A Concept for an Ultra-low Power Sensor Network
Detecting and Monitoring Disaster Events in Underground Metro Systems

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Keywords: Ultra-low Power, Wireless Sensor Network, Energy Harvesting, Tunnel System.

Abstract: In this paper, 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 from terrorist attacks. 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. The total average consumption for operating the sensor sub-system is calculated to be less than 35.9 µW.

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) (SenSE4Metro, 2016), a concept for a wireless sensor system is introduced that can detect the most significant threats and which provides rescue forces with the relevant necessary information in 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 fulfil 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.

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 (e.g. M. Ceriotti, 2011; L. Mottola, 2010; Z. Sun, 2008) or mine tunnels, (e.g. D. Wu, 2010; H. Jiang, 2009). 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 (e.g. M. Li, 2007). Of the former, Ceriotti et al. presents 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. (2011) 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.

Vincke J., Kempf S., Schnelle N., Horch C. and SchÃďfer F.
A Concept for an Ultra-low Power Sensor Network - Detecting and Monitoring Disaster Events in Underground Metro Systems.
DOI: 10.5220/0006186901500155
In *Proceedings of the 6th International Conference on Sensor Networks (SENSORNETS 2017)*, pages 150-155
ISBN: 421065/17

(2010) 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 (2005) 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. (2011). 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 and especially Raza et al. (2016) showed that only the power consumption of the data acquisition is of interest when using a wake up receiver. Therefore, the focus of this paper lies on the conception of the sensor system 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 (S. Kempf, 2016). 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 (A. Pflitsch, 2010), 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 must be 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 (see Figure 1) with cable wired gateway nodes at each metro station. The topology provides added robustness via path redundancy, as both nodes can be used to forward messages. 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 (O. Gnawali, 2009), 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 data from different nodes may be combined or filtered to only update for significant changes instead of simply forwarding all generated data towards the nearest gateway. This however remains an area of active research and development.

The upper nodes can be used to measure smoke and impact pressure and are powered using a wind energy harvester. The lower nodes measure water ingress and temperature and are powered using a piezoelectric vibration energy harvester attached to a rail. In standard (non-emergency) operation, situational status messages are transmitted during

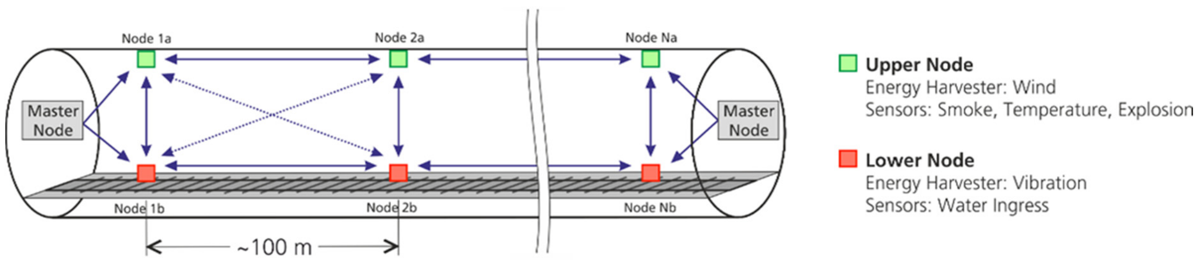

Figure 1: Applied WSN topology in underground tunnel.

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.

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 their shapes are limited. On the other hand they are independent on 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. The simulations (ThermoTun Online, 2016) 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 of up to 1.36 kPa in the tunnel. This would be equivalent to a water level of 138.7 mm. How the pressure is disturbed over the cross section and over the time in a real tunnel has to be investigated.

As an example for the advantages of pressure sensors, two MS5806 can be used to measure the pressure at the bottom and above the water level. Using these values, water levels of up to 9 m with a precision of 0.13 cm can be measured in theory while consuming less than 3 µW for each sensor when measuring once per second. A temperature sensor is also included that can be used for the other sensors in addition, reducing the overall power consumption.
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 sensor 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 the sensor and goes to the ground as shown in Figure 2.

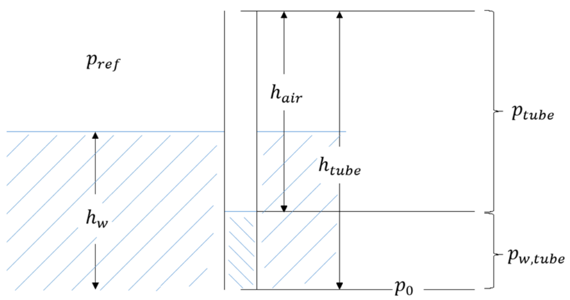

Figure 2: Schematic of the water level measurement system using a tube to measure the pressure at the ground of the tunnel.

The water ingress depth h_w can be determined using the pressure at the base of the tube, assuming that the media is water:

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

In order to determine the pressure p_0, it is necessary to consider the air compression induced by the water ingress within the tube. Using the ideal gas law (pV=nRT), the reference pressure (external sensor) and assuming constant mass, temperature and cross-sectional area within the tube, the height of the air column can be determined:

$$h_{air} = h_{tube} \cdot \frac{p_{ref}}{p_{tube}} \tag{2}$$

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

$$p_0 = p_{w,tube} + p_{tube} \tag{3}$$

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

$$p_0 = \rho_w \cdot g \cdot (h_{tube} - h_{air}) + p_{tube} \tag{4}$$

With (2):

$$p_0 = \rho_w \cdot g \cdot h_{tube}\left(1 - \frac{p_{ref}}{p_{tube}}\right) + p_{tube} \tag{5}$$

Finally, inserting back into (1):

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

4.2 Fire

To detect fires, heat and smoke are measured. Heat is measured using the integrated sensor of the pressure sensor. Three classical smoke detection 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 (Z. Moktari, 2013) 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 (M. Mitchell, 2012). Based on this and because of the German regularities regarding ionic materials, the smoke detectors are realized based on the photoelectric effect. 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 (M. Mitchell, 2012), a measurement is done every 8 seconds. If smoke is detected, the interval is reduced down to 4 seconds. After three detections an alarm is triggered.

4.3 Explosion

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 (A. Stolz, 2010; O. Millon, 2013; F. Schäfer, 2014), 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.

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 (O. Millon, 2013; M. Erd, 2016). 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. As in previous work, the most power saving system is to measure the exceedance of several thresholds. For this purpose three MOSFETs are used that will consume up to 9 µW. 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. Using several nodes this is enough to estimate the severity of the blast as well as the energy released.

5 EXPERIMENTS

The validation of the system is ongoing. 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. In Figure 3 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.

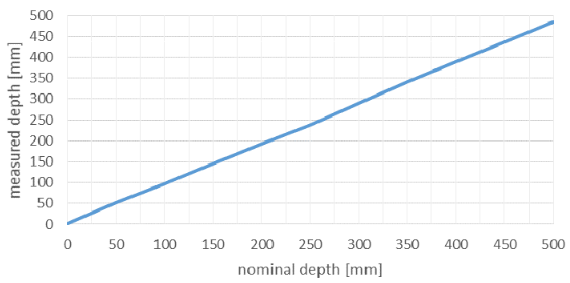

Figure 3: Calculated depth from pressure readings.

The results of the system are shown in Figure 3. The water depth is calculated according to equation (6) using the measured 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 Figure 4.

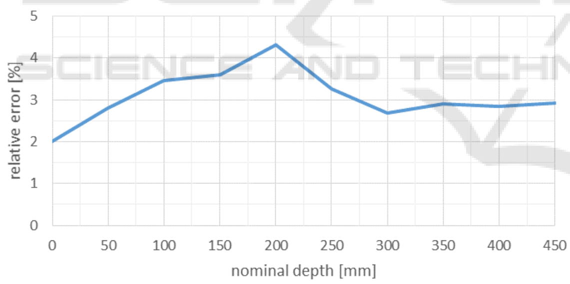

Figure 4: relative difference between the nominal and measured depth.

The power consumption of the smoke sensor is 4.06 µW in the case of one measurement every 8 seconds. The response of the sensor to the application of a test spray is shown in Figure 5. 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 of 203.77 mV up to 758 mV.

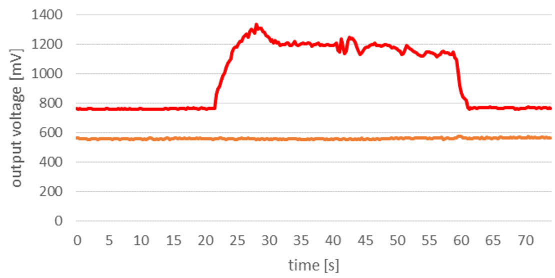

Figure 5: Response of the smoke sensor when using a test spray as a function of voltage (mV) over time (s). Red: IR LED turned on, orange: IR LED turned off.

6 CONCLUSION

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 13.06 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, the sensor system will be integrated and validated. For the pressure sensor, a hose ending has to be developed that ensures the 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 also has to be analyzed.

Using the presented sensor system, a larger security management and emergency response system will be developed, whereby all interested parties, such as metro network operators and rescue forces, will be informed in real-time of critical developments, for instance degradation of tunnel structural integrity and impairment of traversability of tunnel segments due to emergency events in order to minimize the secondary damage (e.g. in terms of human life) of these events.

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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