Intelligent Road Infrastructure - A Concept Study

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***Abstract*—A promising approach for future road construction is based on a surface which is manufactured in a production plant and can be unrolled on a conventional base. This paper deals with the idea to make the road ”intelligent” by integrating a net of sensor nodes. Equipped with acceleration sensors the sensor net can detect the traffic situation. With the knowledge of the exact position and velocity of each car a driver assistance system is able to find the fastest route or to give an accident warning on a very reliable level. This concept study describes the main idea of a low cost, energy harvesting sensor node containing an MEMS accelerometer with frontend, a processing unit, a photovoltaic energy harvesting power supply and a wireless communication link.**

***Keywords*—road construction, intelligent road, MEMS, energy harvesting, sensor node**

I. Introduction

The next step in road building is to introduce a high quality, centimeter thin top cover manufactured in production plants probably on the base of a synthetic material. A better noise reduction and a lower rolling drag can be achieved since a production in a plant is done under best conditions. The feasibility of a ”rollable” road has been shown in [1] and [2].

A conventional street needs a large amount of (oil based) bitumen, which is running out and therefore more expensive. In order to damp down the cost increase the amount of bitumen needed has to be reduced by decreasing the thickness of the bitumen based top layer of the road or to find a low priced suitable alternative material.

The road networks of developed countries are the backbones of their economies. To increase their capacity without building new roads intelligent traffic management systems are needed. These systems need exact information about the traffic flow to avoid traffic jams and minimize the individual traveling times. The quality of traffic management heavily depends on good input data.

Further it is getting more and more challenging and expensive to enhance the safety with vehicle based systems. In near future driving assistance systems will be upgraded to highly automated, nearly autonomous systems which need more reliable data to proceed. Vehicle based sensor systems are not able to provide these systems with data on the required quality level in every situation as shown by [3]. In contrast to this the here proposed infrastructure can be used for autonomous driving in the long run. Furthermore it can also provide information about the road situation ahead of the individual vehicle like humidity, temperature and slickness which are unknown for vehicle based systems.

II. System Concept

Fig. 1 shows a cross section of the ”intelligent” road. The base layer can be build conventional, the top layer is called car-pad (analogy to carpet). The centimeter thin, high quality, industrialy produced car-pad is unrolled and mounted to the conventional base. Therefore the time required for construction works is short.

The industrial fabrication of the car-pad enables the integration of sensors inside the top layer of the road (colored dots in Fig. 1). Integrated wireless sensor nodes allow to measure passing vehicles and different ambient road conditions like temperature or moisture. The cost of the sensor net is almost insignificant compared to present-day’s overall road costs.

Each passing vehicle generates structure-borne sound which propagate through the top layer of the road and can be detected by an accelerometer (see Fig. 2). Accelerometers have very small dimensions, are cheap and can easily be integrated inside a sensor node.

After preprocessing, the data are transmitted to small base stations mounted in beacons at the side of the road. These base stations combine the information of the different sensor nodes to a more global view of the traffic flow at this part of the road. The base stations transmit this information to a central traffic management center and to the passing cars.

Due to the very dense sensor network not only the traffic flow but also local events like accidents or other dangerous situations like cars in blind spots can be detected and road users can be warned. Since the information is determined by the infrastructure and not by a car based system, the system will even work if most users are *not* equipped with a vehicle on-board unit. To participate from warning signal no special hardware is needed. The on-board unit can be integrated into the navigation system.

Subsequently the energy harvesting sensor node is discussed. Besides the utilization in the road, this sensor node can also be used for structural health monitoring (e. g. in bridges or buildings).

III. Initial Measurements

To the knowledge of the authors this is the first project which wants to use the structure-borne sound of vehicles for their detection. Since there were no data available for the

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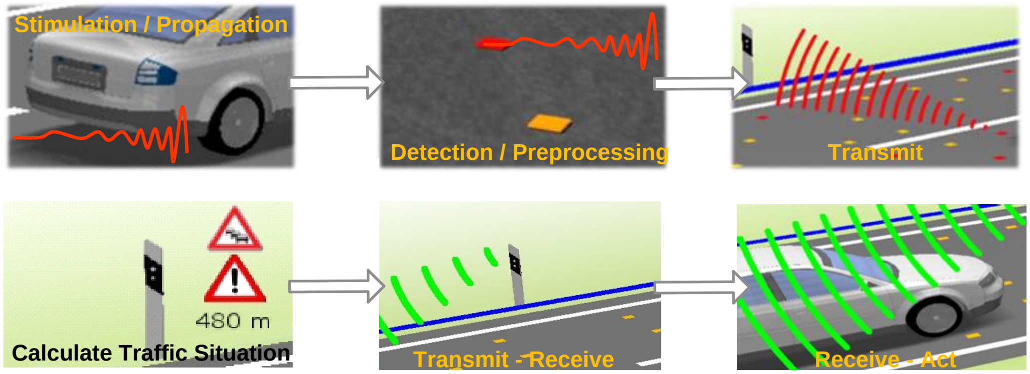

Fig. 2. Working principal.

damping of the structure-borne sound nor the spectrum and the amplitude of that sound a measurement series was performed.

A commercial accelerometer with a sensitivity of 2270 mVs^2/m was used. Fig. 3 shows the accelerometers output for a passing car with 50 km/h in a distance of 30 cm. The peaks in the acceleration show the points when the car's axes passes the sensor.

In order to reduce the amount of transmitted data, preprocessing is needed inside the sensor node. This can be realized using a straight forward filter as shown in Fig. 4 which can recognize the axes of passing vehicles.

The filter output is drawn in Fig. 5. Its period was experimentally determined to 10 ms, the sample time to 1 ms.

IV. Sensor Node

The structure of the sensor node to be integrated in the top layer of the road is shown in Fig 6. The power supply of the sensor node consists of series connected solar cells, power regulators, an energy storage and a power management unit. A MEMS (Microelectromechanical System) accelerometer is the primary sensor of the node to detect the structure born sound of passing vehicles. Further sensors for temperature and

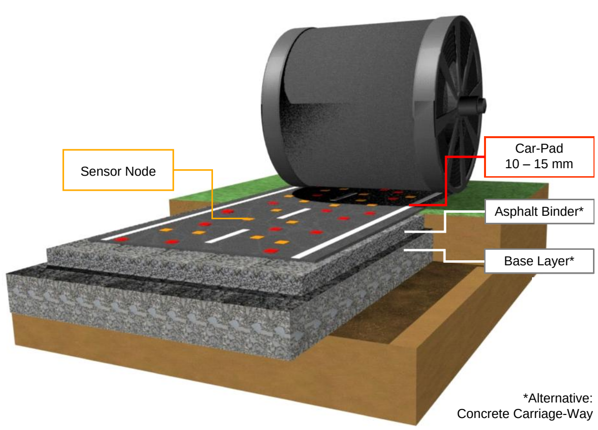

Fig. 1. Structure "intelligent" road.

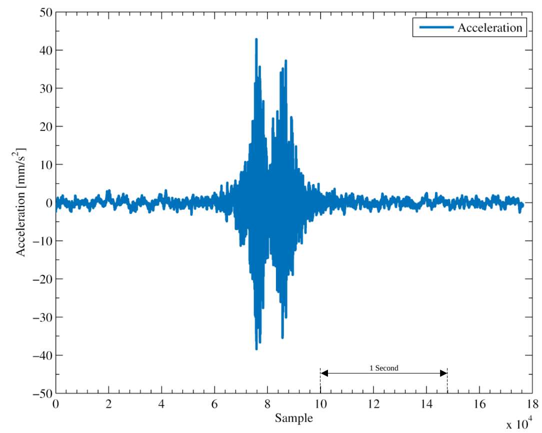

Fig. 3. Passing car with 50 km/h in 30 cm distance.

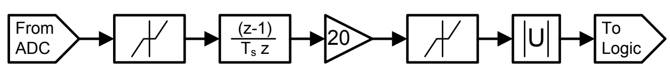

Fig. 4. Digital Filter Algorithm.

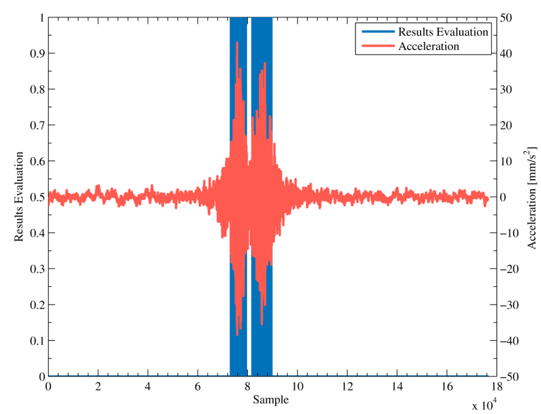

Fig. 5. Recognition with the filter of a passing car with 50 km/h in 30 cm distance.

humidity can also be attached to the ASIC. Only the solar cells, the supercapacitor and the accelerometer sensing element are

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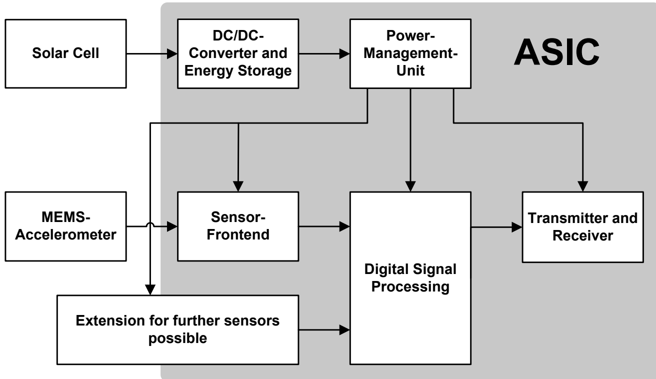

Fig. 6. Block diagram sensor node.

external components. All other functions are fully integrated into the ASIC. By this the sensor node dimensions, its power consumption and its price are drastically reduced.

In the following section the power supply and its components are described. Afterwards the different building blocks of the sensor node, the transmitter, the MEMS accelerometer and the accelerometer frontend are presented.

A. Power Supply

The power supply for the sensor node inside the top layer of the road is a critical issue. A lifetime of 10 years is targeted for the top layer of the road. Therefore it is necessary that the senor node can operate for an even longer period of time. Batteries are not suitable for this application, because it is not possible to operate the sensor nodes for the required lifetime with affordable and small enough batteries inside the top layer of the road. Especially the high temperature differences during a year shorten the lifetimes of batteries and make their use in this application impossible [4].

Since primary batteries are not an option energy harvesting has to be used for the power supply. In [5] different energy sources like solar cells, vibration or temperature energy harvesting have been compared to find the optimal energy source for this application. Solar cells have been selected, because they offer the highest energy density for this application. Furthermore they are well studied and available for low cost. Their only drawback is the need for a transparent package with low reflection to maximize the irradiated power for the solar cell. To keep the sensor node operating during night or times when the solar cell is covered with e. g. snow an energy storage is required. In addition a power management unit is needed to control the electronics to maximize the harvested energy and the operation time of the sensor node. This section describes the structure of the power supply and its components.

1) Photovoltaic Cell: Today different types of solar cells based on different materials like monocrystalline silicon or organic polymers are available. In comparison to the other types silicon thin film solar cells offer medium efficiency of more than 10 %, low price and long term stability [6]. Furthermore the efficiency of amorphous silicon is quite constant even for weak irradiated powers [7]. To consider the life time degradation an efficiency of only 7.8 % is assumed for the power supply.

2) Energy Storage: The output power of the photovoltaic cells depends on the irradiated power which varies strongly. Therefore an energy storage is needed to supply the sensor node with enough energy if the solar cell cannot power it alone. For this application the specific energy and the number of charge-discharge cycles are the most important parameters for the energy storage. The specific power is not important because the sensor node needs less than 1 mW. Li-ion rechargeable batteries and supercapacitors are the most promising energy storage technologies for this demands [8]. Due to the harsh temperatures between -40 and 80°C in this applications batteries are not suitable because their capacity would drastically decrease within the first years of operation [4]. That is why supercapacitors have been selected as energy storage technology. They do not limit the lifetime of the sensor node nor lose much capacity due to the temperature range.

3) Power Management System: Besides the energy source and storage DC/DC-converters are needed to improve the available power for the sensor node. A direct connection of the solar cell to the ASIC with the supercapacitor in parallel would not work, because the supply voltage would change between 0 V and the open circuit voltage of the solar cells. Therefore the power supply concept depicted in Fig. 7 was developed. Instead of one large solar cell, 6 smaller ones with the same area are connected in series to increase the output voltage. A multiplexer can connect the supercapacitor or the solar cells to a charge pump. Instead of directly connecting the solar cells to the load, a charge pump is used to keep the cells in their maximum power point. This can increase the harvested energy by more than 25 % despite the losses in the charge pump [9]. The output energy from the charge pump can be used to charge the supercapacitor or directly power the LDO. Using the Multiplexer (MUX) and Demultiplexer (DEMUX) lowers the efficiency for the direct connection due resistive losses. Since the blocks only switch infrequent the transistors can be quite large minimizing the resistive losses. These multiplexers are used to enable four different operation modes. The first one is used to charge the supercapacitor with the energy out of the solar cells. In this mode the charge pump performs the maximum power point tracking and can increase the output voltage of the solar cells to utilize the full voltage range (up to 5 V) for the supercapcitor and maximize the stored charge. The ASIC is powered in the second operation mode from the supercapcitor. A LDO is used to stabilize the power supply voltage. Since the losses in the LDO are proportional to the voltage drop across it, the charge pump is used to minimize it. The ASIC can also be direct powered via the charge pump and the LDO if the output power of the solar cells is sufficient. Furthermore a mixed supply from the solar cells and the supercapacitor for the ASIC is possible, too.

The power supply of the sensor node has been designed for an operation in Germany but by adapting the solar cell area and supercapacitor size it can by used all over the world.

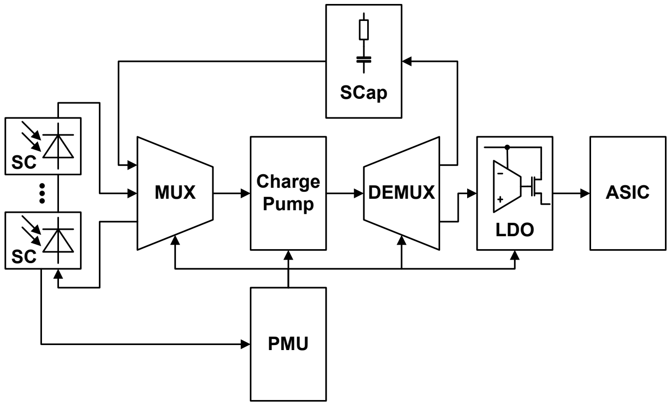

Fig. 7. Power Supply Sensor Node.

The ASIC has to be active every $20\,\mathrm{ms}$ for $2\,\mathrm{ms}$ to be able to detect passing vehicles with a speed up to $180\ \mathrm{km/h}$. During its active phase the ASIC needs less than $3.3\ \mathrm{mW}$. Therefore it consumes maximal $248\ \mathrm{mW}$ per month. Using the method described in [10] for the area around Aachen in Germany an average irradiated power of $0.69\ \mathrm{kWh/m^2}$ per day can be calculated for an availability of $95\,\%$. For an efficiency of $7.88\,\%$ an area of $3\ \mathrm{cm^2}$ of the solar cells is enough for the operation of the sensor node. The efficiency of the charge pump is assumed to be $90\,\%$ with a quiescent current of $2\ \mathrm{\mu A}$. Taking the production variations and degradation over the lifetime into account the supercapacitor size has been set to $106\ \mathrm{mF}$ which is $40\,\%$ larger than needed. The size of the energy storage enables the sensor node to operate in total darkness for 31 days which should ensure operation even during winter with a lot of snow. A more detailed design based on exact data will lead to a drastic size reduction for the solar cell and the energy storage, which will lower the price per sensor node.

B. Transmitter

The transmission of the senor data from the sensor node to the base station has to be wireless since a wired transmission would be too complex and expensive. For an approximation of the required energy for the data transmission the data packets and the attenuation have to be estimated. One data packet needs to consists of an ID, the sensor data and a checksum. It can be dimensioned to be less than 256 bit. The frequency band for the data transmission should be selected below $1\ \mathrm{GHz}$ due to the better propagation properties. Therefore the frequency ranges $869.40 - 869.65\ \mathrm{MHz}$ or $869.70 - 870.00\ \mathrm{MHz}$ have been selected for the data transmission. The attenuation for the radio wave could be calculated to be less than $61\ \mathrm{dB}$ for a German highway with three lanes per direction. This calculation assumes the absorption coefficient inside the top layer of the road to be 1.67. Since the base station will have more power available a transmitted power of $0.5\ \mathrm{mW}$ is sufficient for a stable data transmission. For this application the data transmission can be achieved with less than $2.4\ \mathrm{J}$ per data packet and fits well in the calculated power budget of $3.3\ \mathrm{mW}$ for $1\ \mathrm{ms}$ [11].

C. MEMS Accelerometer

Acceleration can be detected with different techniques like capacitive, piezoelectric or piezoresistive sensing. For this application capacitive MEMS accelerometers are most suitable, because they offer a small outline, low cost, low power consumption and constant quality. Due to their small size they have a low seismic mass which causes a high mechanical noise floor limiting the achievable resolution. The initial measurements on the test track have shown that the required resolution for the sensor nodes is $1\ \mathrm{mg}$, which can be achieved with MEMS accelerometers [12]. The challenge for this application is to maintain the required resolution with as little power consumption as possible and for a competitive price. Therefore the MEMS accelerometer have to be optimized for the structure born sound detection and for lowering the requirements for the readout circuits and its power consumption.

D. Accelerometer Readout Circuit

One main challenge of sensor node design for the ”intelligent” road infrastructure is the power efficient readout of the capacitive MEMS accelerometer. For a small parasitic capacitance at the readout node of the sensing element continuous time voltage sensing (CTV) is superior to other readout techniques like switched capacitor [13]. Furthermore it shows a better performance for low power readout circuits, because the resolution is not limited due to noise folding. In [5], [14] a special readout circuit was designed to meet the requirements for this application.

The accelerometer readout circuit is based on [12], [15] and uses dual-chopper stabilization for noise and offset reduction as well as power saving. As depicted in Fig. 8 the frontend uses energy efficient square wave stimulation with the frequency PHH $\pm$ PHL on port 1 and 2 of the sensing element. The acceleration dependent charge variations are evaluated on the middle port (M) of the sensing element. The first operation amplifier converts the charge into a voltage and adds flicker noise and offset to the signal. Its gain can be selected with the *gain0* and *gain1* switches. A passive mixer is used to mix the signal down from PHH $\pm$ PHL to PHL. Since the flicker noise and offset is around DC it is mixed up to PHL and apart from the signal. The second operational amplifier further boosts the signal and is more energy efficient since it operates at lower frequencies. After the second mixer the signal is mixed to DC and the noise is at PHL and PHH $\pm$ PHL, respectively. Therefore the noise can be reduced with a lowpass filter. The signal is digitized with an analog to digital converter.

To increase the resolution different calibration cycles are intended in the readout circuit. The sensor offset, which can drive the sensor frontend into saturation, is coarse reduced with an capacitor array at the middle port of the sensing element. A fine reduction is achieved with an DAC in the input stage of the second operation amplifier (not depicted in Fig 8). Furthermore the gain and offset for other building blocks are calibrated. To achieve the needed resolution of $1\ \mathrm{mg}$ a gain of more than

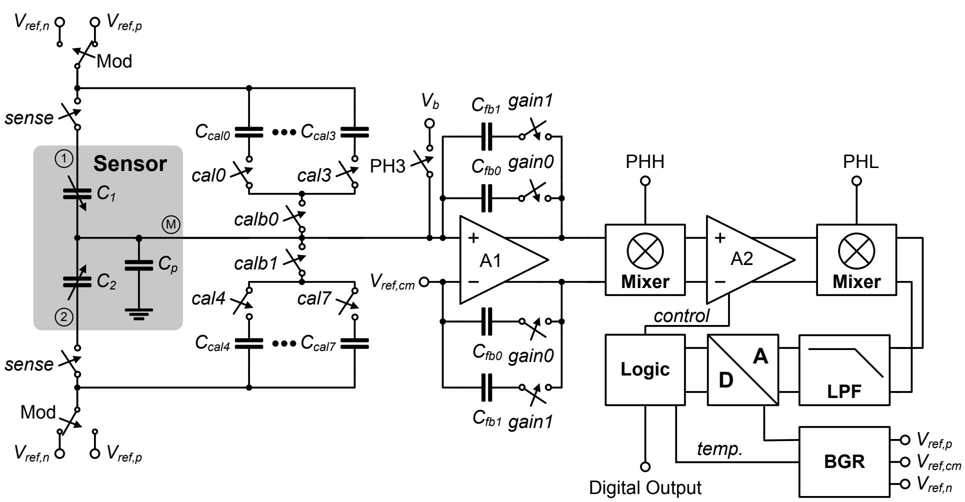

Fig. 8. Accelerometer Frontend.

60 dB is required which limits the input acceleration range to less than 1 g. The gains of both operational amplifiers are controlled by the logic to keep the frontend from saturating and therefore increase the acceleration input range.

V. Conclusion

In this paper a promising concept study of an "intelligent" road has been shown. With this road the traffic situation can be determined without having special equipped cars. Due to the absolute and accurate position information of each car the exact traffic situation can be derived. Traditional navigation systems extended with a receiver can be used as vehicle on-board units. The system can not only be used for optimal routing but also to enhance security by giving drivers assistance and warnings.

It could be shown in a measurement series that structure born sound can be used to detect vehicles and their speed. The proposed sensor net can easily and at low cost be integrated into an industrial fabricated "rollable" road. We have shown the sensor node on block level and listed the specifications. These specifications have been verified by reported circuitries listed in literature or by own transistor level simulations.

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