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Green Transport System: A Technology Demonstration of Adaptive Road Lighting with Giant Magnetoresistive Sensor Network for Energy Efficiency and Reducing Light Pollution

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Abstract. To enhance energy efficiency and reduce light pollution of overnight road lighting in suburban traffic, we propose a novel green transport system based on giant magnetoresistive (GMR) sensors. The basic principle is to detect the perturbation to the earth magnetic field by a ferrous vehicle with GMR sensors. This system can switch on the road lighting to full illumination gradually before the motor vehicle arrives and dim it out after the vehicle leaves without the driver noticing. Based on a sparse suburban road in the countryside of Hong Kong, a demonstration model was constructed to illustrate its feasibility. GMR sensors and the associated electrical energy control components including signal processors, relays, and dimmers were integrated into a complete system. The experimental result indicates that the sensing principle is feasible and the whole system can function together coherently to achieve over 90% energy saving. Such system can be scaled up to be implemented in real road conditions.

Introduction

A green transport system, referring to a low-pollution and sustainable transport concept, is capable of improving the transportation efficiency with less energy consumption. However, in conflict with the green transport concept, the usage of overnight road lighting in sparse suburban roads incurs significant energy waste. It was reported that the conventional public lighting system nearly consumes 3.19% of global electricity generation, and the carbon dioxide produced to generate these amount of electrical energy is almost equivalent to 70% of global emission from passenger vehicles and 300% of the emission from aviation [1]. The road lighting in areas with low traffic in the middle of the night contributes significant proportion of the total waste. Another problem of traditional road lighting system is light pollution which originates from excessive illumination. There is usually a variety of wildlife and plants in the suburban area, and the excessive outdoor lighting may disorient their physiological cycles and even disrupt the surrounding ecological balance [2]. To reduce power waste and light pollution disturbance, some solutions were previously proposed or executed. For example, installation of light-emitting diode (LED) to replace the common light bulbs, construction of user-centered road lighting switching fixtures to adjust the luminance, and application of opto-sensors to control the online time based on the road visibility. However, these methods suffer from limitations of manual operation and weather influence, and unable to realize the function of adaptive road lighting. For adaptive road lighting, the streetlights can be lightened automatically when the motor vehicle comes nearby and dimmed out when it leaves. This method can effectively limit the unnecessary usage of road lighting in the suburban area and thus reduce the energy waste and light pollution.

To realize the adaptive road lighting, we herein propose a novel road-lighting control platform based on giant magnetoresistive (GMR) sensors. As a magnetic field sensor with high sensitivity, the output signal of GMR sensors varies with a nearby vehicle and thus the road lighting is controlled accordingly. In addition, traffic statistics, for example, the number of vehicles using the road in daytime and nighttime, can be obtained from the system. The information such as profile and driving speed of a vehicle can also be extracted from its magnetic signature in the measured magnetic field. Therefore, we can distinguish the type of vehicle using the road as well. These information will be useful for transport planning. In this work, a demonstration model was constructed to illustrate the feasibility of the road-lighting control platform. Six GMR sensors were mounted in different zones of the model and the logic control system was programmed with LabVIEW software. The experimental result shows that the green transport system is capable of controlling the road lighting according to the traffic condition and feasible of being scaled up to be implemented in the real road conditions.

Feasibility and demonstration

Vehicle detection by GMR sensors

The fundamental principle of vehicle detection is to detect the perturbation in earth magnetic field with GMR sensors when a ferrous vehicle passing by [3-5]. The geomagnetic fields emanated from the earth are uniform without any external magnetic interfaces over a wide area and a ferrous vehicle is capable of disturbing these fields locally due to its magnetic moment. It was reported that a typical American automobile possesses a magnetic moment of 100-300 $A\cdot m^2$ [3]. The magnetic disturbances induced from a moving ferrous vehicle can be detected by magnetic field sensors. Vehicle detection by magnetic field sensors has been studied for decades using fluxgate sensors [3], anisotropic magnetoresistive (AMR) sensors [4] and giant magnetoimpedance (GMI) sensors [5]. However, these magnetic field sensors suffer from the disadvantages of being costly, bulky, and the power-consuming problem. Very few studies were focused on using GMR sensors to detect the vehicles. A GMR sensor is a solid-state spintronic multilayered device, in which a nonmagnetic barrier separates two ferromagnetic layers. The magnetization of one of the ferromagnetic layers aligns with the external applied field. For parallel-aligned ferromagnetic layers, the electrons pass through the structure with less scattering whereas for anti-parallel configuration, the scattering is much larger. In consequence, the resistance of GMR sensor changes with respect to the external magnetic field. Compared to the traditional magnetic sensors, GMR sensors exhibit the advantages of high detectivity of nanoTesla, low cost, and compatible with standard CMOS technologies [6, 7]. Therefore, they are an ideal sensing element for vehicle detections.

LED for adaptive road lighting

To ensure the safety of drivers, the response of adaptive road lighting should be swift within an instant. LED is regarded as one of the competent candidates for this purpose. The traditional high pressure sodium (HPS) lamps, which are a common type for road lighting used since 1980s, need a re-strike time of 0.5-1.5 minutes for warming up [8]. In contrast, LEDs can be re-lit almost without delay. Another merit of LEDs is that they possess a lifespan of 60,000-100,000 hours, which is longer than the HPS of 20,000 hours [9]. This long lifespan can save the maintenance expenses. In addition, LEDs are solid-state devices and they emit no greenhouse gasses in the working status. Compared to traditional HPS lamps, LEDs also possess advantages in lower power consumption and lower cost. It was reported that the application of LEDs can save about 50% of the energy spent on artificial light and can obtain a payback of six thousand dollars per year after replacement of HPS with LED for one light point in the US [9, 10]. Last but not the least, for road lighting applications, the color rendering index and color temperature of LEDs are superior to HPS, which makes the objects lightened appear much closer to the natural colours [9, 10]. This comforts the eyes of drivers for long driving and thus potentially enhances the safety of driving. As such, LEDs are more suitable to be installed in the adaptive road-lighting system.

Demonstration

Model of adaptive road-lighting system

A demonstration model was constructed to illustrate the feasibility of the adaptive road-lighting system. This model was designed based on a real suburban road in the countryside of Hong Kong. According to the statistical data in the Annual Traffic Census in 2009 provided by the Transport Department of Hong Kong [11], the number of vehicles passing through in the midnight almost reduces by 80% compared with daytime. In Hong Kong, the road lighting adopts 400W HPS lamp with 50,000 lumens. If the 210W LED with 15,000 lumens is applied, the electrical energy and expense will be saved by 47.5%. The adaptive road-lighting system is estimated to curtail the electrical energy and expense by nearly 90% in the above suburban area. Another reason for selecting this area as the demonstration model is that there are country parks, farms, and botanic gardens nearby. It is an ideal location to perform the study of light pollution after the implementation of the adaptive road-lighting system in the future. Therefore, it is a suitable prototype for the demonstration. Figure 1 illustrates the overview of the demonstration model. Six GMR sensors (solid dots in Fig. 1 (a)) were mounted in different locations for the purpose of controlling the corresponding LED road lighting along the two sides of the road in specific areas. Figure 1 (b) shows the detailed parameters of the model and the solid triangles represent GMR sensors mounted in the areas with gradient.

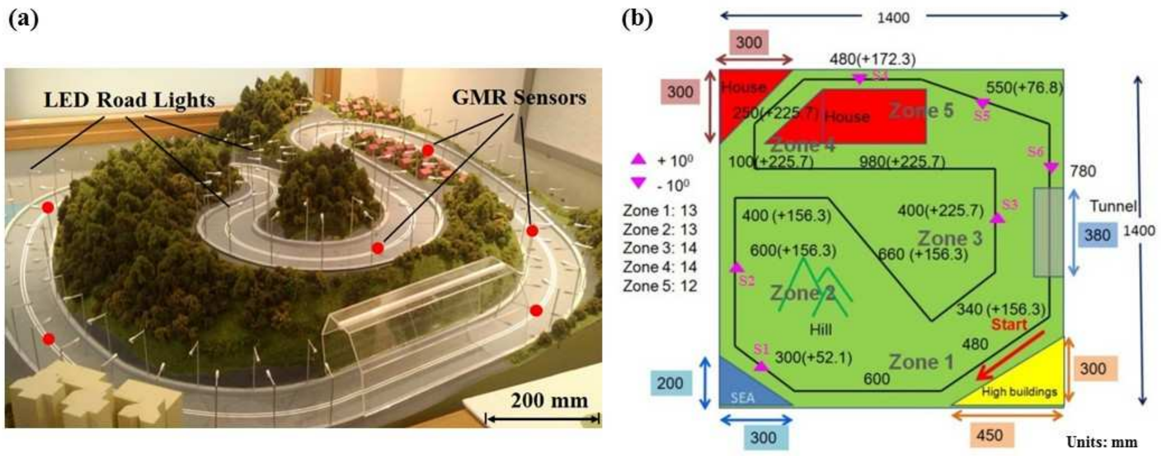

Fig. 1. Demonstration model of the green transport system. (a) The snapshot of the real model. The solid dots indicate the locations of the GMR sensors and the LED lights are installed on both sides of the road. (b) The design drawing of the model. The number before the bracket is the length of that part of the road and the number inside the bracket is the height of the ending point. The number with no bracket indicates it is on the horizontal level. The solid triangles represent the GMR sensors with different gradients and are identified from S1 to S6.

Overall architecture

Figure 2 illustrates the overall architecture of the adaptive road-lighting system. When a vehicle passes through the GMR sensor, the output signal of the GMR sensor varies and the signal is inputted to a controller consisting of A/D converter and signal processors. The GMR sensors of model NVEAA002-02e were selected and the connecting circuit includes Wheatstone bridge with instrumentation amplifiers, operational amplifiers, and high/low pass filters [12]. The output signal from the controller serves as the reference voltage to control the online status of the road lights through a relay which is connected between the electricity power supply and the road lights. The control is also functionalized with pre-lighting scheme that the LED road lights in the next zones can be lightened in advance before the entering of vehicle into the area. A LED fader is designed to prevent the sudden on/off of the road lighting that might discomfort the eyes of drivers and result in traffic accident. The logic control system was programmed with LabVIEW and the selected interfaces are shown in Fig. 3 and Fig. 4. When the GMR sensors detect the presence of a vehicle nearby, the signal waveform from all the sensors can be obtained with a digital oscilloscope and displayed visually in the interface of the software as shown in Fig. 3. The status of all the LED road lights can be monitored by the indicators in real time and the on/off status can also be switched manually through the manual control panel as illustrated in Fig. 4.

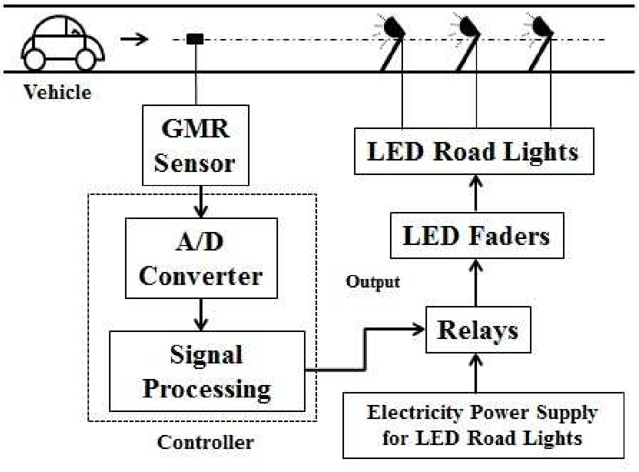

Fig. 2. Schematic drawing of the adaptive road-lighting system.

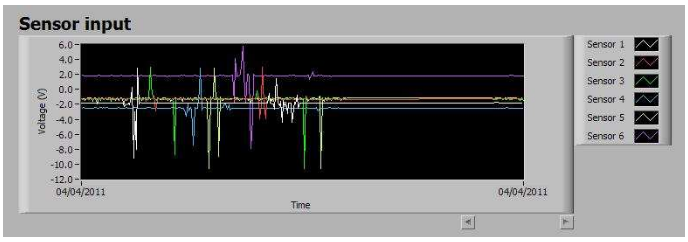

Fig. 3. Interface of the digital oscilloscope showing the output signal from the GMR sensors.

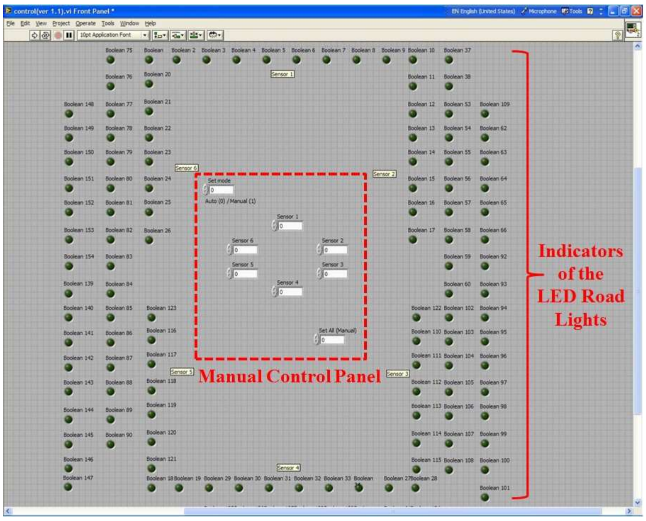

Fig. 4. The interface of LabVIEW program for LED lights monitoring and controlling. The middle area is the manual control panel for the six GMR sensors and is surrounded by the LED road-light indicators for different zones.

Results and discussion

A remotely controlled toy truck with a magnet installed inside was employed in the demonstration to serve as a demo ferrous vehicle passing through the demonstration model. To verify the reliability of the adaptive road-lighting system, the truck was driven along the road in a clockwise route. The experimental result shows that the indicators in Fig. 4 can be switched on when the demo vehicle was within the sensing area of a specific GMR sensor and was switched off after it left. The clockwise route process was repeated for 100 cycles to justify the accuracy of the vehicle counting algorithm and the experimental results are shown in Table I. In general, the adaptive road-lighting system can work in principle. However, the miscounting phenomenon can be occasionally observed with an overall percentage error of around 5%. To study the influence of route direction, another two tests were carried out: the demo vehicle moving in anti-clockwise route, and two demo vehicles moving in the opposite directions. However, the miscounting phenomenon also occurred. This might be attributed to the mismatch between the trigger time and pre-sample settings in the LabVIEW programme. Therefore further improvements should be made to enhance the reliability of the system. Besides that, there are also some limitations in our demonstration model. For example, objects such as trees and tall buildings, improper driving such as over-speed, and other magnetic-field sources such as overhead transmission lines, are neglected in the demonstration model.

TABLE I
EXPERIMENTAL RESULTS FOR 100 CYCLES IN CLOCKWISE ROUTE

Sensor identification	Number of indicator counted	Percentage error (%)
S1	99	-1
S2	97	-3
S3	105	+5
S4	100	0
S5	100	0
S6	103	+3

Conclusions

We have investigated an adaptive road-lighting system with GMR sensor network to realize the function of lighting up the road lighting automatically when the motor vehicle comes nearby and dim out when it leaves. The GMR sensors are applied in the system for vehicle detecting due to its superb characteristics. A demonstration model was constructed and the experimental results indicate that the GMR sensor networks are feasible for adaptive road lighting. However, further improvements are needed to enhance the stability of the system. Moreover, the system can also be expanded and include more features. For example, two GMR sensors instead of one can be used to obtain the speed of the passing vehicles by deducing from the two sensor output signals [13]. The sensitivity of magnetic sensors continues to improve. It was reported the detectivity of tunneling magnetoresistive (TMR) sensors are approaching 1 picoTesla level [14, 15]. This high sensitivity can effectively increase the accuracy of vehicle detection and expand the detecting area. These improvements will make the adaptive road-lighting system promising for contributing to the green transport system and thus enhancing the energy efficiency and reducing light pollution.

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