A SMART INTERIOR LIGHTING MEASUREMENT SYSTEM FOR TRAINS

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***Abstract* — This paper presents the design and an analysis of a smart interior lighting measurement system for trains. It was required that a system have a bandwidth of at least 100 Hz and that the application be used for any form of electric transportation. The objective of the system designed is to maintain a constant user-determined level of brightness. The system designed follows Bentley's generalised model such that four G1963 photodiodes are used, and each photodiode's output signal is conditioned using a current-to-voltage converter circuit before using an averaging amplifier to get an average output. The output of the averaging amplifier is processed using ATmega328 Arduino Nano. To display the measured and user-determined brightness level, an ST/16X2Y LCD display is used. The designed system has a bandwidth of 1.48 kHz, rise time of 5 ms and a settling time of 15 ms. Error analysis depicts a static error of 4% and a dynamic error of 5%. The system is estimated to cost R1222.48. It is recommended that integrated circuits be used instead of stand-alone components to increase system efficiency and reliability, and decrease overall costs of the system.**

Keywords: Smart-Transducer, photodiode, smart-lighting, calibration, trans-impedance, luminous

1. Introduction

Approximately 89% of the electricity produced in South Africa is generated using coal, a non-renewable resource [1]. Research across the world on Global warming has raised concerns to reduce the greenhouse gasses emitted by power stations using this resource. Parallel to this issue is the issue of reducing electricity consumption, which has also become a high concern in most of recent electrical engineering works of research. In this document, a detailed design of a smart interior-lighting measurement system for electric trains is investigated, simulated and analysed. The development of this system will help in resolving the electrical engineering problems above by ensuring that interior lights of the trains are on only when necessary. The measurement system's design is to follow the generalised model from Bentley in [2], and is to have an overall system bandwidth greater than 100Hz.

Section 2 outlines a brief background on lighting systems used in trains and applications that mimic the proposed system. An overall system overview is discussed in section 3. Static and dynamic characteristics of the system are discussed in section 4 and 5, respectively, followed by a critical analysis of the system in section 6. Section 7 comprises of recommendations for future projects.

2. Background

Train lighting has evolved from using candles and oils, then later to gas lighting before electric lighting was introduced by using stationary batteries in 1897 [3]. The lighting system has furthermore evolved from a simple bulb to a system that caters passenger needs, by using specialised types of lamps (different illumination) for different compartments of the train.

These lamps are chosen using variables such as lumens, lux, and candlepower. A lumen is the unit of total light output obtained from a light source [4]. Lux is a unit that explains the density of light that falls on a surface. Lastly, candlepower indicates the concentration of lighting in a light beam.

These three terms are helpful in contextualizing the concept of brightness. However, the main concern is that cognitive lighting systems are being employed, whereby the lights need user input to adjust light levels to what they want. This sometimes means keeping lights on even if they are not needed. The proposed measurement system uses ambient light to control interior-lighting systems by dimming lights during daylight, and gradually turn on with the decrease in ambient light.

Systems that use the same technique include cell phone's auto-adjusting screen brightness feature, street-lighting system, as well as the lux meter device. Most smartphones have a software that adjusts the display screen brightness in response to the ambient light. The display screen brightness decreases when it's dark, and it increases when the light detected is plenty. This feature helps in saving battery life.

3. System Overview

The smart interior-lighting measurement system is meant to maintain a constant light intensity inside fast moving trains as they enter and exit dark places (such as tunnels and bridges) at high speeds. As the system's sensing element, a photodiode integrated to the system will be used to register the ambient light inside the moving train. When light is shone on the photodiode, photocurrent is generated.

This system consists of two stages for signal conditioning, namely, the trans-impedance amplifier and the averaging amplifier. The photocurrent from the photodiode is converted into a proportional voltage using a trans-impedance amplifier circuit. This helps with achieving a linear relationship between light intensity and voltage to ease interpretation when processing and analysing the signal. This interior-lighting measurement system is using four photodiodes, one at each corner of the compartment, to get a more accurate value of the ambient intensity. The output from the four trans-impedance amplifiers connected to photodiodes then serve as inputs to the averaging amplifier to calculate the average light intensity, in the form of a voltage. The averaged value from the averaging amplifier is sent to an ATmega328 Arduino Nano microprocessor for processing. To calculate the amount of artificial lighting needed to maintain the user desired light intensity, the microprocessor uses *equation1:*

$$\varphi = \rho * A \tag{1}$$

Where: φ is the luminous flux in lumens, ρ is the illuminance in lux and A is the area of the train compartment in square meters.

The output of the system is then an adjustment to the compartment's lights and a display on an LCD screen, showing the current light intensity and the user determined intensity in percentage form.

The overall system overview is shown in *Figure2.*

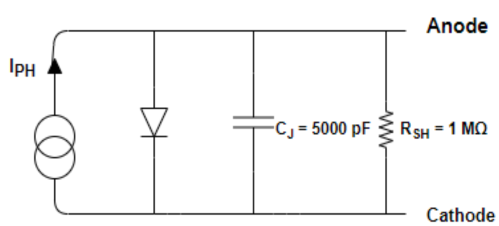

Figure 1: Photodiode circuit model

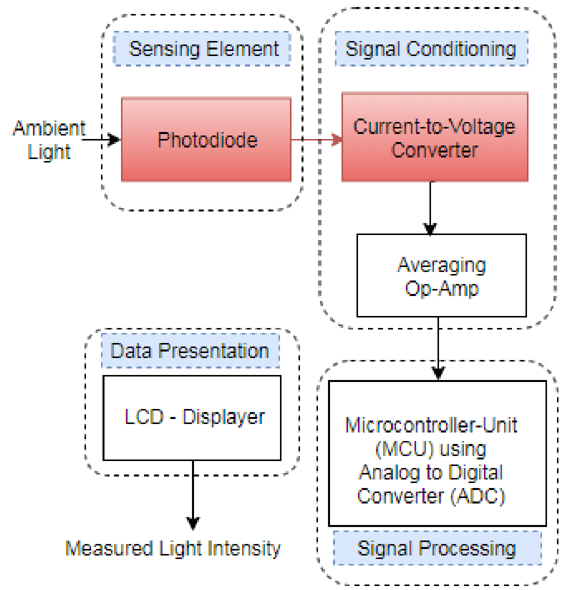

Figure 2: The system overview

3.1. Modelling the sensing element

A number of photodetectors exist to choose from to monitor a change in the intensity of ambient light inside a train compartment. These include phototransistors, light dependant resistors (LDR) and photodiodes. The system needed a sensing element with a wide bandwidth (much greater than 100Hz), a fast time response and a high precision. The photodiode was therefore chosen as the sensing element for the system since it possesses these characteristics.

Figure1 shows an equivalent model of the Hamamatsu G1963 GaP photodiode. The photodiode has a photosensitivity of 0.12 A/W, a rise time of 30 μs and a bandwidth of 30 kHz. The parameters of the model are: the junction capacitance, which represents the capacitive behaviour in the junction of the diode, with a value of 5000 pF, the shunt resistance, which is used to determine the noise current, has a value of 1 MΩ.

3.2. Signal Conditioning

The signal conditioning stage is comprised of two elements: a current-to-voltage converter and an averaging amplifier. Both these elements use an LM741 operational amplifier.

Current-Voltage Amplifier: This amplification circuitry is necessary because photodiodes have a small output current.

The connection between the photodiode and the current-to-voltage converter element forms a trans-impedance amplifier. The red-coloured segments shows the trans-impedance amplifier. The light hitting the photodiode can be modelled as an AC source because it is not constant. This alternating nature results in an unstable circuit because there is a lot of high-frequency noise due to op-amp properties [5]. The feedback capacitor in this circuit is used to stabilize this circuit as it will significantly decrease noise. *Equation2* below shows the transfer function of the trans-impedance amplifier circuit, while *Figure3* shows the corresponding bode diagram.

$$H(s) = \frac{V_{out}}{I_{Ph}} = \frac{-R_F}{1+sC_FR_F} \qquad (2)$$

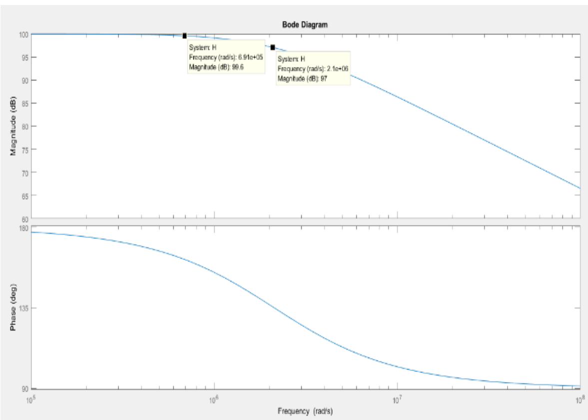

Figure 3: Bode plot for the trans-impedance circuit

Averaging Amplifier: A four-input averaging amplifier with 10 kΩ input resistors is used, and using operational amplifier theory, the feedback resistor will be 2.5 kΩ. This circuit is used to increase accuracy of results by averaging the output from the trans-impedance amplifier.

3.3. Signal Processing

The amplified and averaged signal is processed in this stage using an ATmega328 Arduino Nano. This microprocessor is chosen specifically for its 10-bit Analog-to-Digital Converters (ADC) feature, which allows for high resolution. This feature is used to convert the conditioning stage output voltage to digital format, in order to perform necessary calculations to determine the ambient light, store it in memory and then display it in the next stage.

3.3.1. Smartness

Calibration: The microprocessor is programmed to automatically carry out two calibration routines: offset and gain calibration. For offset calibration, when a 0 V or very small voltage is applied and the output obtained is greater than zero, then the offset value will be subtracted from the output. Alternatively, the offset value will be added to the output if the output is negative. Gain calibration is achieved through applying a full scale to the ADC. Figure 4 shows the logic of this calibration.

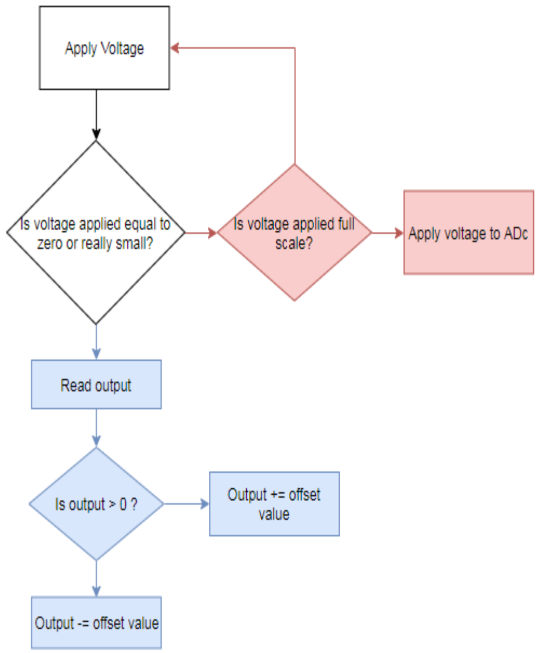

Figure 4: Flow chart showing the calibration logic

3.4. Data Presentation

The main element used to display data is a ST/16x2Y LCD display model. This model is a 2- line display, with 16 characters each and an operating voltage of 5 V. Using its corresponding driver integrated circuit (IC), this element uses the output obtained from the microprocessor to display the user required brightness as well as the measured light intensity in percentage units.

4. System Static Characteristics

The static characteristics of the entire system are shown in Table1. The resolution of the measurement system is calculated from the microcontroller's 10-bit ADC resolution, while the sensitivity is determined by that of the sensing element.

Table 1: Static Characteristics of overall system

Parameter	Value
Input ADC resolution	4.88 mV
Photocurrent range	0.04 µA – 2.5 mA
Photosensitivity	0.12 A/W
Output lighting Resolution	0.25 fc/lux

5. Dynamic Characteristics

The overall response of the system is a result of constituent elements in it, the sensor and signal conditioning elements being the main contributors. The system's transfer function is therefore a cascade of the sensor transfer function and that of the signal conditioning. *Equation3* shows the resulting overall system transfer function.

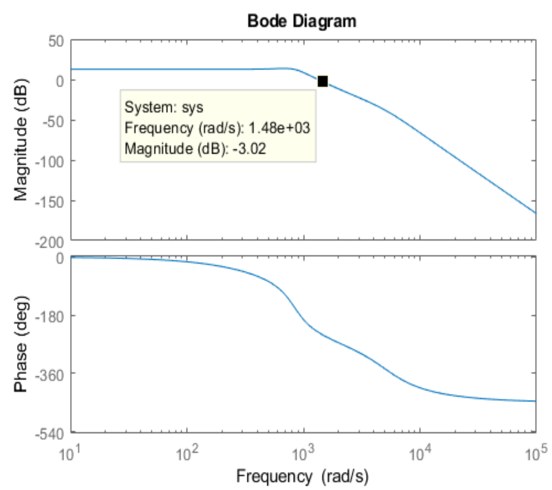

Figure 5: System frequency response

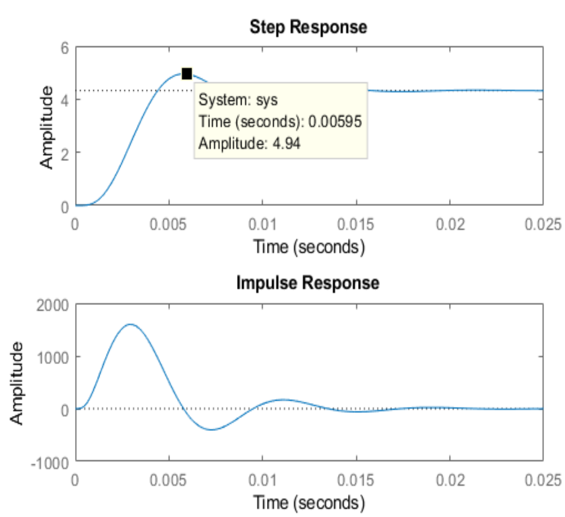

Figure 6: System time and impulse response

$$G(s) = \frac{s(s2.8*10^{-8}+1)}{s^2 8.91*10^{-14}+s2.82*10^{-4}+1} \qquad (3)$$

6. Critical Analysis

6.1. System Dynamic Characteristics

A bandwidth of 1.48 kHz was obtained for the overall system as shown in *Figure5*. The system time response reveals an under-damped response with a 5% overshoot, a rise time of 5 ms and a fast settling time of 15 ms. This means that the designed system has a fast response as well as a fast settling time to a sudden change in light intensity, such that a human eye cannot detect the rapid change thus achieving a virtually constant light intensity (human eye reacts to a visual stimulus after 250 ms [6]).

6.2. Error Analysis

Table 2: System static error contribution

System Element	Error
Sensing Element	1%
Trans-impedance	2%
Averaging amplifier	2%
Overall system error	4%

Static errors: Largest errors introduced to the system are a result of analogue circuitry and parasitic effect. These are mostly seen in the sensing element, trans-impedance amplifying circuit and the averaging amplifier. *Table2* shows these system components with their corresponding approximated error values. An overall system error of 4% was calculated.

Dynamic errors: From the step response of the system, a rise time of 5 ms**,** and an overshoot of 5% can be seen. It is also noted that the system takes 15 ms to reach steady state. The main contributor to the system's dynamic errors is the overshoot. This error will only span for a small period of time and will barely be noticeable. Using the results from the simulations, an error of 5% was calculated.

6.3. System Costs

The total costs expected to be incurred in this system is given in *Table3*. The system costs are approximated to be R1222.48.

Table 3: System costs

Component	Quantity	Price
G1693 Photodiode	4	R50.00
LM741 Op Amp	2	R4.95
Resistor	5	R0.56
Capacitor	1	R5.00
ST/16*2Y LCD	1	R510
Atmega328 Arduino Nano	1	R430
Vero board	1	R 64.78
Total		R1222.48

7. Future recommendations

In future, given that constraints of the project are different from this one, integrated circuits (IC) can be used to design this system to save costs, decrease power consumption, increase speed functionality (less parasitic capacitance effects) and achieve a better functionality as more complex circuits can be fabricated to achieve better. For example, a trans-impedance amplifier IC can be used instead of using separate components. A photo IC, which comprises of a photo diode and a signal processing circuit in one package, could also be used. The advantage of this IC is that it is more ideal for mass production and it is resistant to electromagnetic induction noise [5].

8. Conclusion

A unique smart measurement system that measures ambient light and uses it to control interior-lighting system in trains has been presented. The electrical signal generated from the photodiode is conditioned using operational amplifiers, then processed using artificial intelligence to achieve smartness and ADC to digitalize the signal. The system has a bandwidth of 1.48 kHz**,** which meets the project requirements. Systematic errors are 4% and 5% for dynamic and static errors respectively. Techniques such as gain and offset calibration has been implemented to minimise errors. The paper has also presented ideas that may be taken into account in the future.

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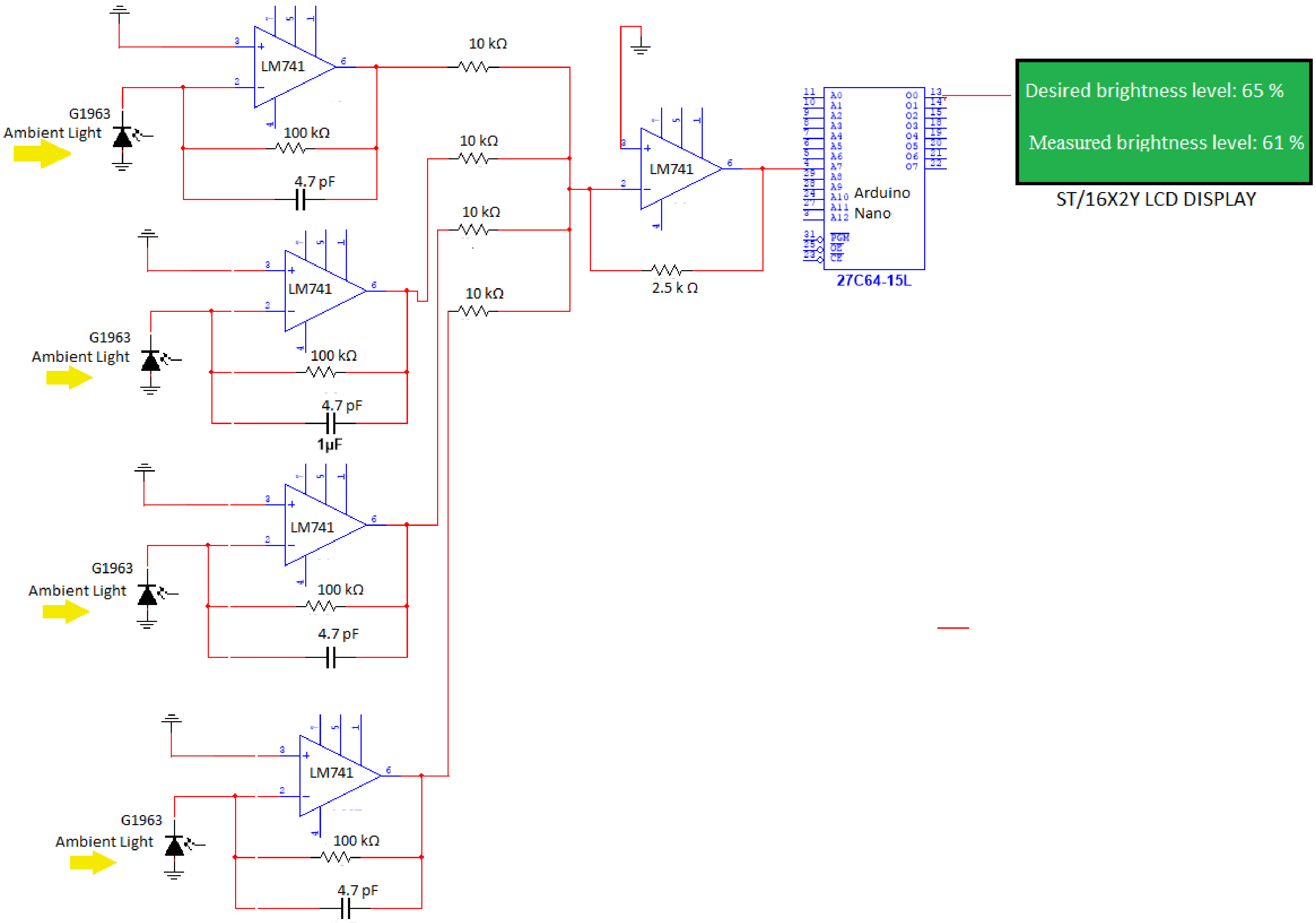

Figure 7: The complete circuit diagram of the smart interior-lighting system