Smart river monitoring and early flood detection system in Japan developed with the EnOcean long range sensor technology

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***Abstract*—Smart city is a term which is heard very often nowadays. It is a synonym for a variety of IoT solutions integrated into the daily city life, for the benefit of its inhabitants. One of these solutions, presented in this paper, is a river monitoring and early flood detection system. The proposed solution consists of an ultrasonic sensor adapted to the EnOcean solar-powered, long range sensor module. This maintenance free, self-powered sensor module was deployed in a couple cities in Japan to monitor river water level. The specially designed generic sensor interface allowed the adoption of the off-the-shelf MaxBotix ultrasonic sensor with a 10 meter measuring range. This can then be turned into a flood detection system which satisfies the standards prescribed by the Japanese River Bureau under the Ministry of Land, Infrastructure, Transport and Tourism. The detailed communication between the ultrasonic sensor and the sensor module via EnOcean Generic Sensor commands is shown. In addition, the transmission of the measured data over greater distances with the use of the EnOcean long range, low power communication protocol, is outlined.**

***Index Terms*—ultrasonic sensor, water level monitoring, EnOcean, energy harvesting, long range, sensor module.**

I. INTRODUCTION

With today's extreme climate changes and global warning effects, floods are continuously occurring on a global scale. In Japan, this situation is very unique, because the majority of rivers are very steep with a short distance from the source to the sea (Fig. 1). This results in rapid flow of water [1].

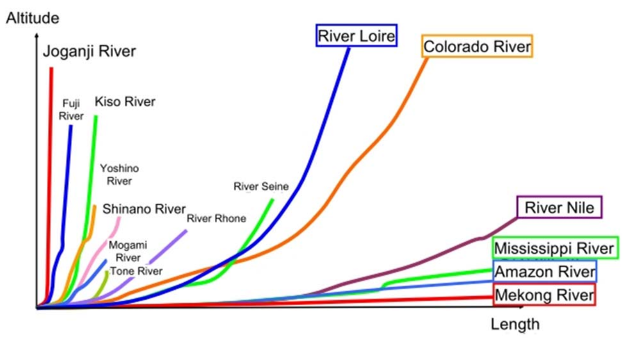

Fig 1. Comparison of different riverbeds from all around the world [1].

Additionally, approximately half of the population and three-quarters of total assets are concentrated in low-lying areas. Major damage is anticipated when flooding occurs. Furthermore, most urban areas are located in low-lying areas that are lower than the water level during floods [1]. Using the early flood detection system would save many assets and moreover, allow prompt evacuation thus, saving human lives.

River level monitoring is not a novelty and different sensors and techniques are used for this purpose. Authors in [2] developed a very large and expensive system based on the horizontal acoustic Doppler current profiler (H-ADCP). Attempts with a cheaper ultrasonic sensor resulted in a very simple prototype. However, it is not completely applicable in outdoor conditions due to lack of robustness and measurement accuracy [3]. Other authors rely on video surveillance systems [4] which require specific infrastructure and a deeper data analysis. There are also solutions with a rainfall sensor network [5], although these are not very applicable as an early flood detection system. Newer solutions include river monitoring with inclined LiDARs [6]. The proposed solution in this paper relies on a very robust and compact ultrasonic sensor. This is then attached to a completely energy independent, self-powered and maintenance free sensor module from EnOcean. Our solution is not expensive, allows easy installation and deployment, and transfer of measured data over larger distances.

This paper is organized into five sections. After the Introduction, Section II describes the ultrasonic sensor used. Section III provides more detail about EnOcean's self-powered module. Section IV describes the measurement protocol and the specifications required when water level is measured on Japanese rivers. Section V. contains experimental results and real use cases of the developed smart river and early flood detection system.

II. ULATRASONIC SENSOR

As a measuring element, the ultrasonic sensor MB7383 from MaxBotix is used [7]. It has a maximum measurement range of 10 meters with a 10 mm resolution. The measurement values are obtained on the serial output pin and

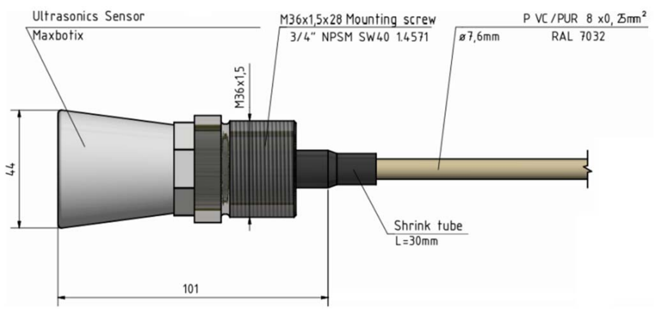

Fig. 2. MaxBotix ultrasonic sensor enclosed in housing with the attached cable.

the data format is TTL (transistor-transistor logic), where +Vcc represents logic 1, and 0 V represents logic 0. The maximum range reported is 9998 mm, while a range value of 9999 corresponds to no target being detected in the field of view. Different supply voltage levels have been tested to obtain the maximum range and accuracy of the ultrasonic sensor. Table I shows how different supply voltages affect ultrasonic sensor performance.

TABLE I. Measurements of the distance from the bridge to the river in mm for different ultrasonic sensor supply voltages. Value 1068 represents false measurement.

	3.6 V			4.0 V			5.0 V	
1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
819	818	823	820	1068	820	823	817	819
817	819	1068	821	820	819	818	818	817
818	819	818	818	821	820	819	818	817
820	820	822	818	818	1068	817	818	818
1068	821	821	1068	819	817	819	817	1068
820	820	823	819	818	818	821	819	821
824	823	822	821	817	819	1068	817	818
824	1068	1068	820	819	821	819	819	817
826	823	822	819	1068	819	1068	817	819
823	1068	1068	821	821	820	823	822	821

Three times 10 measurements of distance have been recorded on a relatively steady river and the measurement success rate is expressed for 3.6 V, 4 V and 5 V. F-measure [8] from the results above gives the following measurement success rate: 80% at 3.6 V, 87% at 4.0 V and 90% at 5.0 V. A compromise can be made between a slightly lower measurement success rate and energy consumption. The ultrasonic sensor supply voltage level is proportional to the sensor`s current consumption. Table II shows the sensor's energy consumption for different supply voltages of 3.6 V and 5 V respectively. Due to the better success rate closer to the maximum measurement range, 5 V was chosen for sensor supply voltage.

A. Generic sensor PCB

To be able to communicate with the existing EnOcean long range sensor module, the ultrasonic sensor needs some additional logic components. A small PCB was built which contains a low power microcontroller STM32L071K and a step-up converter. This ensures a stable 5 V supply voltage to the ultrasonic sensor from the variable input voltage, which can be seen on the block diagram in Fig. 3.

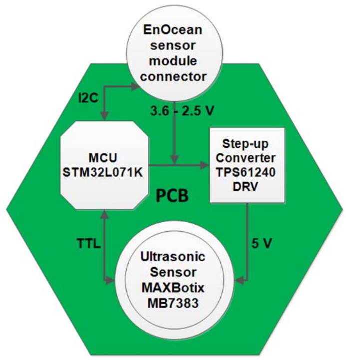

Fig. 3. Generic sensor PCB block diagram.

All the communication between the microcontroller on the generic PCB and the microcontroller on the EnOcean sensor module is done via I^2C lines. The same lines are also used to update the firmware when needed. This is done by triggering the bootloader mode of the STM32L0x microcontroller. The microcontroller on the generic sensor PCB is always powered, but 99% of time it spends in sleep mode. During this time, the ultrasonic sensor is shut down. The entire generic sensor PCB drains a constant current of around 3 μA. After connecting the MaxBotix ultrasonic sensor to the PCB in Fig. 3, the sensor becomes a generic ultrasonic sensor. It is then capable of communicating with the EnOcean sensor module via generic sensor commands described in chapter IV.

III. SOLAR-POWERED ENOCEAN SENSOR MODULE

The main source of the energy supply and central unit of the water level measurement system, is the EnOcean solar-powered long range sensor module. The sensor module characteristics and its unique communication protocol are described in [9]. Since the sensor module has a limited power supply in the form of a 40 F supercapacitor, the ultrasonic sensor needs to fulfill certain current consumption criteria so to not drain the supercapacitor within one measurement cycle. As it can be seen in Table II, at 5 V the sensor's average energy consumption per one measurement cycle is 8 mWs. The available energy from the supercapacitor (while taking into consideration the operating supply voltage from 3.6 V to 2.5 V) is expressed with (1):

$$Energy = \frac{1}{2}CV^2 = 134.2\ Ws \qquad (1)$$

where,

C is the capacity of the supercapacitor (40 F).
V is the difference (1.1 V) between maximum and minimum supply voltage.

Equation (1) shows that the sensor module has enough energy stored to support 20 water level measurements, and three radio transmissions of measurement results per every wake-up cycle. Three radio transmissions need around 67.5 mWs, making it the most consuming operation.

TABLE II. Energy consumption of the MaxBotix ultrasonic sensor when powered with two different supply voltages.

Sensor@3.6V	Start-up time [s]	Average current [A]	Peak current [A]	Capacitance [F]	Measure time [s]	Energy [Ws]
MB7383-100	1.60E-01	2.30E-03	4.90E-02	4.70E-05	1.66E-01	**3.54E-03**
	34.32%		22.85%	7.23%	35.60%	**100.00%**
Sensor@5.0V	**Start-up time [s]**	**Average current [A]**	**Peak current [A]**	**Capacitance [F]**	**Measure time [s]**	**Energy [Ws]**
MB7383-100	1.60E-01	3.10E-03	9.80E-02	4.70E-05	1.66E-01	**8.09E-03**
	30.65%		30.28%	7.26%	31.80%	**100.00%**

The sensor module communicates with the ultrasonic sensor via the above mentioned generic PCB, and the specially developed GSI (Generic Sensor Interface) commands described in the next chapter. Fig. 4 shows the generic ultrasonic sensor attached to the EnOcean self-powered sensor module, with compact housing and small integrated solar cell.

Fig. 4. EnOcean self-powered sensor module with the attached generic ultrasonic sensor.

IV. MEASUREMENTS AND COMMUNICATION

To satisfy the measurement criteria prescribed by the Japanese government [10], the developed river monitoring sensor system has to adapt its operation to the type of the river as shown in Table III.

TABLE III. Definition of measurement intervals and number of the observations for different types of rivers [10].

River size	Interval	Duration	# of observation
Great river	10min	24hrs	Ca 150
Mid and small	5min	12hrs	Ca 150
River with a rapid rise in water level	2min	5hrs	Ca 150

Besides measurement interval, it is also defined that the minimum measurement resolution has to be 1 cm and that water level should be measured in the following way:

1. One measurement sampling is done within 1 second.
2. Total measurements per cycle should last min. 20 seconds.
3. 2 maximum values or 2 minimum values can be neglected to minimize the influence of incorrect measurement data.

The generic ultrasonic sensor has two modes of operation: “monitoring” mode and “critical” mode. In monitoring mode, the measurements will be taken by default every 10 minutes, but only transmitted every 2 hours (default value). If the water level rises and the measured distance drops below a certain threshold level, the device will enter critical mode. In critical mode, measurements are taken by default every 5 minutes and every measurement will transmitted. After 150 (default value) measurements, if the distance to the surface of the water rises above the threshold level, the sensor system will return to normal mode. If the water level doesn’t drop enough, the device will remain in critical mode and take another 150 measurements before checking again. Each measurement cycle performed by the ultrasonic sensor will last for 20 seconds. During this time, the distance will be measured by the ultrasonic sensor every second. At the end of the measurement cycle, the median value will be selected and used as the result of the measurement.

It is intended that the ultrasonic sensor controls when the measurements are performed and when they should be transmitted. Interrupts will be generated to inform the EnOcean sensor module that a new measurement is available. If the sensor module requests a measurement, the last measured value will be reported, instead of starting a new measurement. If a measurement is requested before a measurement has been taken, a measurement value of 0 meters will be reported. This will happen when the generic ultrasonic sensor is for the first time connected to EnOcean sensor module. After start-up, the generic ultrasonic sensor will start a measurement cycle and then generate an interrupt. Before emitting an ultrasonic wave and measuring distance, the ultrasonic sensor, for about 120 ms on the UART line transmits factory stored data relevant to sensor identification. This is not optimal behavior of the MaxBotix ultrasonic sensor, as this action is consuming energy and it is not relevant for the measurement process. Current peaks, as well as UART communication and supply voltage level after ultrasonic sensor is powered, can be seen in Fig. 5.

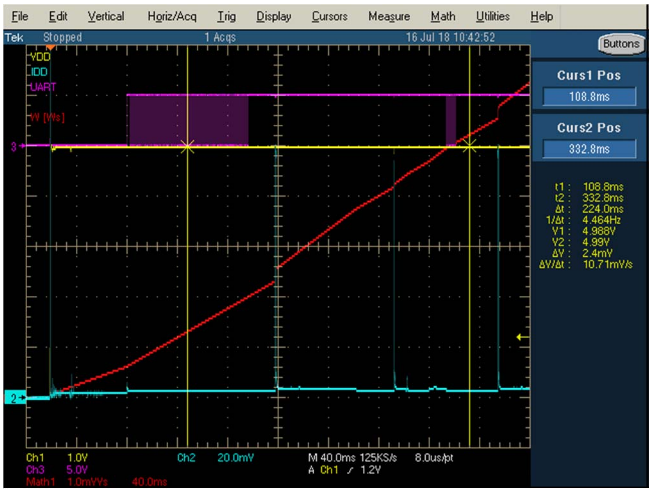

Fig. 5. Start-up of the ultrasonic sensor and measurement data transfer (purple line) together with the current peaks (blue line) and calculated energy consumption (red line).

A. *Generic Sensor Interface commands and communication protocol*

The main aim of the interface is to enable the connection of different sensors to the EnOcean sensor module with no additional effort inside the sensor module itself. The protocol is specified on all OSI (Open System Interconnection) layers [11]. On the lower layers, it incorporates the I^{2}C standard with dedicated lines for interrupt handling. The Generic Sensor Interface defines the communication between the EnOcean long range sensor module and a generic sensor, which is in this case an ultrasonic water level sensor [12].
The flow of the data between the ultrasonic sensor and the EnOcean sensor module, is based on the exchange of the GSI commands (Tables IV-VII) and it runs using the following algorithm:

1. Sensor module wakes up generic ultrasonic sensor by pulling separate power-on line high.
2. The generic ultrasonic sensor creates an interrupt on the interrupt line. This tells the sensor module that it is ready for operation.
3. The sensor module sends a Start Measurement Request (SMS) via I^{2}C lines to the generic ultrasonic sensor.
4. After the measurement is done, the generic ultrasonic sensor creates an interrupt on the interrupt line. Then the sensor module receives the measurement result with the Get Measurement Result (GMS) command.

At the end of every command, the 16 bit cyclic redundancy check (CRC) ‘CCITT-FALS’ is used. Generator polynomial is 0x1021 with an initial value of 0xFFFF [12].

TABLE IV. Request command structure [12].

REQUEST	Offset	Size		Value	Description
	0	1	Add + Op	0xC4	I2C Slave Address: 0x62, Operation: Write
	1	1	Length	0xnn	Specifies length of DATA_PL
Data_PL	2	1	**Packet Type**	0b0XXX XXXX	
	3	x	Content	0x...	Contains the actual data payload with topics: - Data (e.g. settings) - Function codes x = variable length of Content
	3+x	2	CRC16	0xnnnn	Data integrity check over Data_pl

TABLE V. Response command structure [12].

RESPONSE	Offset	Size		Value	Description
	0	1	Add + Op	0xC5	I2C Slave Address: 0x62, Operation: Read
	1	1	Length	0xnn	Specifies length of DATA_PL
Data_PL	2	1	**Packet Type**	0b1XXX XXXX	
	3	1	Return Code	0x00	Return code of the requested command.
	4	X	Additional content	0x...	Additional content returned by the requested operation if available. Can be also none. If included or not is defined by REQUEST type, actual Return code value. It is also signalized by LENGTH of DATA_PL.
	4+x	2	**CRC16**	0xnnnn	Data integrity check over Data_pl

TABLE VI. Examples of the request packet types [12].

Type	Name	Description
0x00	NA	Reserved
0x01	INFO_SIGNAL	Detecting presence of the slave by a default and short request message.
0x02	INTERRUPT_SIGNAL	Detecting & confirmation of interrupt by sensor signal.
0x03	START_MEASUREMENT	Triggering measurement.
0x04	GET_MEASUREMENT	Receiving measurement results
0x05	TUNNEL_COMMAND	Tunnels a command to another connected Sensor
0x06-0x0F	RESERVED	Reserved for future versions
0x10	SET_PARAMETER	Overall parameterization command to set parameters.
0x11	GET_PARAMETER	Overall parameterization command to get parameters.
0x12-0x1F	RESERVED	Reserved for future versions
0x20-0x2F	DEBUG	Debugging commands manufacturer specific
0x30-0x7F	RESERVED	Reserved for future versions

TABLE VII. Examples of the response packet types [12].

Type	Name
0x80	NA
0x81	INFO_RESPONSE
0x82	INTERRUPT_SIGNAL_RESPONSE
0x83	START_MEASUREMENT_ RESPONSE
0x84	GET_MEASUREMENT_RESPONSE
0x85	TUNNEL_COMMAND_RESPONSE
0x86-0x8F	Reserved for future versions
0x90	SET_PARAMETER_RESPONSE
0x91	GET_PARAMETER_RESPONSE
0x92-0x9F	Reserved for future version
0xA0-0xAF	DEBUG_ RESPONSE
0xB0-0xFF	Reserved for future versions

V. Experimental Results

Before the developed sensor system was installed in the field, dark time run operation had to be tested. Dark time operation represents the sensor module operation time with the attached generic ultrasonic sensor and without the supercapacitor being recharged via the solar cell. During this test, one generic ultrasonic sensor was set in critical mode by changing the distance threshold to 2 meters. The solar cell of the EnOcean sensor module was also covered to prevent recharging of the supercapacitor. Measurements and the transmission of the measurement results over the air occurred every 5 minutes. The entire sensor system ran until the voltage on the supercapacitor dropped to 2.5 V. This is when the sensor module shuts down automatically until is recharged again. In parallel, another sensor module ran with another generic ultrasonic sensor, but now set in the monitoring mode. In this mode, measurements were triggered every 5 minutes while the transmission of the data over the air occurred every 2 hours. Fig. 6 compares the dark time operation for these two different operation modes.

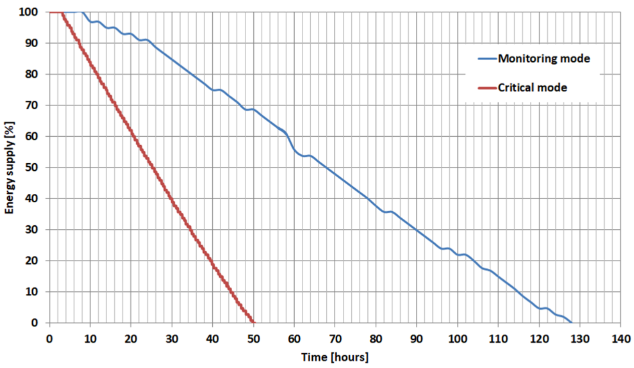

Fig. 6. Dark time operation of the sensor system for two different surveillance modes.

It can be seen when the generic ultrasonic sensor operates in critical mode, its dark time operating life is 57% shorter. This needs to be taken into the consideration so that entire sensor system has enough energy to operate, even in the worst case conditions.

After energy consumption is defined, different types of 3D printed cones for the ultrasonic sensor, were tested above different river flow variations. Table VIII summarizes the measurement success rate depending on the cone used and the river conditions. In Fig. 7 the different types of cones used are depicted and Fig. 8 shows an example of “calm” and “very wild” river flow respectively.

TABLE VIII. Measurement success rate for different cone types and different river flow.

Cone type	River type and the distance to the bridge		
	Calm (9.1 m)	Wild (9.6 m)	Very wild (8.5 m)
No cone	100%	38%	14%
Extended cone	100%	97%	24%
Cylinder cone	100%	56%	4%
Spy cone	100%	100%	69%

Fig. 7. Different 3D printed cone types used during water level measurements.

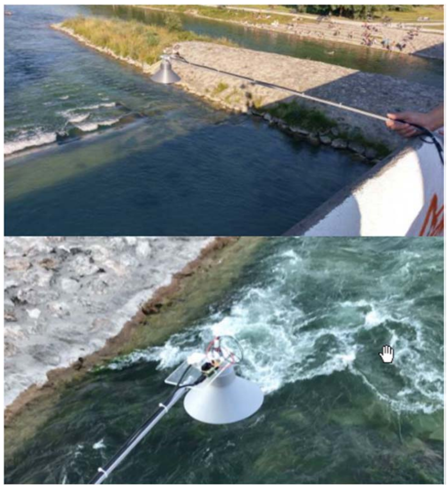

Figure 8. Measurements with the spy cone on a “calm” river flow and a “very wild” river flow.

The complete system installed above the river in Hyogo prefecture in Japan can be seen in Fig. 9. All the benefits of the EnOcean self-powered sensor module are exploited; compact size, self-powered, maintenance free and long-range transmission. The closest receiver is 2 km away from the EnOcean sensor module itself.

Fig.9. Complete smart river monitoring and early flood detection system installed above the river in Hyogo prefecture, Japan.

ACKNOWLEDGMENT

Special thanks to Tobias Meyer for his contribution to the Generic Sensor Interface specification development and to Rajdeep Deo for the paper review and the grammar check.

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