# *Traffic flow counts using a moving variance weighting method on vehicle magnetic signatures for traffic control applications*

Kaone Bogopa
University of Botswana: Dept. of Electrical/Electronic Engineering

***Abstract*— Traffic light control systems require real time vehicle observations to be able to accurately optimize traffic flow in road intersections and junctions. This paper presents an effective method based on the measurement of the earth's magnetic field in order to detect passing vehicles on the road for applications in traffic control. Wireless magnetic sensors nodes were designed and setup so as to detect disturbances in the earth's magnetic field due to presence of vehicles on the roadway. Vehicles have heavy ferrous content which is measured using highly sensitive magnetic sensors. An algorithm was implemented that computes the rate of magnetic field deviation from the earth's magnetic field baseline when there is an approaching vehicle. The algorithm consisted of a 10-point moving variance calculator to identify vehicle entrance and departure points. Vehicle counts were derived using an adaptive threshold state machine and 100% vehicle detection accuracy rate was attained during the testing phase.**

***Keywords—Anisotropic Magneto-Resistive (AMR), Vehicle Detection, Moving variance, Intelligent Transporation Systems (ITS), Traffic control, Wireless Sensor Networks (WSN)***

## I. INTRODUCTION

Earth's magnetic field or simply geomagnetic field, penetrates everything between south and north magnetic poles and once an object with significant magnetic content enters a point close to the earth's surface, it causes a geomagnetic disturbance. The perturbations in the earth's magnetic field can be measured by a magnetic sensor. Since vehicles have significant ferrous metal content to disturb geomagnetic field, then magnetic are suitably applicable for vehicle presence detection. Magnetic sensors, or simply magnetometers, are fairly attractive because of their fairly miniature size, magnetic range capabilities, resolution and improved electrical interfacing that makes integration to other electronic systems easy. Different types of magnetometers include magneto-inductive and fluxgate magnetometers, but the most common one for vehicle detection is the Anisotropic Magneto-Resistive (AMR) sensors, which is a semiconductor device that changes resistance with respect to the change in the earth's magnetic field, [1]. AMR sensors have higher accuracy at low magnetic field changes and require very low operational power supply. AMRs generate varying signals over time as vehicles passes over or near the sensor. These signals are known as magnetic profiles or signatures of vehicles and they differ in pattern, amplitude, duration, frequency and other statistical parameters that can used as a basis for detection of vehicles.

## II. RELATED WORK

Magnetometers detect magnetic field along a sensitive axis or direction and they can be embedded on the roadway or on the side of the road. A vehicle detection system based on a single axis magnetic signal has been tested using a fixed threshold state machine such that when a vehicle is passing over the detection zone, the magnetic signal fluctuations crosses a set threshold [2]. The system relied on a signal to stay above the threshold for some set duration and that is when a vehicle detection decision will be generated. This resulted in 80% detection accuracy from 37 passing vehicles. Another systems has used a 2 axis magnetometer for vehicle detection [3]. The axis of the AMR sensor node were placed along the y-axis (vertical) and z-axis (perpendicular) to the road surface such that the magnetic phase difference between these axes is used for detection decision when a vehicle passes by. A detection baseline was calculated to adaptively track and match natural magnetic phase difference between the two axes by using a signal correlation method described by Zhang [4]. An adaptive double-threshold state machine algorithm was designed for detecting phase changes in moving traffic. By setting double-thresholds, the entry and departure of a vehicle were defined. This system was tested on a single lane road resulting with the detection accuracy up to 97.5%, while on a double lane scenario yielded 15.3% detection inaccuracy. Balid, Tafish and Refai [5] designed an intelligent vehicle counting system (iVCS) that used wireless magnetometer sensor for real-time traffic surveillance. They developed different machine learning algorithms based on decision Trees (DT), Support Vector Machines (SVM) and Naïve Bayes Classification (NBC) for vehicle detection, speed, length estimation, and baseline drift compensation. Their investigations revealed consistent and accurate performance under both free flow and congested traffic on highway and urban roadway conditions. The experimental tests resulted in 99.98% detection accuracy, 97.11% in speed estimation accuracy, and 97% of length-based vehicle classification accuracy.

From the aforementioned studies, a variety of methods have been proposed for vehicle detection using AMR sensors, but very limited evaluation was performed over a full range of vehicle classes. Trucks, busses and vehicles with 2 or more axles were highly underrepresented. Limited information is provided in the literature about the electronics circuit design, algorithm development and comprehensive analysis under various traffic scenarios.

This paper focusses its investigation on producing a 3 axis AMR sensor node to detect a wider range of vehicles types in real-time. AMR sensor design will be uncovered as well as a 10-point moving variance algorithm that calculates vehicle presence from magnetic perturbations. This paper is organized as follows, Section III discusses the prototype circuit design and its setup for data collection. Section IV presents the vehicle detection algorithm, while test results are in Section V and finally conclusions in Section VI.

## III. Sensor Node SetUp

Magnetic field is a vector quantity, it has both magnitude and direction. At any arbitrary point, the earth's geomagnetic field, $\vec{B}$ is specified by direction and field strength. It is practically impossible (and not necessary either) to perform magnetic measurements for all points on the earth's surface. However, one can make an estimate of the earth's magnetic field by observing magnetic field on finite dipole moments at any arbitrary point. Mathematically, magnetic flux density $\vec{B_i}$ of an object from the $i^{th}$ magnetic moment can be defined as;

$$\vec{\boldsymbol{B}}(\mu_i, r_i) = \frac{\mu_0}{4\pi}\,\frac{3(\mu_i \cdot r_i)r_i - \mu_i|r_i|^2}{|r_i|^5} \qquad (1)$$

Where r is the vector distance from dipole and $\mu_0 = 4\pi * 10^{-7}\ Vs/Am$ is the permeability in vacuum. The total magnetic field is the magnitude of all individual moments and the phase is approximated by the tangential resultant of the moments.

In this study, we will measure three magnetic field moments as vehicle passes, along the three common Cartesian axis, x, y and z-axis. The x-axis is the direction perpendicular to the direction travel, y-axis is parallel to the direction of travel and z-axis is perpendicular to the road surface. The square deviation of these three fields defines the average magnetic field intensity $\vec{\boldsymbol{B}}_e(t)$ as,

$$\vec{\boldsymbol{B}}_e(t) = \sqrt{(\vec{\boldsymbol{B}}_x(t))^2 + (\vec{\boldsymbol{B}}_y(t))^2 + (\vec{\boldsymbol{B}}_z(t))^2} \qquad (2)$$

The earth's magnetic field strength ranges from 0.4 to 0.7 gauss, and this will be expected values for $\vec{\boldsymbol{B}}_e(t)$ in the absence of any vehicle. Single axis surface AMR sensors from Honeywell's HMC1002x range [6] are used in this project particularly for their benefit of high sensitivity at low magnetic fields. These sensors have a magnetic field measurement range of -6 to +6 gauss, they are compatible with most high speed electronic circuits and they cost only about 5 dollars (About 50 Rands) each. The sensor require low supply voltage of around 5 volts for operation and require signal conditioning circuits to monitor changes in magnetic field.

3 sensors are used to measure magnetic field in three defined orthogonal axis. They are each setup with similar conditioning circuits. The conditioning circuits includes an amplifier with low pass filters, analog to digital converters, set/ reset circuits and a power module. A wireless transmitter is also incorporated to send data to a controller. *Figure 1* below shows the block diagram of the sensor circuit design that was used in this project. A PIC16F883 microcontroller [7], is used for analog to digital transmission as well feeding the transmitter with digital data packets over a serial communication port. A ZigBee wireless networking protocol is adopted for this system [8]. A ZigBee based radio frequency module called XBee is utilized in the circuit [9].

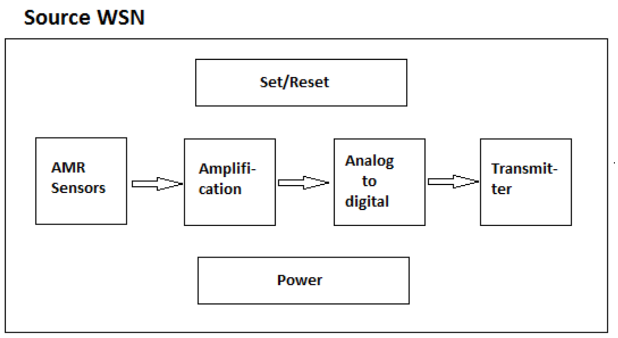


*Figure 1 Sensor Node design*

The right orientation of the sensor node would yield good results. *Figure 2* below demonstrates a fabricated circuit output with clearly marked directions of orientation and as it was used to detect vehicle in the experiments. The rate of field shift depends on the distance of the vehicle from the sensor, it is important to have the sensor on roadway for this experiment to influence greater chances of signal detection.

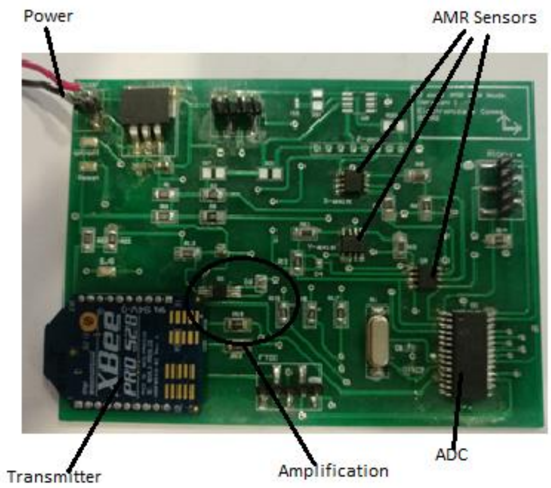


*Figure 2 Fabricated sensor Node*

A sink node was simulated in a computer for this experiment to collect data from the sensor node and run an algorithm that will compute vehicle detection from incoming live stream of field data.

## IV. Vehicle Detection Algorithm

If a vehicle passes or parks overtop a fixed sensor, the magnetic field will shift away from the baseline field and this. Up to 3 gauss of the magnetic field spikes can be realized when a vehicle comes into proximity with the sensor. The output signal from the sensor node will represents the vector magnitude of the X, Y and Z-axis magnetic field variations. Digital filters have been implemented to remove noise and get a smoother sensor signal for analysis. A 5 point triangular moving average (TMA) technique is implemented for signal smoothing. TMA uses data points in a current window to compute a weighted smoothing output a described mathematically below for a 5 point smoothing function.

$$\vec{\boldsymbol{B}}_{e,smoothed}(t) = \frac{\vec{\boldsymbol{B}}_e(t-2) + 2\vec{\boldsymbol{B}}_e(t-1) + 3\vec{\boldsymbol{B}}_e(t) + 2\vec{\boldsymbol{B}}_e(t+1) + \vec{\boldsymbol{B}}_e(t+2)}{9} \quad (3)$$

A fast Fourier Transform (FFT) filter is used for white noise removal. A time domain signal is transformed into frequency domain using FFT and applied a low pass filter to retain low frequencies below 10Hz. An Inverse Fourier Transform (IFFT) function is applied next to convert the signal back to its original time domain form as described in equation 4 below.

$$\vec{\boldsymbol{B}}_{e,filtered}(t) = fftfilt(\vec{\boldsymbol{B}}_{e,smoothed}(t)) \quad (4)$$

Vehicle detection is based on a 10 point moving variance calculator and an adaptive threshold state machine for decision making. A combination of these two methods will determine the vehicle's entrance and departure points and subsequently compute vehicle counts. The variance describes the squared deviation of the data points from the magnetic baseline. The moving variance is evaluated on the current data point and previous 9 most recent data points, equating to 10 data points. Equation below summarized the variance calculation implementation.

$$\vec{\boldsymbol{B}}_{e,variance} = \frac{1}{10}\sum_{k=t-9}^{t}\left(\vec{\boldsymbol{B}}_{e,filtered}(k) - \mu\right)^2 \quad (5)$$

μ is the mean of the 10 data points. This is described as a 10-point variance calculator and it will automatically slide to neighboring elements as more data points are read. A significant change in variance will highlight an activity in the magnetic field. To normalize the data, the variance points are multiplied with the original signal which acts as a weighting factor as shown below.

$$\vec{\boldsymbol{B}}_{e,processed}(t) = \vec{\boldsymbol{B}}_{e,variance} * \vec{\boldsymbol{B}}_{e,filtered}(t) \quad (6)$$

An adaptive state machine is used to decide the entrance and departure points of a vehicle by setting thresholds on the variance. By applying the processed signal's data set, it is possible to determine and define mean and quantiles of the processed signal values, and these components can provide objective methods for setting thresholds and comparing signal activity levels. For every 60 seconds long signal envelope, the mean and 1st quantile of the processed signals are set to define the High threshold and low threshold, respectively. This criteria is completely arbitrary and reasonable to describe activity patterns of the magnetic field.

The decision state diagram that decides vehicle presence is shown in Figure 3 below. *L-threshold* is the Low-threshold and *H-threshold* is the High-threshold. At the start state, the state machine in un-activated until the variance exceeds the *L-threshold*, the state machine will then be triggered into the *vehicle entrance* state. If the processed signal does not go beyond H-threshold after *n* timed samples, the detection will be deemed false and then return to the *start* state. If however, it occurred that while in the *Vehicle Entrance* state and the signal increased beyond *H-threshold*, the state machine switches to *Vehicle count* and vehicle detection is recorded. At this state, the signal variation will be observed for "*m*" samples until it returns to normal. On the transition to the baseline, it is expected to surpass the L-threshold, this is where the vehicle departure point is defined. After vehicle departure, the system will wait for another vehicle entrance and the cycle will go on and on.

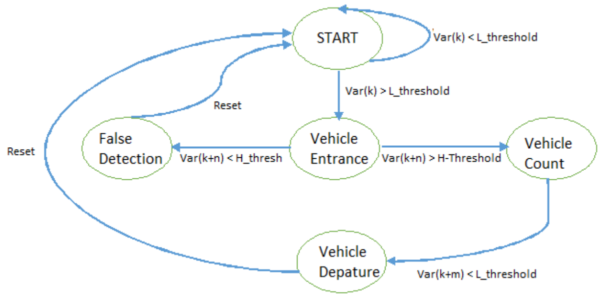


*Figure 3 Vehicle detection state machine*

Visualization of vehicle entrance and departure points on the real time magnetic signal from system testing is discussed in the next section.

## V. Results and Analysis

The wireless sensor node was tested in Gaborone, Botswana along the Magang Avenue in the Phakalane neighborhood (GPS coordinates - 24°33'51.0" S 25°58'33.4" E). Table 1 below summarizes number of vehicles visually observed whilst testing the system. Three vehicle classes were noted, type I represented hatchbacks and sedan cars, type II are vans/pick-up trucks and mini busses and type III are trucks with 2 axles or more. The test was conducted on a single lane with low speed moving traffic for safety reasons. Temperature was at about 32 degrees Celsius on the day.

| Total Vehicles observed | Vehicles Types | | |
|---|---|---|---|
| | *Type I* | *Type II* | *Type III* |
| 221 | 122 | 71 | 28 |

*Table 1 Vehicle observations for system testing*

A sample filtered magnetic field signal recorded over time from is visualized below.

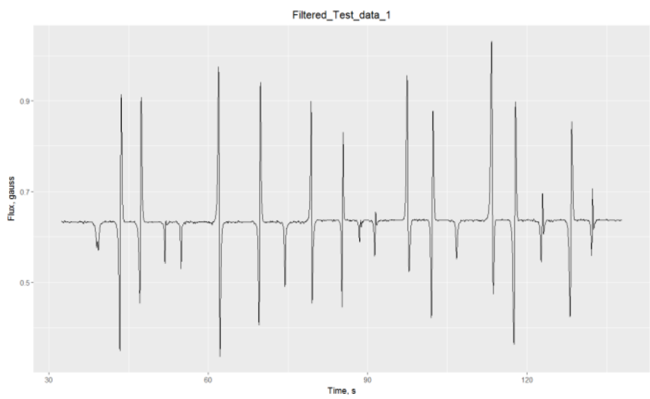


*Figure 4 Magnetic field variations measured*

The variations in magnetic field are a result of a vehicle movement over the sensor. These spikes are what defines magnetic profiles of each vehicle. Magnetic profile length can be used to estimate the speed of a vehicle and the amplitude for estimating the amount of magnetic content in a vehicle.

Applying a 10-point moving variance calculator on the above signal yielded a variance signal as shown below.

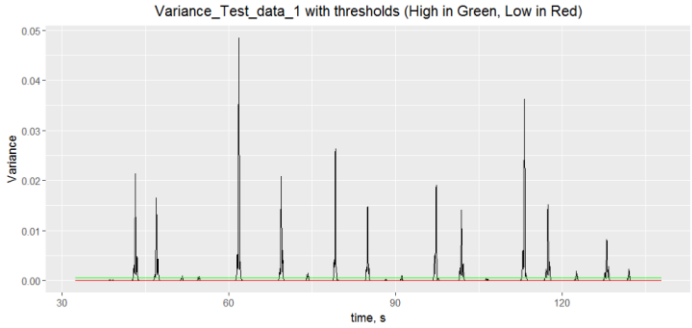


*Figure 5 Variance of the magnetic field signal*

The red line is the low threshold while the green line is the high-threshold. A state machine algorithm has been defined and used to decide the vehicle entrance and departure points. Figure 6 below shows computed entrance and departure points from the magnetic signal.

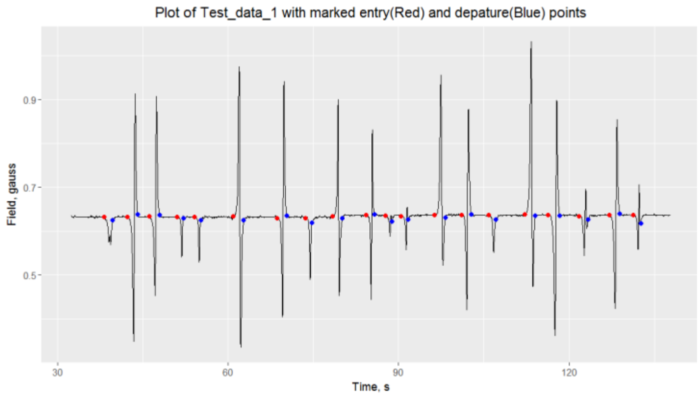


*Figure 6 Magnetic signal with calculated entrance and departure points*

It is clear from the above figure that every magnetic field deviation from the baseline is detected. Entrance points have been highlighted in red and departure points in blue. The vehicle detection results yield an impressive 100% detection out of 221 vehicles that were visually observed.

## VI. Conclusion

This paper has introduced a vehicle detection system applicable for implementation in intelligent transportation systems. An AMR sensor node was developed and tested with the capability to wirelessly transmit data to a local traffic lights controller. Vehicle magnetic signatures were observed and vehicle counts were extracted using a moving variance algorithm. Vehicle entrance and departure points were noticed by using an adaptive threshold decision state machine which enabled the system to produce 100% vehicle detection accuracy on 221 observed vehicles. The flexibility of this solution has demonstrated strength and capability for application in intelligent transportation systems. It can be used to support traffic lights controller's decision making and timing strategies for junctions and intersections by providing them with vehicle counts from each lane.

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