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Methodology for the Choice of a Right Digital Magnetometer for the Vehicle Detection Purposes

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Abstract: The paper is aimed at the problematic of vehicle detection, which is based on the employment of standard digital anisotropic magneto-resistive magnetometer sensors. There is a number of suitable sensor modules available in the market, which can be used for this purpose. The sensors, however, differ in parameters, such power consumption, maximal sampling frequency, measurement range, or measurement sensitivity. The aim of this paper is to provide a kind of coherent comparison of such as sensor performance. The bank of sensors is tested first in the laboratory environment and then, the sensors with the best results are further tested in the outside scenario. During the test, the needs of the final application were stressed, that the proper sensor module will be chosen. This paper is an extended version of the conference paper [1], with an added section dedicated to the outside measurements.

Keywords: Magnetometer, Sampling, Performance, Power Consumption, Vehicle Detection.

1. Introduction

The world of information technology is now more than ever characterized by the interconnecting of individual systems. According to IoT Analytics [2], more than 17 billion devices are currently connected, of which about 7 billion are the Internet of Things (IoT). It should be noted that smartphones, tablets, and laptops are not included in this amount. The number of active IoT devices is expected to rise to 10 billion by 2020 and t22 billion by 2025.

The largest number of devices are currently connected via short-range technologies (e.g. Bluetooth, ZigBee, Z-wave).

In summary, these technologies are referred to as Wireless Personal Networks (WPAN). It is expected that a large part of the future growth of IoT devices will be provided by the development of low-power Wide Area Networks (LPWANs). The main standards in this area (Sigfox, Lora, NB-IoT) currently account for more than 25 million connected devices, up to 2 billion by 2025. Very low power consumption (i.e. long battery life, possibility to use green power supply) and a very large range that can be more than 20 km promises to increase to a large number of applications. All these technologies use mainly free frequency bands for communication. The only way to achieve growth with limited resources such as the frequency band is to use it as efficiently as possible [3].

Most of the IoT data goes to public or private cloud storage where are saved, processed and visualized. This trend is unlikely to change in the future. But what must be changed is the qualitative content of data transmitted to cloud servers. Due to the limited capacity of wireless technologies, it is impossible to transfer all data in a raw, unprocessed state. The further, the greater it is the importance to have the data preprocessing directly at the capture place. Moving data processing closer to its place of origin (of moving applications and functionalities closer to the user) is currently a much-discussed topic and is generally referred to as “Edge computing”. The importance of this trend in the IoT field is also evident from the activities that the largest cloud companies such as Microsoft, Google and Amazon are developing in this area. As an example, Google Edge TPU is a processor that is focused on using machine learning and artificial intelligence “on the edge” [4].

Thanks to the continuous development of technologies in all areas of electronics (from sensors, through microcontrollers to radio modules), the number of IoT applications is growing rapidly. Lower power consumption, as well as higher computing power for even the simplest processors, also allows the use of sensor types that could not be used in the past due to the large amount of data they produce. This applies mainly to image and sound recording but also to other signals with higher data volume (vibration measurement, magnetic field changes, etc.).

The relatively high computational power available at the place of signal acquisition allows the data volume to be reduced to an acceptable level with respect to the communication channel used.

2. Problem Description

Vehicle detection technologies were massively developed in the last couple of decades. Their developments went hand in hand with the requirements, which are currently put on the measurement strategies, where the accuracy is viewed as a necessity. According to the resources available, different measurement methods can be applied, with different results reached. For example, with camera and image recognition techniques, different statistics can be derived, such as the number of vehicles of different types, speed averages, problematic drivers, etc. Problems only occur, where the measurement scenario provides only a limited number of resources, but the measurement requirements are still high. For this purpose, it is necessary to build special sensory devices.

Because most of all vehicles have noteworthy measures of steel material in their body, AMR sensor magnetometers represent a good technical mean for identifying vehicles. As mentioned, authors in [5], the application of such sensors for the purposes of traffic monitoring provides a cost-effective and easy-to-install solution. After the application of Discrete Fourier Transform and Principal Component Analysis (PCA) for extracting features from magnetic signatures, the detected vehicles can be easily classified into three different categories. Beside not so demanding application as is the detection of the static vehicle at, for example, parking lot [6], the most applications ask for the real sensor performance, so just the features with time-stamp can be extracted from the measured magnetic field. It is therefore evident, that signal pre-processing at the sensor side, or “sensor edge”, is very important.

Different approaches can be applied at the sensor side, with different performance requirements. For example, authors in [7] proposed and implemented a simple algorithm based on a nonlinear transformation of the measurements as correlation-based driving direction classification. In [8], a simple five-state machine process algorithm was developed and implemented for real-time vehicle detection and counting. Speed estimation there relied on precise time-stamping of vehicle arrival and departure instants, which depended on T-sync algorithm accuracy. However, sometimes it is necessary to add some other supporting sensors to increase the measurement accuracy. In this case, particle filtering can play the role. In [9], an accelerometer sensor was added into the system. The paper showed that this approach can serve as a kind of feasible solution. For the sensor fusion, multi-rate particle filter was used.

Examples above proved that AMR sensors can be considered as reliable, low-power and cost-effective technology, which is suitable for vehicle detection. An integration of AMR sensors into the traffic infrastructure opens the space for novel applications, aimed at the topic of intelligent transportation systems (ITS). These sensors can be used for example for the traffic monitoring (traffic volume, gap times, speed) or intelligent traffic control including the real-time adaptive control of the traffic lights [10].

3. Structure of Magnetic Traffic Counter

As was mentioned within the examples above, the utilization of AMR sensors would be very tough without signal preprocessing at the sensor side, or eventually, signal post-processing at the side of the final application - magnetic traffic counter. Therefore, though the AMR sensor can be considered as a very important part of the final application, there are also other parts (Fig. 1):

- Control unit – this is a crucial part of any ITS sensor because it controls all algorithmizing processes. Parameters such as floating-point operations per second (FLOPS), as well as power requirements, are the key features to be considered when selecting an appropriate controller.

- Power – in most application scenarios, the power cords are missing, therefore requirements on power efficiency are very important. Different energy harvesting techniques are obviously used as supporting technologies for the sensor lifetime extension.

- Memory – in applications where the data are stored at the sensor side, it is necessary to integrate power-efficient solution for the data storage (SD card 50 mA @ 3.3 V, SPI Flash (25 mA @ 3.3 V).

- Communication subsystem – communication with user or with parent application should be primarily used for the data download, secondary for the settings adjustments. Communication can be event-based (button, shake,) or synchronous waking and sending the data in a defined time window. Wireless (Bluetooth, Xbee, ISM proprietary protocols...) or wired (USB, RS485, Ethernet...) means can be used for these purposes.

- Sensor subsystem – beside magnetometers, which are going to be described in another section, other supporting sensors could take place according to the application specifics. For example, GNSS sensors for timing purposes, sound sensors for the classification of voices, or gas sensors for the measurements of environmental conditions.

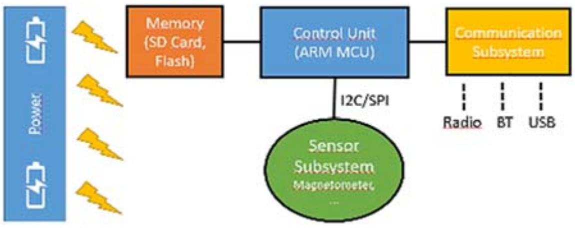

Fig. 1. ITS sensor structure.

4. Magnetometer Selection

There are several digital AMR magnetometers as SoC applicable for ITS applications available at the market with different performance and quality measures. To select the right one, first, the application scenario must be described.

The desired application scenario comes out from the project "Innovative monitoring and analysis of traffic on the cross-border road network", which is aimed at the development of special low-cost, low-power, wireless, portable magnetic traffic counter for the analysis of the traffic volume at the cross-border area between the Slovakia and the Czech Republic. This area can be described with mountains and forests, where the electricity is provided rarely. The proper sensor should be able to detect the disturbances of the magnetic field relied on its proximity, and thus to detect the vehicle size and direction (Fig. 2).

Fig. 2. Earth's magnetic field through vehicle [20].

For this purpose, a market analysis was performed, resulting in the choice of 10 magnetometers for further evaluation. The list of chosen magnetometers is provided in the Table 1, together with the basic parameters which were extracted from [11-20]. We were focused on chips, which are without any problems available at the market either from re-sellers or from specified suppliers in a number of single pieces.

Table 1. List of the tested magnetometers [11-20].

	Magnetometer Type	**Output Noise**	**Sensitivity [uT/LSB]**	**Measurement Range +- [uT]**	**Output Data Rate [Hz]**	**Current Consumption [uA]**	**Idle [uA]**
1	**LSM303AGR**	0.3 uT RMS	0.15	5000	100/150	950/250 @ 100 Hz	2
2	**LIS2MDL**	0.3 uT RMS	0.15	5000	100/150	950/250 @ 100 Hz	1.5
3	**LSM303AH**	0.3 uT RMS	0.15	5000	100/150	950/250 @ 100 Hz	2.5
4	**LSM303C**	0.35 uT RMS	0.058	1600	80	270/40 @ 20 Hz	6
5	**LSM9DS1**	0.35 uT RMS	0.014 - 0.058	1600	80	600 @ 20 Hz	6
6	**MPU9250**	N/A	0.15	4900	100	280 @ 8 Hz	3
7	**FXOS8700CQ**	<100 nT/Hz @ 100 Hz	0.1	1200	800	575 @ 400 Hz	2
8	**MLX90393**	varies acc. to settings	0.16 - 5.8	4800	700	100 @ 10 Hz	2.4
9	**RM3100**	30-15 nT	0.05 - 0.013	800	1600/n	70-260 @ 8 Hz	1
10	**HMC 5983**	N/A	0.07 - 0.40	100-800	220	100 @ 7.5 Hz	2

From the reference sources is also obvious, that we were focused on the magnetometers with digital output for minimization of power consumption. From the table is evident, that there are some parameters, which can be left out from the comparison since they are almost the same among all of the sensors. What is important in terms of the aimed measurements is the following:

- Output noise – lowest (around 0.3 uT and less) – to enable the sensor to measure accurately, with low own noise, and invulnerable to any noise source,

- Measurement sensitivity – highest (around 0.1 uT/LSB and higher) – to enable the sensor to sense any change of magnetic field properly,

- Measurement range – low – to provide the best measurement quality to sense with the highest sensitivity in relatively low measurement range,

- Output data rate – highest – to sample the data at the highest possible speed (not to lose any information),

- Power consumption – lowest – power consumption of the whole device is very important.

What is however also important, and what could be easily investigated in laboratory conditions is the measurement repeatability, resp. the spread of measurement data of each magnetometer axis under the same laboratory conditions. In terms of measuring the variability of data spread, the standard deviation S is the preferred and most used measure as a square root of the variance (1):

$$S_K = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}|M_{Ki} - \mu_K|^2}, \qquad (1)$$

where μ_K is the mean of the measured value in all three axes X, Y, Z of magnetometer of N measures, where $K \in \{X, Y, Z\}$ (2):

$$\mu_K = \frac{1}{N}\sum_{i=1}^{N} M_{Ki} \qquad (2)$$

Interpretation of the coefficient of variation (CV) for each magnetometer can be then used to interpret the variability of a sample relative to its mean by dividing the standard deviation by the mean (3):

$$CV = \frac{S}{|\mu_K|} \qquad (3)$$

To properly measure the data, as to interpret the inputs for (1), (2) and (3), the special measurement set was developed and installed as can be seen in the block schematic in Fig. 3.

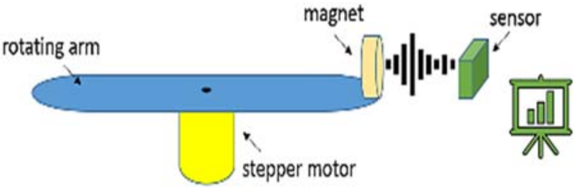

Fig. 3. Block schematic of the measurement set.

The measurement scenario consisted of the rotating arm which was fixed on the precisely driven stepper motor which was controlled through the AtMega8 MCU and two H-bridges. On the arm was placed strong neodymium magnet which was moved across the defined track. The track consisted of 42 measurement points, on which the magnet stops for exactly 1200 ms. Every tested magnetometer from the group available in Table 1, was place exactly on the same position fixed at a certain distance of 1 cm from the magnet installed at the rotating arm. So, during the measurement of each magnetometer, the same measuring conditions were achieved:

- The same distance between the moving magnet and the statically placed measuring unit,
- The same movement of rotating arm, characterized with the same speed and the same track,
- The same position of magnetometer relative to the rotating arm.

The magnetometers were set to the maximum output data rates with no filter implemented, thus the real raw data could be measured. All magnetometers were interconnected through the I2C interface with Raspberry Pi v 3.0, through which all settings were adjusted and where all data were recorded. The influence of rotating magnet to the magnetometer can be seen in Fig. 4.

The whole test scenario in real can be seen in Fig. 5.

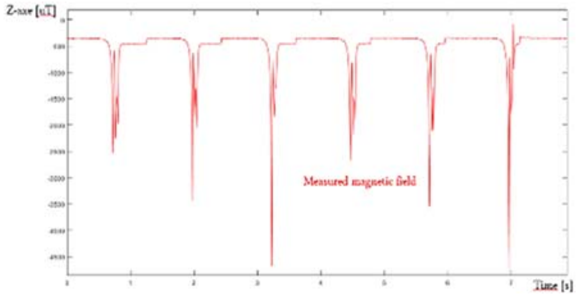

Fig. 4. Influence of rotating magnet to the magnetometer.

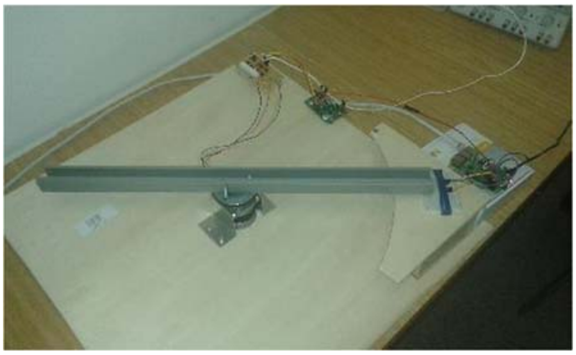

Fig. 5. Test scenario.

The measurement results can be seen in Table 2 as the interpretation of the coefficient of variation for X, Y and Z axes of every tested magnetometer.

Table 2. Measured results.

	CV(X)	CV(Y)	CV(Z)
LSM303AGR	0.0750	0.0075	0.0332
LIS2MDL	0.0748	0.0073	0.0331
LSM303AH	0.0748	0.0073	0.0332
LSM303C	0.0209	0.0037	0.0100
LSM9DS1	0.0207	0.0038	0.0149
MPU9250	0.0237	0.0062	0.1391
FXOS8700CQ	0.1010	0.0441	0.0221
MLX90393	0.2560	0.2837	0.0583
HMC 5983	0.0273	0.0086	0.0283
RM3100	0.0031	0.0042	0.0106

From the results is evident, that magnetometers LSM303AGR, LIS2MDL and LSM303AH have probably the same AMR core. From the results is also evident that LSM303C, LSM9DS1, FXOS8700CQ and RM3100 provide the best results. From the selected modules above, two sensors were chosen for further investigation in the scenario of real traffic - FXOS8700CQ and RM3100. Though RM3100 is quite costly, and has the biggest size, it provided really the best results. This is because it is based on the different technology as opposite to AMR – proprietary magneto-inductive technology. However, its output data rate depends on the settings – its sensitivity depends on the number of sensed channels. FXOS8700CQ was preferred over the LSM family mainly because of its high output data rate (800 Hz vs. 200 Hz), even it provided worse measurement results (Table 2).

5. Testing in the Scenario of Real Traffic

For the purpose of measurement, the special testing scenario was set up in the village Porúbka, which is situated on the road of Ist class I/64 in Slovakia. The road connects nearby towns Žilina and Rajec with relatively high traffic load in terms of Slovakia. The measurement scenario consisted of the special construction, on which HD camera together with sensors and control unit was fasten. The block schematic of the measurement set-up can be seen in Fig. 6.

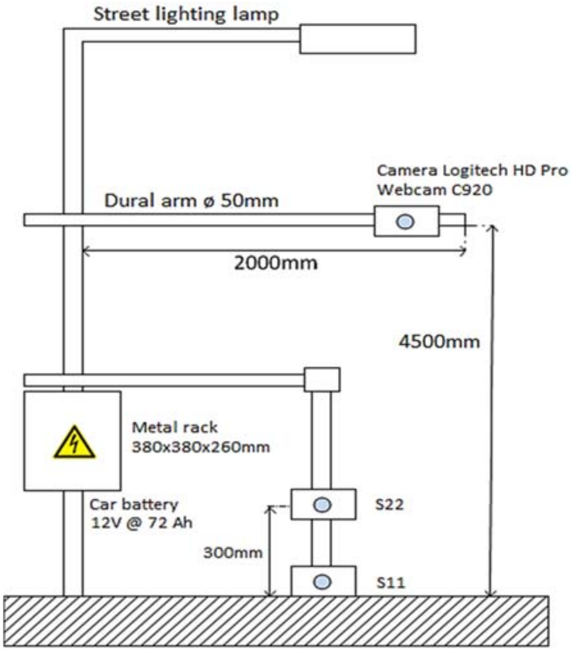

Fig. 6. Block schematic of the measurement set-up.

As it is obvious from the schematic, for the measurement purposes, two sensor modules – S11 an S22 were introduced. Both modules had the same structure – they consisted of one RM3100 sensor and one FXOS8700CQ, both interconnected with Raspberry Pi v 3.0 single-board computer through the I2C bus. The modules shared the same physical bus, which served enough throughput for the maximal sensor sampling. Raspberry Pi was used as the data logger. For better imagination, in Fig. 7 and Fig. 8, there is displayed the whole measurement scenario in detail.

Fig. 7. Measurement scenario in Porúbka.

Fig. 8. Measurement scenario in Porúbka.

From the figures is evident, that sensor modules were installed in two levels. The first sensor module, named S11, was installed in parallel with the pavement ground, the second sensor module was installed at a height of 30 cm. As it was also mentioned, all sensors were set to maximal output data rates with maximum possible sensitivity in all three axes of the magnetometer. Then the recorded raw data were analyzed with simple band-pass filter applied, as for example in [5].

To keep the measurement integrity, the camera recording of actual traffic was performed in parallel with the magnetometer measurement. Measured data could be then in post-processing compared with the extracted images of traffic flow. The results can be seen in Fig. 9. In the upper images, there are displayed figures of two vehicles extracted from the camera record – the van and the car which drove in line just behind. In the lower pictures can be seen the measured data. From the figures is evident, that RM3100 served much better results – as in measurement sensitivity, as in output noise.

In Fig. 10, the comparison of the sensor performance, when placed in the ground vs. 30 cm above the ground was done on the example of truck, car and van sequence. From the figure is evident, that slightly better results are provided, when the sensor is placed a bit above the pavement ground when the sensor is placed aside the road.

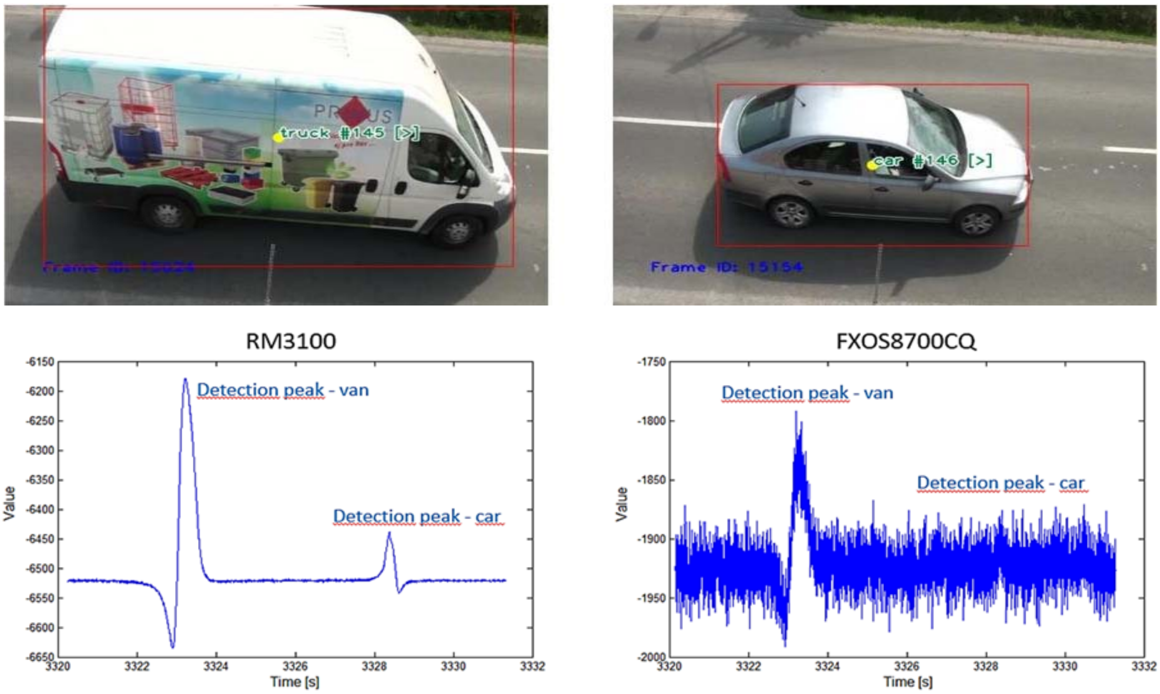

Fig. 9. Measured data – comparing the performance between RM3100 and FXS8700CQ in the S11 scenario.

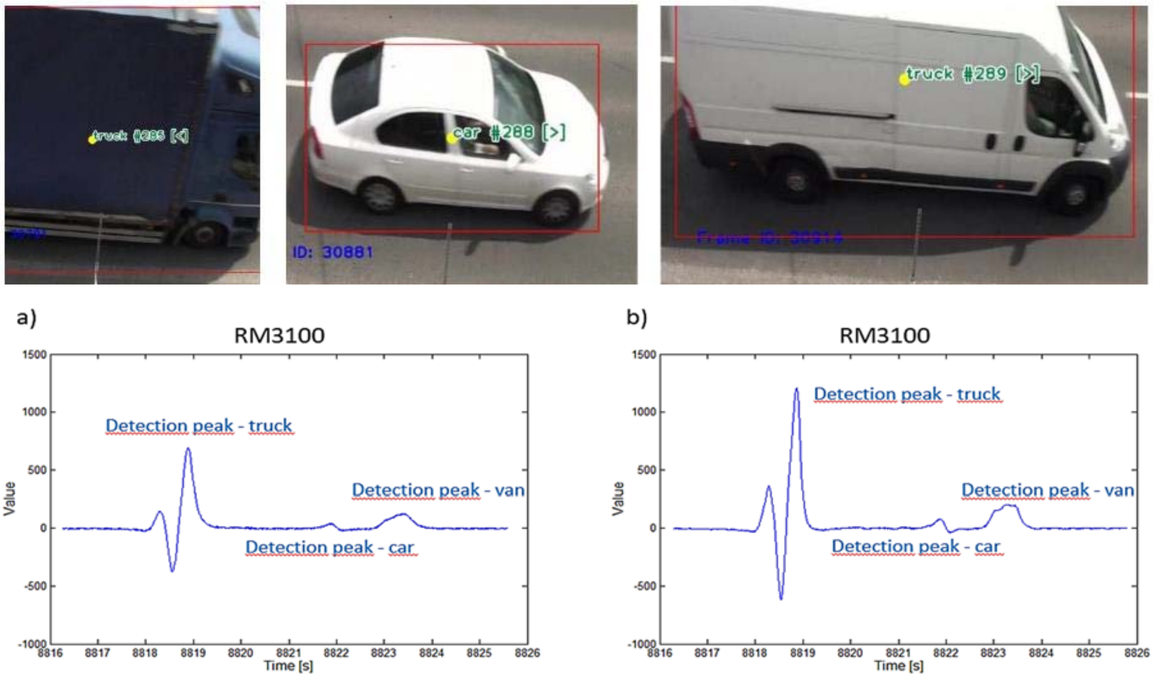

Fig. 10. Measured data – comparing the performance of RM3100 between a) S11 and b) S22 scenario.

6. Conclusion

In this paper, the basic selection and performance investigation of market-available magnetometers was made. The sensors were selected according to the final application requirements which are summarized below:

- Non-invasive;
- Reliable;
- Long working time;
- Low power consumption;
- Vehicle presence;
- Vehicle type;
- Easy & fast set up.

According to measurement results in the laboratory, the smaller groups of magnetometers for further evaluation were selected. In the selection, we considered output data rates of single magnetometer together with the measurement repeatability as the important parameters, which serve the additional information about the quality of the measured signal. After the laboratory tests, we continued with the testing in the scenario of real traffic. From the measurement results, we concluded that the best sensor which most suited the needs of the final magnetic traffic counter application is RM3100. In future research, the first prototype built on the selected sensor will be introduced and further tested in the application scenario.

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