-forwarding nodes, which can dynamically switch to a forwarding role when an ongoing situation is detected. This however remains an area of active research and development.

Modifications to the Contiki Collect protocol as well as the uncommonly long path lengths have been evaluated in simulations using the Cooja simulation framework where dozens of nodes can be tested without time intensive reflashing. Additionally tests have been performed on real hardware using SensorTag boards which use the same chip in a convenient package. Development in this area remains ongoing as prototype boards and tunnel testing opportunities become available.

For all nodes, the CC2650 from Texas Instruments is chosen as the MCU due to its very low power consumption and integrated RF module.

4. Sensors

To achieve low power consumption, a holistic concept has been developed. This includes the application of modern ultra-low power sensors, enabled only when necessary, as well as the re-application of the same sensors for various disaster events if possible. The precision of the sensors is of less importance in contrast to the power consumption. A robust detection of a dangerous event is sufficient.

4.1. Water Ingress

There are several methods for the detection of water ingress and determination of the resulting water level. These vary from mechanical solutions using floats to change a resistance, a capacitance or to close a contact to pure capacitance or resistance measurements as well as hydrostatic, ultrasonic and radar methods. Many can be realized with an ultra-low power consumption but vary with respect to their robustness, dependence on the medium and the tunnel's shape.

Mechanical solutions have the disadvantage that their dimensions need to be in the same range as the measurable water level and that their shapes are limited. On the other hand they are independent from the media and can be realized as ultra-low power systems.

Optical or ultrasound distance sensors are not dependent on such limitations nor on the media or the shape of the tunnel. But they lack on the measurable distance and power consumption. As an example the infrared distance sensor GP2Y0A710 from Sharp needs above 1 mW for one measurement every 5 seconds while only covering a distance of up to 5 m. Ultrasonic sensors that can measure distances of up to 8 m or more have commonly a power consumption of over 1 Watt during operation and need several hundreds of milliseconds until the first measurement is possible. As an example the UC30-2 from SICK needs up to 1.2 W for approximately 450 ms until a measurement can take place. Sensors for smaller distances such as the LV-MaxSonar-EZ have a power consumption of about 10mW for half a second for a measurable distance of 6.45 m.

Of the other solutions, measuring the hydrostatic pressure seems most promising for achieving very low power consumption. Here the pressure caused by the water ingress at the bottom of the tunnel has to be measured as well as that above the water level. The disadvantage of this principle is that calculating the water depth according to the induced pressure difference is dependent on the mediums density by design. Also, the system's robustness in a harsh environment such as an underground tunnel has to be investigated. Since passing trains induce pressure disturbance, the measurement has to be adjusted during train passage events. As an example simulations [16] have shown that a train with a cross-sectional area of 8 m² in a 5 m high tunnel with a speed of 200 km/h creates a pressure difference (in time) of up to 1.36 kPa in the tunnel. If this would be measured as the spatial pressure difference it would be equivalent to a water level of 138.7 mm. How the pressure is disturbed exactly over the cross section and over the time in a real tunnel has to be investigated in further works.

Because of the independence on the tunnel's shape, the water ingress detection will be based on measuring the pressure induced by the water. Since in most cases the media will be ground water the density of the media will be similar in most cases and therefore the dependence of the system on the media can be neglected. The sensors will be located at the wall. The pressure at the bottom of the tunnel is measured using a tube mounted to the wall that is connected to one of the sensors and goes to the ground as shown in Fig. 2. Using two MS5806 pressure sensors, water levels of up to 9 m with a precision of 0.13 cm can be measured while consuming less than 3 µW for each sensor when measuring once per second in theory. A temperature sensor is also included that can be used for the other sensors in addition, reducing the overall power consumption.

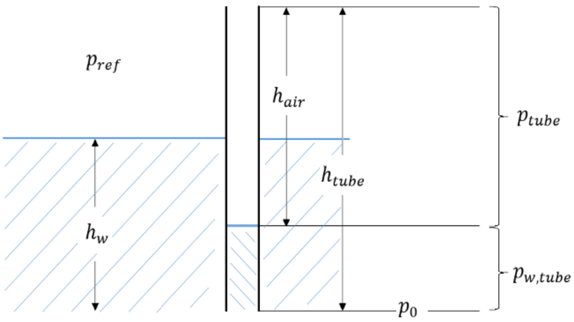

Fig. 2. Schematic of the water level measurement system using a tube to measure the pressure at the ground of the tunnel.

The water ingress depth h_w can be determined using the pressure p_0 at the base of the tube, the reference pressure p_{ref} above the water and assuming that the media is water:

$$h_w = \frac{p_0 - p_{ref}}{\rho_w \cdot g}, \tag{1}$$

where ρ_w is the water's density and g is the acceleration of gravity. As the air in the tube is compressed by the water ingress within the tube, the measured pressure p_{tube} is lower than the real pressure at the end of the tube. In order to determine the pressure p_0, it is necessary to compensate the compression. This can be done using the ideal gas law:

$$p \cdot V = n \cdot R \cdot T, \tag{2}$$

and assuming a constant amount of air n and a constant temperature T. Therefore the product of the pressure and the Volume is constant. Assuming a constant cross-sectional area within the tube the height of the air column can be determined as:

$$h_{air} = h_{tube} \cdot \frac{p_{ref}}{p_{tube}} \tag{3}$$

The pressure at the tube base is a summation of the air pressure due to compression and the water ingress within the tube:

$$p_0 = p_{w,tube} + p_{tube} \tag{4}$$

Reapplying the water depth equation, the total pressure p_0 can be determined as:

$$p_0 = \rho_w \cdot g \cdot (h_{tube} - h_{air}) + p_{tube} \tag{5}$$

With (3):

$$p_0 = \rho_w \cdot g \cdot h_{tube}\left(1 - \frac{p_{ref}}{p_{tube}}\right) + p_{tube} \tag{6}$$

Finally, inserting back into (1):

$$h_w = h_{tube}\left(1 - \frac{p_{ref}}{p_{tube}}\right) + \frac{p_{tube} - p_{ref}}{\rho_w \cdot g} \tag{7}$$

This results in an air compression compensated formula to determine the water depth with respect to the measured pressure in the tube and above the water level.

4.2. Fire

To detect fires, the temperature and the amount of smoke are measured. Heat is measured using the integrated sensor of the pressure sensor. For the smoke detection three classical systems exists. While measuring the concentration of carbon monoxide either consumes too much power or is limited in life time, ionic sensors can reach a power consumption as low as 25 µW [17] but consist of a radioisotope. Common photoelectric smoke detectors consume approximately 90 µW. This power can be reduced down to less than 6 µW by using ultra-low power microcontroller units (MCUs) and operational amplifiers and by reducing the sampling ratio down to one sample each 8 s [18]. Based on this and because of the German regularities regarding ionic materials, the smoke detectors are realized based on the photoelectric effect.

As shown in Fig. 3, an infrared LED emits light in a smoke chamber that has to be reflected by particles such that the reflection can be measured by a photodiode. To increase the robustness of the sensor against disturbances such as ambient light, the sensor measures the output of the photodiode when the IRLED is turned off additionally. As in [18], a measurement is done every 8 seconds. If smoke is detected, the interval is reduced down to 4 seconds and after another detection to 2 seconds. After three detections an alarm is triggered. This is done to reduce false alarms, while still keeping the response time lower than 22 seconds in the worst case.

Fig. 3. Schematic of a photoelectric smoke detector.

4.3. Explosion

A typical blast wave as shown in Fig. 4 consists of a leading shock wave and positive pressure phase followed by a negative pressure phase. To estimate its effect on the tunnel's structure and the potential harm on train passengers the most important information is its peak pressure and its impulse of the positive pressure phase.

To measure the blast wave, an acoustic emission sensor, the VS150-M, has been chosen which has been tested successfully in previous projects performed by researchers at the EMI [19-20]. It generates an electrical signal from the deformation of the sensor using a piezoelectric element and therefore needs no supply power. Nevertheless, to measure its signal, an electric subsystem is needed because it is damped if the ADC of the CC2650 is used directly. As in previous work, the most power saving system [21] is to measure the exceedance of several thresholds instead of amplifying the signal. For this purpose three MOSFETs are used that will consume up to 9 µW during normal operation. As opposed to the water ingress and fire detection sensors, the signal of the VS150-M can be used to wake up the MCU in case of an explosion. This allows measuring the start time of the event, the exceedance of different thresholds and the duration of the blast. As it is not important for the system to be sustainable during a disaster event, as it will have enough stored power, the power consumption after the wake up can be neglected.

Given the time how long the thresholds are exceeded, the peak pressure and impulse of the blast wave can be approximated. Using several nodes this is enough to estimate the severity of the blast as well as the energy released.

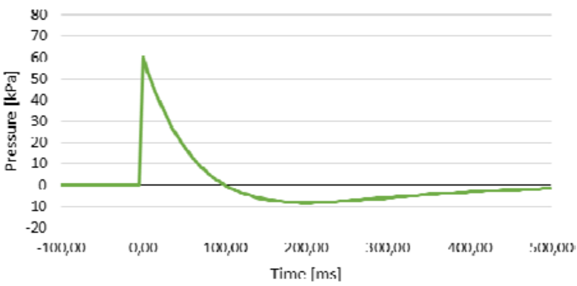

Fig. 4. Example of the Friedlander waveform of a blast wave.

Due to the physical sensor node layout and the limitations of ultra-low power WSNs with regard to time resolution and synchronization, an exact determination of explosion position is not feasible. Using empirically determined thresholds based on the results of in-house explosion experiments at the EMI [19], [22-23] the sensor system can however determine the remaining structural capacity of tunnel walls based on the peak pressure and specific impulse observed at the node. The expected variable impact distance of 0-50 meters (based on 100 m node spacing) can be taken into account when establishing these thresholds.

5. Sensor Nodes

The sensor nodes consists of 3 boards, one for the communication, one for the sensors and one for the energy supply. The communication board consists of the TI CC2650 EM board and an adapter board for the node's stack (as shown in Fig. 5). The microcontroller has an integrated radio module and is used to control all other boards. The EM board integrates a PCB antenna and has the option to mount an external antenna using a SMA connector. It has a sensitivity of -97 dB and a maximum transmission power of +5 dBm. On outdoor range tests distances of up to 200 m where possible without packet losses.

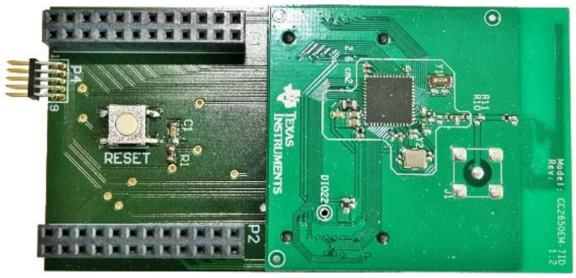

Fig. 5. CC2650 EM Board and Stack Adapter.

The sensor board (see Fig. 6) integrates all three sensor types. The explosion detection circuit is shown on the left side. It consists of the three MOSFETs in combination with an adjustable voltage divider for the threshold exceedance detection and an operational amplifier for the direct signal measurement.

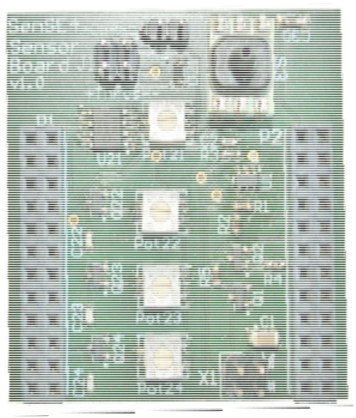

Fig. 6. Sensor Board.

The smoke detection circuit is shown on the right. It consists of a constant current source and a current to voltage conversion circuit. The IR LED and photo diode as well as the ultrasound sensor are located externally. The pressure sensor is shown at the upper right corner and is connected to the I2C interface of the microcontroller.

The energy harvesting board is under development.

6. Experiments

To measure the different sensor subsystems power consumption, the Agilent B2901A has been used as the power source and measure unit. In all cases the power consumption of the whole system has been measured. The power consumption of the single parts is then derived as the difference between the power consumption of the system when the subsystem under test is not powered by the microcontroller and when it is powered and used for data acquisition. This is done according to parasitic effects that occurs for example when the pressure sensor if powered directly but connected via I²C to the sensor board. It is also necessary to measure the subsystems integrated in the sensor board.

For the water ingress detection system a single pressure sensor increases the power consumption by 14.79 µW when no measurement is done and 40.08 µW if the pressure and temperature is measured once per second. Therefore the power consumption of the data acquisition is 25.29 µW which could be reduced to 3.16 µW if the pressure is measured only once every 8 seconds. This would result in a total power consumption of 17.95 µW for the water ingress detection sensor system.

The power consumption of the smoke sensor varies between 4.06 µW for the breadboard design as shown in [1] and 7.75 µW for the sensor board. In both cases one measurement has been taken every 8 seconds. This time interval is chosen as an acceptable response time.

The power consumption of the explosion detection system is measured to be 0.05 µW during normal operation. As the power consumption of the explosion detection system after a detection is not of importance it has not been measured.

To validate the sensor system different functional tests has been done. In Fig. 7 a depth measurement in a water pipe filled with tap water is shown. The hydrostatic pressure at the bottom is measured using a hose connected to a MS5806 pressure sensor located above the pipe.

The water depth is calculated according to Equation (7) using the measured pressure and a previous measured reference pressure. The compression of the air is compensated for the 645 mm long hose. Here the mean error between the nominal and measured depth increases from 1.2 mm for a real depth of 0 mm up to -14.6 mm for a real depth of 500 mm. This corresponds to a relative error of up to 4.32 % as shown in Fig. 8.

To validate the smoke detection system its response to the application of a test spray is shown in Fig. 9. Here a measurement is done every 0.25 seconds in contrast to normal operation. The response of the smoke detector when the IRLED is turned on is shown in red. This can be compared with the response when the IRLED is turned off as shown in orange. The induced difference between both measurements is increased from an average difference of 203.77 mV before the test spray is applied to 758 mV for the peak difference after the application.

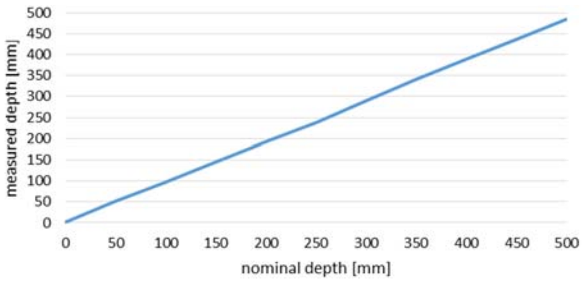

Fig. 7. Calculated depth from pressure readings.

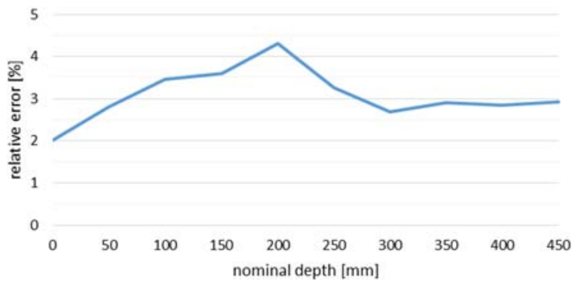

Fig. 8. Relative difference between the nominal and measured depth with respect to the nominal depth.

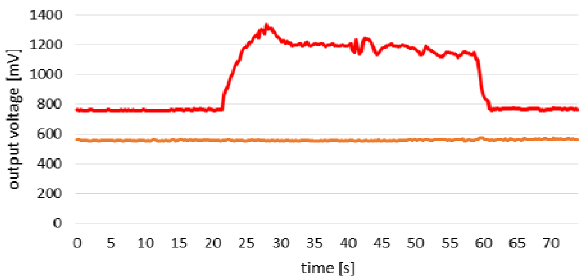

Fig. 9. Response of the smoke sensor when using a test spray as a function of voltage [mV] over time [s]. Red: IR LED turned on, Orange: IR LED turned off.

The explosion detection system has been validated in previous work. The characterization of the actual system and its adaptation to a metro tunnel is ongoing.

7. Discussion

The power consumption of most subsystems complies with the previous assumptions. Only the pressure sensor increases the power consumption higher as predicted. The power needed for taking one measurement per second of 25.29 µW can be also caused by the activation of the I²C interface of the microcontroller. In contrast to that even the needed

14.79 µW when no measurement is done is about five times higher than the power consumption given by the sensors datasheet. A final explanation cannot be found. Nevertheless the output of the senor is very good. Its response is very linear and the accuracy of the derived water depth is sufficient for the rescue forces to get a situational awareness as its relative error is always lower than 4.32 %. The functional test is not sufficient to draw a conclusion, what the reason is for the more or less constant relative error. To exclude a gain error of the sensor itself a measurement of specific pressures would be necessary. More likely the several assumption for the compression compensated formula to calculate the depth will be the reason. Nevertheless, this error is acceptable to create a situational awareness.

The power consumption of the smoke sensor varies between 4.06 µW for the breadboard design and 7.75 µW for the integrated system. This difference can be caused by losses induced by the printed circuit board track and by slightly different components used for the PCB design. All in all the power consumption lies in the range expected with respect to [18]. The response of the smoke detector to the application of a test spray caused an increase of the output difference of a factor of up to 3.7. This verified the general functionality of the sensor. A more precise application of a specified amount of smoke particles per volume would be necessary to characterize the smoke detector.

The power consumption of 0.05 µW for the explosion detection circuit is less than the power consumption that can be measured reasonably with the given test setup. Therefore it can't be seen as a correct measurement. But it shows that the power consumption will be less than the predicted one according to the maximum ratings of the datasheet of the MOSFETs. The functional test and calibration of the integrated explosion detection system remains an area of active research and development.

8. Conclusions

A concept for a wireless sensor network for monitoring underground metro systems, specifically focusing on the requirements and design of the sensors themselves, has been presented. As energy autonomy is desired, low energy consumption of the components, while maintaining the minimum sensing integrity and resolution, is of highest priority.

Using a highly integrated MEMS pressure sensor, ULP components for a smoke detector with a reduced sampling rate and an acoustic sensor for the explosion detection, the expected average power consumption for the sensor system in normal operation can be reduced to 7.8 µW for upper nodes and 35.9 µW for lower nodes. In this case, smoke and water depth are measured every eight seconds. The accuracy of the depth measurement is capable for giving the rescue forces a situational awareness. The smoke detector is very sensitive as its output is increased by a factor of more than three. Therefore, the combination of both nodes provides the capability of detecting explosion, fire and water ingress, while only consuming very low power.

In further work, a hose ending for the pressure sensor has to be developed that ensures robustness of the system in such a harsh environment like a metro. In addition, the pressure disturbances in the tunnel systems induced by passing trains has to be analyzed.

Using the presented sensor system, a larger security management and emergency response system will be developed. All interested parties, such as metro network operators and rescue forces, will be informed in real-time of critical developments. This includes the degradation of tunnel structural integrity and impairment of traversability of tunnel segments in addition to the direct sensor readings. This will help to minimize the secondary damage (e.g. in terms of human life) of disaster events in metro tunnel systems.

Acknowledgements

This work is part of the research project "Sensor-based Security and Emergency management system for underground Metro system during disaster events" (SenSE4Metro) and is funded by BMBF (German Federal Ministry of Education and Research) through the joint program "International cooperation in civil security research: Cooperation between Germany and India" under Grant No. 13N13039.

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