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Departamento de Electrónica, Telecomunicações e Informática

Krzysztof Marek Machnicki

Sistema de Gestão de Iluminação em Ambientes Industriais

Lighting Management System in Industrial Environments

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Lighting Management System in Industrial Environments

System Zarządzania Oświetleniem w Środowiskach Przemysłowych

Dissertation submitted to the University of Aveiro as part of its Master's in Electronics and Telecommunications Engineering Degree. The work was carried out under the scientific supervision of Doctor Luís Filipe Mesquita Nero Moreira Alves, Assistant Professor of the Department of Electronics, Telecommunications and Informatics of the University of Aveiro and Engineer António Manuel Rodrigues Tavares of Diferencial - Electrotécnica Geral Lda.
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This thesis is dedicated to my family
for their love, endless support
and encouragement.

o júri

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palavras-chave

iluminação, sistema de controlo de iluminação, ambientes industriais, gestão de iluminação, eficiência energética, controlo automático.

resumo

A presente dissertação aborda a concepção e implementação de um sistema de gestão de iluminação para ambientes industriais. O objectivo principal deste sistema é fornecer controlo avançado em instalações de iluminação já existentes de forma a reduzir o consumo de energia e aumentar a eficiência global do sistema, sem recorrer a mudanças significativas na infra-estrutura de iluminação.

Em ambientes industriais, as instalações de iluminação convencionais são geralmente baseadas em lâmpadas de alta potência com um controlo básico de ligado/desligado, através de interruptores manuais que actuam sobre contactores. A ideia do sistema proposto é oferecer um controlo automático que ajuste a iluminação, medida por um conjunto de sensores, a níveis pré-definidos pelo usuário. Tal é conseguido através da actuação sobre os contactores, ligando/desligando lâmpadas ou grupos de lâmpadas específicos. Por exemplo, durante o dia quando a luz natural é maior, o sistema deve compensar reduzindo o número de lâmpadas que estão acesas, reduzindo assim o consumo de energia e aumentando a eficiência do sistema de iluminação.

O estudo sobre sistemas de gestão de iluminação começa com uma introdução à problemática do elevado consumo energético das instalações de iluminação industriais, e possíveis soluções. É seguido por uma descrição de soluções disponíveis destinadas a clientes industriais. Dispositivos e tecnologias que podem proporcionar uma solução, com melhor relação custo-benefício, mais flexível e fiável são também apresentados.

Segue-se uma visão global do design do sistema, fornecendo os pontos de vista que levaram à escolhia das estratégias utilizadas no desenvolvimento do sistema. As principais linhas condutoras do projecto juntamente com componentes individuais do sistema, são também apresentados. Este estudo conceptual foi fundamental, permitindo a comparação de diferentes hipóteses levando à escolha da solução apresentada.

Após definição da estratégia a seguir, o sistema actual foi desenhado e implementado. Os principais componentes são descritos separadamente a fim de proporcionar uma melhor perspectiva do princípio operacional do sistema. O custo de implementação do sistema de controlo projectado foi também calculado de forma a avaliar a competitividade do dispositivo.

No final, uma visão geral dos objectivos atingidos e dos resultados obtidos é dada. As principais conclusões são derivadas do trabalho apresentado nesta dissertação, juntamente com orientações para trabalhos futuros.

keywords

lighting, illumination, lighting control system, industry, lighting management, energy efficiency, automatic control.

abstract

This dissertation addresses the design and implementation of a lighting management system for industrial environments. The main objective of this system is to provide advanced control to already existing lighting installations in order to reduce power consumption and increase the overall energetic efficiency, without significant changes to the lighting infrastructure.

In industrial environments, conventional lighting installations are usually built with high power lamps and basic on/off control through manual switches and contactors. The idea of the proposed system is to provide an automatic control that adjusts the illumination levels, measured by a set of sensors, to user-defined values. This is achieved by actuating on the contactors and turning on/off specific lamps or groups of lamps. For example, during daytime when natural light is higher, the system should compensate by reducing the number of lamps that are on, thus reducing power consumption and increasing the system efficiency.

The study on lighting management system begins with an introduction to the problem of high power consumption of industrial lighting installations and possible solutions. It is followed by a description of available solutions aimed at industrial clients. Devices and technologies that can provide a more cost-effective, flexible and reliable solution are also presented.

A system design overview follows, providing the insights that lead to the strategies selected for system development. The main design guidelines along with individual system components are also presented. This conceptual study was critical, allowing the comparison of different possibilities, leading to the selection of the presented solution.

Upon defining the strategy to follow, the actual system was designed and implemented. The main components are described separately in order to provide a better perspective on the system’s operating principle. The implementation cost of the projected control system was also calculated in order to assess competitiveness of the device.

In the end, an overview of the achieved objectives and the obtained results are given. Conclusions are derived from the work presented in this dissertation, along with guidelines for future work.

słowa kluczowe

oświetlenie, system sterowania oświetleniem, przemysł, zarządzanie oświetleniem, wydajność energetyczna, sterowanie automatyczne.

streszczenie

Poniższa rozprawa dotyczy zaprojektowania i wykonania systemu zarządzania oświetleniem dla środowisk przemysłowych. Głównym celem tego systemu jest zapewnienie zaawansowanej kontroli już istniejących instalacji oświetleniowych w celu zmniejszenia zużycia energii i zwiększenia ogólnej wydajności energetycznej, bez istotnych zmian w infrastrukturze oświetlenia.
W środowiskach przemysłowych, konwencjonalne instalacje oświetleniowe są zwykle zbudowane z lamp dużej mocy i podstawowego sterowania, zbudowanego z przełączników i styczników. Idea proponowanego systemu polega na zapewnieniu automatycznego sterowania, które reguluje poziom oświetlenia, mierzonego przez zestaw czujników, do zdefiniowanych przez użytkownika wartości. Osiąga się to poprzez sterowanie stycznikami w celu włączenia/wyłączenia konkretnych lamp lub grup lamp. Na przykład, w ciągu dnia, gdy więcej światła dziennego jest dostarczane do wnętrza budynku, system powinien skompensować poziom oświetlenia poprzez zmniejszenie liczby włączonych lamp, co przekłada się na zmniejszenie zużycia energii i tym samym zwiększenie wydajności systemu.
Poniższa praca rozpoczyna się wprowadzeniem do problemu wysokiego zużycia energii w przemysłowych instalacjach oświetleniowych i możliwych rozwiązań tego problemu. Następnie następuje opis dostępnych rozwiązań sterowania oświetleniem, mających na celu klientów przemysłowych. Urządzenia i technologie, które mogą zapewnić bardziej ekonomiczne, elastyczne i niezawodne rozwiązania są również przedstawione.
Zarys budowy systemu został zaprezentowany, dostarczając modele, które wprowadzają do strategii wybranych do dalszego rozwoju systemu. Także główne wytyczne, związane z projektowaniem systemu oraz poszczególnych elementów zostają przedstawione. Prezentacja koncepcji dalszego rozwoju systemu była bardzo ważna, ponieważ umożliwiła porównanie różnych możliwości, prowadząc do wyboru najlepszych rozwiązań.
Po zdefiniowaniu ścieżki rozwoju, rzeczywisty system został zaprojektowany i wykonany. Poszczególne elementy zostały opisane oddzielnie w celu zapewnienia lepszej perspektywy, przedstawiającej zasadę działania urządzenia. Także koszt realizacji zaprojektowanego systemu sterowania został obliczony w celu oceny konkurencyjności.
W końcu, przegląd osiągniętych celów i uzyskane wyniki zostają przedstawione, a także wnioski pochodzące z niniejszej pracy magisterskiej oraz wytyczne dla dalszego rozwoju projektu.

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CHAPTER 1:
INTRODUCTION

Electrical energy is one of the most important products in modern society. Because of huge amount of electric devices, people use nowadays, the demand for energy is rapidly increasing worldwide (Figure 1). According to the International Energy Agency research [1], demand for electricity will increase about 36% in years 2008 – 2035. Along with increased power consumption, appears a problem of natural environment pollution. It is connected with methods of electricity generation. Just like almost 40 years ago, the main sources were: coal (41%), gas (21%) and oil (5,5%) [2]. During energy transformation from fuel into electricity, a lot of CO_2, which cause greenhouse effect, is emitted into the atmosphere. CO_2 level will grow at the same pace as the demand for energy, unless we will radically change the way of production and the use of energy.

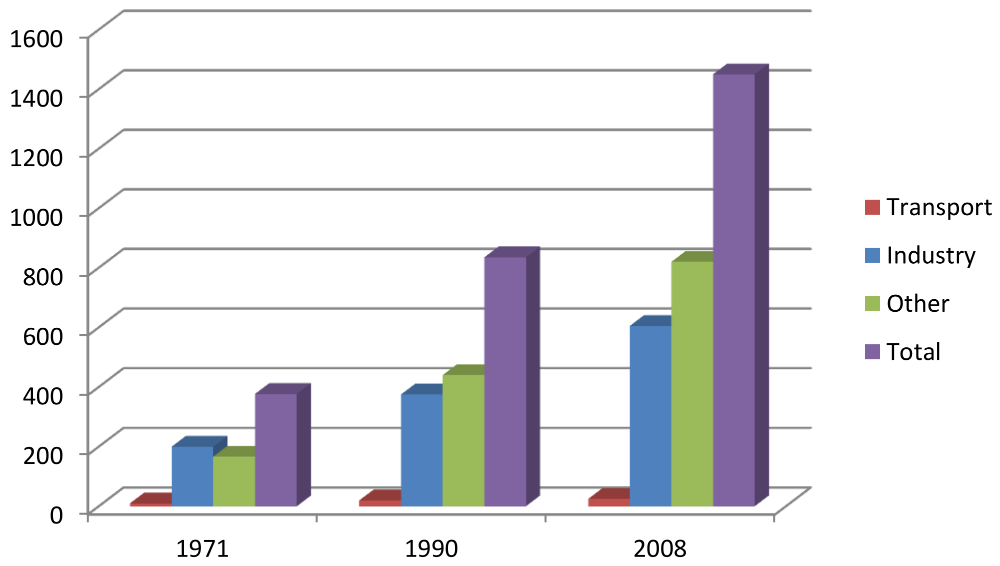


FIGURE 1: EVOLUTION FROM 1971 TO 2008 OF THE TOTAL ELECTRICITY CONSUMPTION (MTOE).

The problem of growing emission of CO_2 caused a public debate about human influence on the climate change. In a consequence issues such as security of power supplies, other methods of electricity generation and energy prices were at the top of the list of the most important topics, discussed at a public forum. Those issues have motivated the European Council to adopt in 2007 the energy and climate change objectives for 2020 [3, 4]:

- reduce greenhouse gas emissions by 20%
- increase the share of renewable energy to 20%
- make a 20% improvement in energy efficiency

To fulfill these objectives until 2020 is a priority for EU. That is why all governments in the EU are forced to support energy-efficient technologies, products and services applied in residential buildings, industry and transport.

In residential buildings changes have begun some time ago. It is advised to use energy – efficient lighting instead of ordinary light bulbs, energy – efficient household devices like washing machines, ovens, refrigerators etc. Moreover, buildings in colder climates have to be isolated properly, in order to lose less heat.

In industry there are no strict rules yet but many companies are already looking for solutions, which will allow them to reduce power consumption. Care of natural environment is not the only reason why they are looking for energy efficient solutions in order to maximize the income. Along with an increase of electricity demand, the price they have to pay is also growing. To be more competitive on the market and gain in the eyes of customers as “natural environment friendly”, factories are trying to lower their electricity consumption.

There are many possibilities to achieve this aim by companies. In this thesis we will consider lowering power consumption by decreasing power consumption due to the usage of discharge lamps, which in many cases consume a lot of energy.

1.1 PROBLEM STATEMENT

Industrial buildings require well planned lighting installations in order to provide good working conditions. This is a key issue for performance and a productivity of employees. Appropriate quantities of lamps are essential but the quality issues are just as important in providing comfortable and safe working environment. According to the British Standard EN12464-1:2002 “Light and lighting – Lighting of workplaces – Part 1: Indoor work places” and the book “Code of lighting” [5], recommended illumination levels inside the factory hall, depend on the use of area and vary from about 100 to 2000 lux.

Nowadays, the most often used lighting installations in industry are based on fluorescent and metal halide lamps because of their high energy efficiency [6]. However, these lamps cannot be switched very often. For example, metal halide, which belong to High-Intensity Discharge (HID) family of lamps, operate under high pressure and temperature. These lamps need to overcome a startup time in order to achieve the required temperature and pressure conditions for optimal operation. This startup time may, in some cases, reach to five minutes. Under these conditions it is difficult to use standard PWM dimmers to control the illumination level. First, because it is not possible to switch on/off instantaneously. Second, because reducing the illumination level would imply changing the operating conditions of the lamps, thus reducing the efficiency.

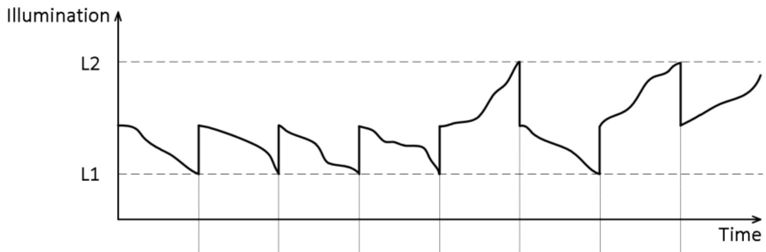
Most of the factory halls have similar lighting installations. High power lamps, described in previous paragraph, are controlled by contactors, which can handle high current flow. They are turned on manually by employees using manual switches. The problem is that, usually all lamps are turned on for the whole day, even if the illumination inside the building is higher than sufficient. Workers are generally too busy to regulate lighting inside the factory hall in order to lower the power consumption. This problem can be solved installing a control system, able to switch lamps in order to provide the minimum necessary illumination.

Simple calculation of how much energy can be saved by turning off lamps, which are not necessary to be on, shows the advantages of these power management systems. For example 100 lamps, 500W each, shining all day consume 1200kWh. If only 80 lamps would be on for only 10 hours at night, they would consume 400kWh, which gives only 33% of energy used by all lamps turned on for whole day. Because in many companies, electricity used for lighting constitute over 20% of whole used energy, a lot of electricity (and therefore money) can be saved using efficient lighting management system.

1.2 THESIS OBJECTIVE

The main objective of this work was to develop and design a universal lighting management system for industrial environments. This include getting familiar with the most often used lighting installations, analyzing already existing lighting control systems and electronic devices in order to develop the best solutions and implement them into new control system.

It is very important to develop a system, which will fully cooperate with existing lighting installations so that lighting management can be provided without obligation of changing or modifying installation. The idea of this project is to add to the switching board which controls the lights, the possibility to override the manual switches with automatic control. The system should be able to monitor the level of lighting intensity in a factory hall (which usually varies between 100 lux and 2000 lux), and depending on preferred illumination settings, adjust it by switching groups of lamps. The user should have also the opportunity to change preferred level of illumination, around which the light intensity should vary. The system should check periodically if the actual illumination is in the range between a minimum and a maximum level of lighting. If not, then it should react by switching on or off groups of lamps. If the measured light intensity would be lower than the minimum level, then the system should turn on more groups of lamps. If it would be higher than the maximum level, then the system should turn off one group of lamps by opening one circuit (Figure 2).



Circuit								
1	0	1	1	1	1	1	1	1
2	0	0	1	1	1	1	1	1
3	0	0	0	1	1	1	1	1
4	0	0	0	0	1	0	1	0

0 – Lamps off
1 – Lamps on
L1 – Minimum Illumination Level
L2 – Maximum Illumination Level

FIGURE 2: CHART PRESENTING THE PRINCIPLE OF MANAGEMENT SYSTEM.

The system should also be characterized with simplicity of architecture and flexibility, so that it could be installed in slightly different installations. It should be simple to use and configure without requiring specialized technical knowledge. All of these assumptions should be fulfilled with the minimum cost possible.

1.3 STRUCTURE OF THE DISSERTATION

The whole dissertation is divided into five chapters. The current chapter presented an introduction to the project development. It described the reasons why energy saving is so important, not only for industry but also for households and what can be done towards utilization of more efficient energy technologies.

Chapter II presents a state of the art on existing solutions available on the market, which can be used as lighting management system, or act as inspiration used for building new solutions. During this survey, the reader's attention is turned on to the most important parameters which determine devices usability. Also available technologies, which may be used for system development, are briefly described and compared.

Chapter III is fully dedicated for the presentation of system design concepts. Ideas for every part of the system are presented, starting with the control strategy, methods of illumination measurement, connection between the system and the lighting installation, communication between system parts and general principles of system operation. Most of these issues contain more than one parallel solution. The advantages and disadvantages of each idea are briefly described so that it would be easier to pick the solution that is the most suitable for the intended application.

Considering system development, chapter IV is the most important one. Chapter IV discusses all the details, concerning project design and implementation. Every part, forming the system is described independently so that understanding of whole system architecture is easier. Beside describing the hardware part, in this chapter, the reader will have also the opportunity to learn the principle of system operation, get familiar with the costs and the power consumption of developed solutions.

The last chapter of this dissertation presents results and conclusions reached, during the execution of system development. Some guidelines for future work are also discussed.

CHAPTER 2:
STATE OF THE ART SURVEY

This chapter presents an overview over the existing solutions suitable for industrial light control. The most important is to find out if there are similar control systems available on the market and decide how to design a new system so that it can represent a good alternative. Next thing, which also has to be done, is to check if there are some electronic components that can be used in project development. The specification of these components needs to be considered first in order to evaluate its impact on the system. If they do not meet the project requirements, then further search for similar devices must be done.

2.1 LIGHTING MANAGEMENT SYSTEMS FOR INDUSTRIAL ENVIRONMENTS

Searching for currently available solutions for illumination control in industrial environments did not produce many results. Either very simple and poor in features or very large and complicated systems were found, which do not fulfill objectives of this project. The main characteristic for this one application is to assure a control system able to cooperate with existing lighting installations. However, this only proves that there is still a place for implements on lightning management systems for industrial buildings.

Nowadays, in order to keep the already existing lighting installation unmodified and provide only the basic control for it, it is advisable to use photoelectric cells, motion sensors or time clock to control each contactor [7]. These devices are placed on power lines in parallel with manual switches allowing the user to choose whether these contactors will have automatic control or they will be overridden with manual switches. If manual switch will be turned off, then automatic control will manage the lighting installation. Depending on requirements, the designer can use photoelectric cells, motion sensors or time clock. First one, will turn on the contactor only when illumination level in factory hall is lower than a certain predefined value. Motion sensors will turn on the light only when there will be somebody detected. Finally the time clock turns the light only within specific period of time. These devices can be used separately or combined, thus allowing to ensure the best lighting conditions in the factory hall (Figure 3).

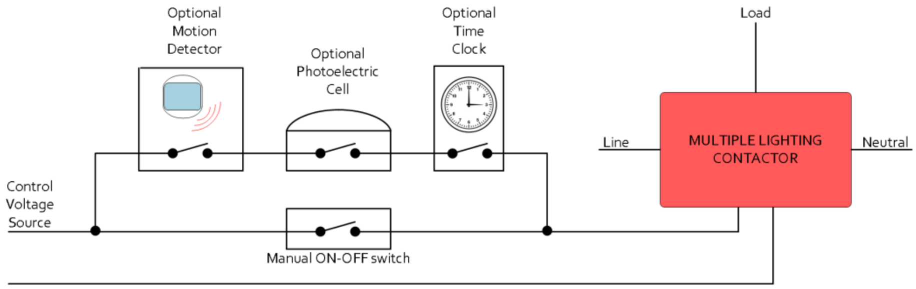


FIGURE 3: EXAMPLE OF A SIMPLE LIGHTING MANAGEMENT SYSTEM.

This solution is good for relatively small controlled areas because of its flexibility and a possibility of keeping the existing lighting installation, but has also some inconveniences. First of all, it is quite expensive, considering large areas and large number of controlled lamps, requiring too many control devices. Other disadvantage of this control system is not having the control board in one place, where the user would be able to adjust lighting settings. In order to change the preferred illumination level, the user would have to set each sensor individually, usually placed in a hard to reach places.

Other solutions for industrial lighting management consist of very complex systems, using the Digital Addressable Lighting Interface (DALI) communication standard. This technology was created in the 90s as a result of the cooperation of several manufacturers and was released as an open standard, which makes devices from different manufacturers fully compatible with each other [8]. DALI provides only the standard for determining the method of communication between network termination elements, like lighting frames interfaces and the control system without being dependent on specific technological solutions.

The basic feature of the DALI standard is the simplicity of the design and its installation. The communication network consists of two low-voltage lines that fulfill both functions of signal cables and power supply for the lamp drivers. An important fact is their total independence from the lamp's installation. High Signal to Noise Ratio and low transmission speed ensures very high resistance for external interferences. Thus, it is not required the use sophisticated anti–disruption procedures and signal lines selection, which can be put together with lamps' power cables.

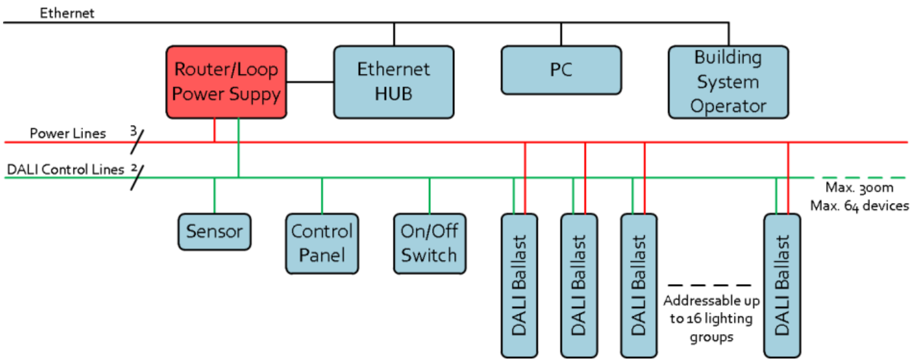


FIGURE 4: DALI SYSTEM ARCHITECTURE.

Every single DALI network can consist of up to 64 individually addressed devices that can be assigned to each of the 16 defined groups. Additionally, the individual memory of each of them can store 16 pre-assigned work programs. Because of its open architecture, connecting additional devices is not a problem. This gives a wide range of control options, allowing the operator to control each lamp, connected to the network, individually.

Using the DALI standard allows to avoid a lot of problems, with which the designers of lighting systems struggle in the early stages of their work. Often, initially it is impossible to precisely determine the destination of specific areas or it may change during building exploitation. The DALI standard allows to deploy the lamps and power installations, even when the exact location of the walls or the general concept of spatial patterns is not known yet. Details of the installation can be changed anytime by simply assigning specific loads to separate groups and control programs as shown below.

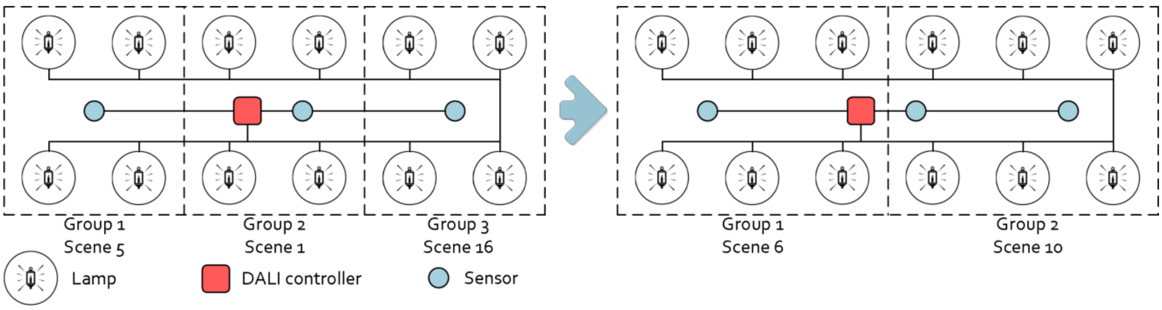


FIGURE 5: FLEXIBLE LIGHTING INSTALLATION.

Beside the advanced lighting control, these types of installations also give opportunities to save the electricity. With digital control protocols it is possible to communicate between lighting installations' controllers and peripheral devices (like different kinds of sensors). It is possible to program the light control system so that it would automatically turn off or dim the lighting in rooms which are used very rarely (or not used at all), such as for example in warehouses, stairwells. The DALI standard provides the ability of smooth lighting control of both individual lamps and entire sections, so that the lighting conditions always correspond to current needs. It is possible to establish separate lighting programs, considering the time of the day or the functions performed by the room at given time.

The DALI systems also enables to handle lighting installations in areas such as, gyms, factory halls or office spaces, which are already partially illuminated by the sunlight through the windows. The installation, in collaboration with sensors of lighting intensity, allows to adjust the individual lamps to ensure uniform and at the same time minimum required level of illumination across the surface and can even completely disable them.

The DALI systems are good solution for light management in factories. However, it is seldom put it into practice with already existing installations. Mainly because it is very expensive and it would imply dramatic modifications on the existing installation, in order to use all functionalities of the standard.

2.2 MICROCONTROLLER

Microcontrollers are the most often used electronic drivers in control systems. The first microprocessor appeared in the 1970s [9]. It was an amazing device, a small computer, closed in comparatively small space. But still, all of other functions like a memory, input and output interfacing, were outside of the microprocessor and had to be done separately.

People, very quickly, spotted the potential of microprocessors and found another use for them in control systems. Designers started to put external peripherals into integrated circuit along with the microprocessor. That way they created the microcontroller, a small control device which had its own microprocessor, memory, I/O ports and lots of other entities, used to provide easy control of external device [10].

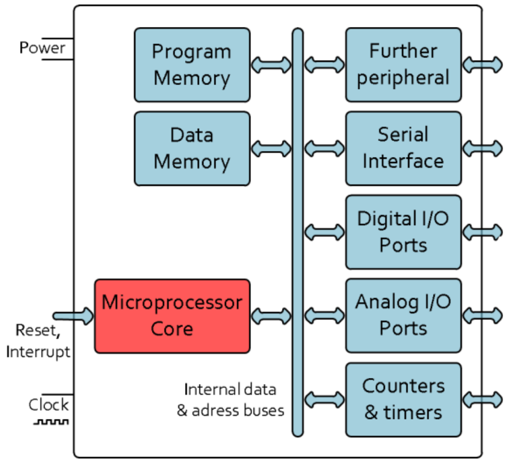


FIGURE 6: A GENERIC MICROCONTROLLER DESIGN.

There is a wide selection of available microcontrollers' manufactures, which have different architectures and capabilities. Some of them may be suitable for the particular application, others may not. However, there are hardware features common to the majority of the microcontrollers [11]. Here we have listed the most important:

- Supply Voltage – microcontrollers operate on low voltages from 2,7V to 6V. There are two mostly often used power supplies: 5V and 3.3V.
- Clock – every microcontroller needs an oscillator in order to work properly. Mostly used are crystals and two capacitors (together with internal oscillator).
- Timers – the timer is a very important part of the microcontroller. Usually it is a 8 or 16 bit wide register. It can be controlled by program and usually is used to generate an interrupt when it will reach a certain count.
- Interrupts – are used when microcontroller has to react very quickly on internal or external event. When the interruption occurs, the microcontroller stops executing normal program sequence and jumps to the special part, which was designed to handle specific interruption. After execution of this special part, the microcontroller goes back to the place in the program, where the interruption was started.
- Analog – to – Digital Converter – is used to convert analog signal, voltage in this case, to digital form so that microcontroller can read it and operate on digital data. A/D converters are especially useful in control and monitoring applications, since most of the sensors produce analog voltage output.

- Serial I/O – there are many types of serial communication, the most often used are RS – 232, SPI and I^2C. Most of the existing microcontrollers support at least one of them.
- EEPROM Data Memory – it is used when the programmer wants to store important data, which will not disappear after turning off the power supply.

The most known microcontrollers' families nowadays are:

- 8051 – developed by Intel
- AVR – developed by Atmel
- PIC – developed by Microchip
- HC11/HC12 – developed by Motorola

All microcontrollers contain a CPU unit which makes them suitable for several projects. However, it is important to choose the most appropriate one. As it was mentioned before, microcontrollers vary with different peripherals and this is the most important issue, which has to be taken into consideration choosing the device. There are also microcontroller families, which possess similar peripherals but differ with number of I/O ports, storage capacity for program and data, number of peripheral entities like A/D converters or comparators, maximum frequency of operation etc.

In the beginning it is very hard to pick the most suitable microcontroller. Although, issues like the number of necessary pins and peripheral devices are usually known from the beginning, the designer does not know what will be the storage capacity needed. It is very common to choose the family of microcontroller unit and then take the one with biggest capabilities in order to design a prototype. Programming microcontrollers within families is very similar so after building a prototype, the designer knowing exactly what features of microcontroller are needed, can change it to a different one, reducing the cost in most cases.

2.3 PHOTODETECTOR

Broadly speaking, a photodetector can be described as solid-state optical receiver, which absorbs optical energy and converts it into an electrical signal. The main principle, which allows photodetectors to measure illumination, is the photoelectric effect. According to James Maxwell's study, the light energy consists of very small packets of energy, which are called photons. When the light stream is directed onto the photodetector device, these photons hit its surface and transfer the energy. The net result is free electron generation, which is an electric charge carrier. Minimum energy, which has to be absorbed from photons, required to generate an electron in semiconductor is defined by energy bandgap (E_g) between valence and conduction bands and can be described by the following equation:

$$h \cdot \upsilon \geq E_g$$

where *h* is Planc constant and *ν* is the frequency of the light radiation. In other words, if the energy coming from photons is large enough, electrons in the valence band can jump to the conduction band, becoming electric charge carriers. This process is called photonic excitation [12]. There is also the opposite process, called recombination. It takes place when the electron loses its energy and goes back to the valence band (Figure 7). Free electrons can “drift” in a specific direction, even under a very small external electric field. When more energy is transferred by photons, more electrons are generated and therefore the resistance of the photodetector decreases, causing higher currents to flow with the same external voltage connected to the detector.

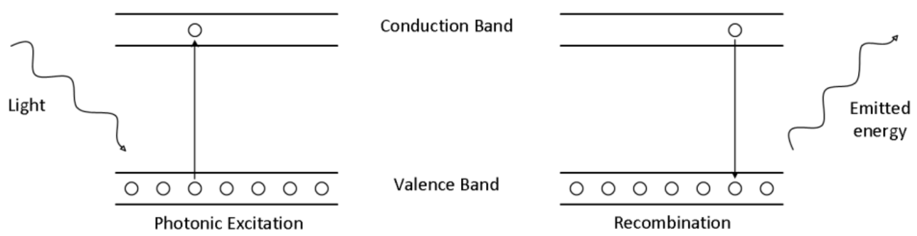


FIGURE 7: PHOTONIC EXCITATION AND RECOMBINATION IN A SEMICONDUCTOR MATERIAL.

Semiconductor photodetectors are made from different materials such as: silicon, germanium, gallium arsenide, indium antimonide etc. Each semiconductor material has a specific bandgap energy (E_g), which determines its light – absorbing capabilities. Absorbing capabilities also depend on the wavelength of light, reaching to the semiconductor’s surface. Light is a complex phenomenon, formed by electromagnetic radiation comprising different wavelengths (λ), as shown below (Figure 8) [13]. Visible light is just a very narrow range of electromagnetic spectrum.

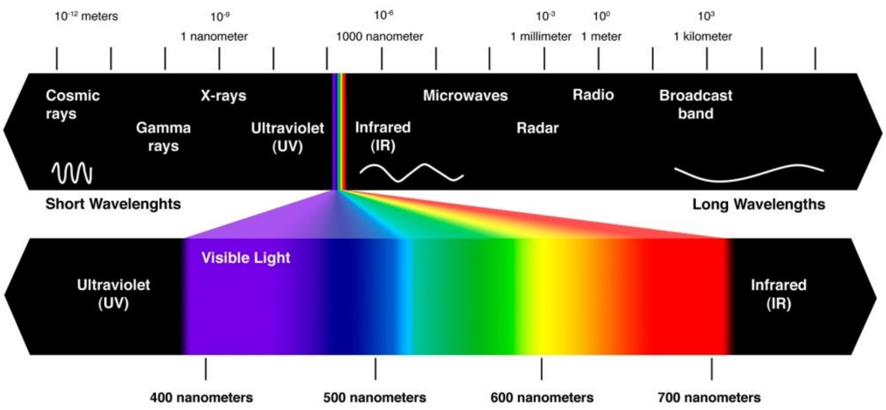


FIGURE 8: ELECTROMAGNETIC SPECTRUM.

There is a relation between the bandgap energy (E_g) and the light cutoff wavelength (λ_c), given by the following equation:

$$\lambda_c = \frac{1.24 \cdot 10^3 nm}{E_g}$$

Making use of that dependence, it is possible to choose a semiconductor material to design a photodetector for an adequate light wavelength range. While the bandgap energy (E_g) is decreasing, the photodetector can "see" farther into the infrared and can detect light with longer wavelengths. According to Table 1, silicon based photodetector would be enough to detect visible light, for which the wavelength is in the rage from about 400nm to 700nm.

Type	E_g(eV)	λ_c(nm)	Band
Gallium arsenide	1.42	875	Visible
Silicon	1.12	1100	Visible
Germanium	0.66	0.66	Near-infrared
Indium antimonide	0.17	5700	Medium-infrared

TABLE 1: RELATIONS BETWEEN BANDGAP ENERGY AND CUTOFF WAVELENGTH IN DIFFERENT MATERIALS AT 300K.

There are few basic types of photodetectors. The most popular nowadays are photoresistors, photodiodes and phototransistors. Most of them can be characterized by several figures of merit to help determine their suitability for a given application.

Quantum efficiency (η) is one of the most important parameters describing the photodetector. It is defined as the ratio between number of charge carriers contributing to the current and the number of photons impinging the semiconductor surface per second. Usually, it is expressed in percentage and can vary from few to almost 90 percent. It is closely related with responsivity (R), which is an expression, given in Ampere/Watt, determining how much photocurrent is produced by the impinging optical power, of given wavelength. Another parameter is the detectivity, which defines how sensitive the detector is to optical signals. Response time is also an important parameter. It describes the time taken by the detector to respond to the changing optical signal.

2.3.1 PHOTORESISTOR

Photoresistor, as the name says, is an electronic device, which changes its resistance adequately to the lighting intensity. With external illumination increase, the resistance of this photodetector decreases.

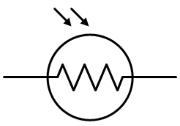


FIGURE 9: SYMBOL OF A PHOTORESISTOR.

Photoresistors are made of a high resistance semiconductors, usually cadmium sulphide or cadmium selenide, and metal contacts in a comb shape (Figure 10). Metal contacts have very small resistance so that the current can easily flow through them, however, semiconductor's resistance between those metal contacts changes under illumination influence, due to photons falling on the semiconductor's surface and the generation of free charge carriers.

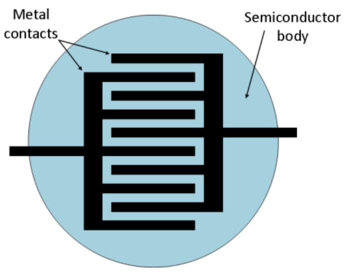


FIGURE 10: SYMBOL AND STRUCTURE OF TYPICAL PHOTORESISTOR.

There are two types of photoresistors: intrinsic and extrinsic. In intrinsic devices there are no external impurities (atoms of other elements). That means the only electrons, which can jump to the conduction band, are in valence band and they need relatively high optical power to do it. In extrinsic photoresistors there are some impurities within semiconductor's body, injected by purpose. Those impurities, atoms, occupy an energy state between the valence band and the conduction band. Extrinsic devices demand less optical power to obtain free charge carriers ($E_i > h \cdot \upsilon$) than intrinsic because electrons can jump to the conduction band directly from the impuritie's energy state (Figure 11). For intrinsic photoresistors it is hard to achieve cutoff wavelengths greater then infrared. In order to measure light within infrared range and higher, extrinsic photoresistors must be used. Their energy bandgap (E_i) is usually lower than 0.1eV, which gives an opportunity to produce photodetectors for higher cutoff wavelengths. Unfortunately, extrinsic photoresistors have low absorption and therefore poor quantum efficiency. Also, because the thermal energy can generate charge carriers, extrinsic photoresistors have to be cooled to liquid nitrogen temperature (77K) in order to get rid of the noise, caused by external environment temperature.

The disadvantage of all kinds of photoresistors is the relatively large response time, what makes them useless in areas, where high frequencies are used, like optical communication.

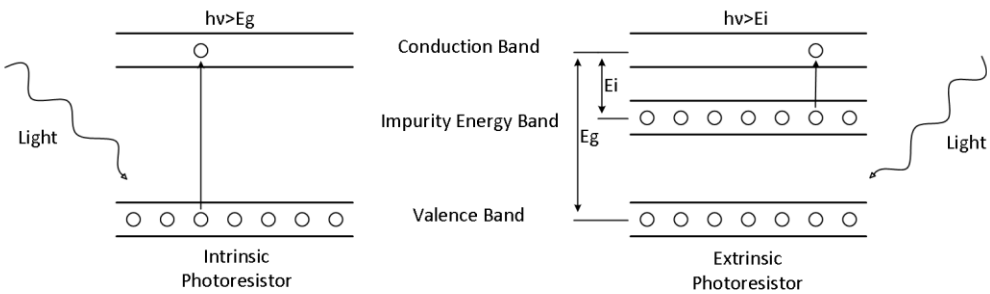


FIGURE 11: FUNCTIONAL DIAGRAM OF INTRINSIC AND EXTRINSIC PHOTORESISTORS.

2.3.2 PHOTODIODE

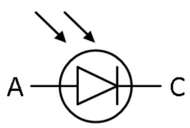


FIGURE 12: SYMBOL OF A PHOTODIODE.

Unlike photoresistors, a photodiode consist of an active p-n junction, usually working in reverse bias. When the diode is exposed to the illumination, a reverse current, proportional to the lighting intensity level flows. It works similar to the photoresistor, photodiodes also use the photoelectric effect to generate free electrons and positively charged electron holes [14]. If the photon absorption occurs in the junction's depletion region or very close to it, then excited carriers are generated and swept by the built-in field of the depletion region. Holes move in the anode direction and free electrons move in the cathode direction, producing a small photocurrent. When there is no external voltage connected to photodiode contacts, then the flow of the photocurrent out of p-n junction is restricted and a voltage builds up. This is a photovoltaic effect, used to generate electrical energy in solar cells. However, an applied reverse voltage, forces the charge carriers towards the external electrodes (Figure 13). The total current, which can flow through a photodiode, under external voltage, is proportional to light intensity, directed on the diode's surface and equals:

$$I_{PD} = I_{SAT} \cdot (e^{\frac{q \cdot V_A}{k_B \cdot T}} - 1) - I_P$$

where I_{SAT} is the reverse saturation current, q is the electron charge, V_A is the applied bias voltage, k_B=1.38 x 10-23 J / K is the Boltzmann Constant and T is the absolute temperature. The first part is an ordinary diode current equation. In photodiodes, additionally there is a photocurrent I_P, which is heavily dependent on light intensity and equals:

$$I_P = R \cdot P$$

where R is photodiode responsivity and P is incident light power. The photocurrent in photodiodes is very small (range of uA or even below) and because of that, usually external amplification circuits have to be employed.

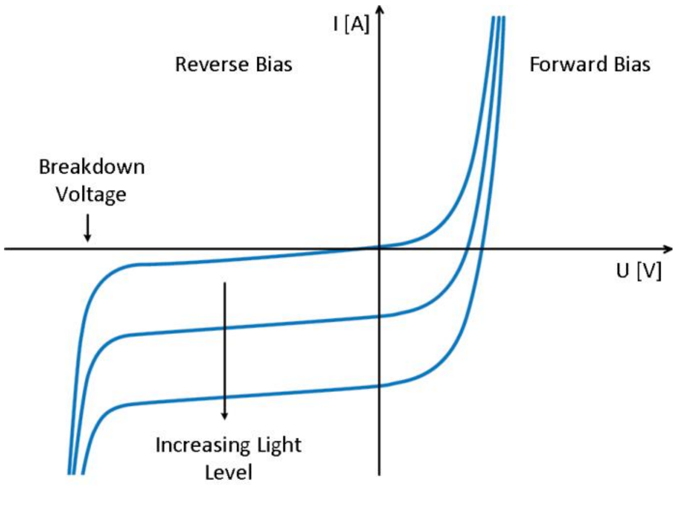


FIGURE 13: CURRENT VS. VOLTAGE PHOTODIODE CHARACTERISTIC.

Most of the charge carriers, available in the p-n junction get lost due to a recombination process. The improved p-n diode, which allows the charge carriers to travel faster through junction, providing higher reverse voltage and therefore wider bandwidth is a PIN photodiode [15]. It includes an intrinsic layer between the P and N layers (Figure 14). The PIN photodiode must be reverse biased because of high resistivity of the intrinsic part. The PIN diode has a larger depletion region which allows developing more electron-hole pairs at a lower capacitance. The PIN diode has larger breakdown voltage, comparing to normal p-n diode, what allows using it with higher voltage. It results in a faster response time and gives opportunity to use it in high frequency systems with bandwidth up to the GHz range.

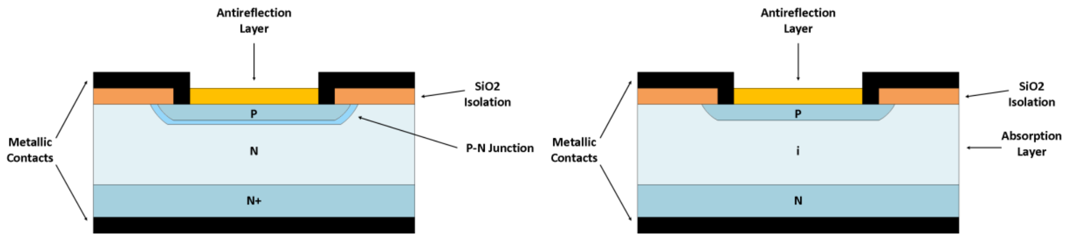


FIGURE 14: STRUCTURES OF P-N AND PIN PHOTODIODES.

Both p-n and PIN photodiodes are available on the market and both have their advantages and disadvantages. The biggest advantage of all photodiodes is their response time. The PIN photodiode needs reverse bias for normal work as a result of the intrinsic region built within the diode, which:

- introduces a noise current which reduces signal to noise ratio
- offers better performance for high bandwidth applications
- offers better performance for high dynamic range applications

A PN photodiode does not need to work in a reversed bias and therefore is more suitable for low light applications.

2.3.3 PHOTOTRANSISTOR

Phototransistor is an alternative to photodiode photodetector with p-n junction. Basically, it is a photodiode with the current amplification. The phototransistor exposes its collector-base junction, reverse biased, to radiant light stream. The principle of phototransistors is similar to photodiode's, with the difference they can provide some current gain and usually are more sensitive for external illumination than photodiodes. Thanks to the current gain, we can observe in a bipolar transistor, currents flowing through phototransistors are 50 to 100 times greater than standard currents of photodiodes. Considering phototransistor as just a normal bipolar transistor with collector-base junction exposed for the illumination, allows converting any normal bipolar transistor into a phototransistor by connecting ordinary photodiode between the collector and the base contacts (Figure 15).

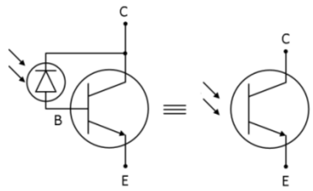


FIGURE 15: SIMPLE SCHEMATIC AND SYMBOL OF A PHOTOTRANSISTOR.

The current gain, present in phototransistors, is a result of bipolar transistor action and for homo-structures, the ones which use the same material for the whole device, may be in a range of about 50 up to a few hundred. Gain aspect looks better in hetero-structure devices, where it may rise even up to ten thousand. Even though, they have high gain, hetero-structure phototransistors are not widely used because of their higher costs.

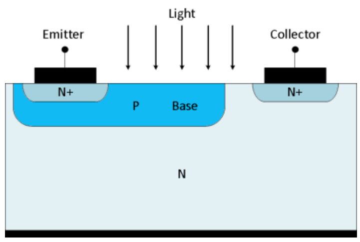


FIGURE 16: STRUCTURE OF A PHOTOTRANSISTOR.

Characteristics of the phototransistor, under influence of different light intensities look very similar to characteristics of an ordinary bipolar transistor. The difference is that the levels of the base current are replaced by levels of light intensity.

Since phototransistor detection is based on the photodiode, it cannot detect light any better. The advantage of the phototransistor in comparison to the photodiode is presence of current gain, wich allows using it in electronic circuits without any additional amplifiers. Unfortunately, in phototransistors, time response is much slower than in photodiodes, what makes them useless in some applications.

2.3.4 OPTICAL SENSOR

For many applications, the output photocurrent signal, coming directly from the photodetector is not adequate to meet system requirements [16]. The photodetector allows converting optical signal into small amplitude photocurrent. However, in many applications for normal operation it is required to convert the photocurrent into a voltage signal. That is why integrated devices, containing the photodetector, signal conversion modules and other peripherals, called optical sensors were designed. The most popular sensors have their output signal given as voltage. Besides that, we can find also sensors with frequency output signal and digital output.

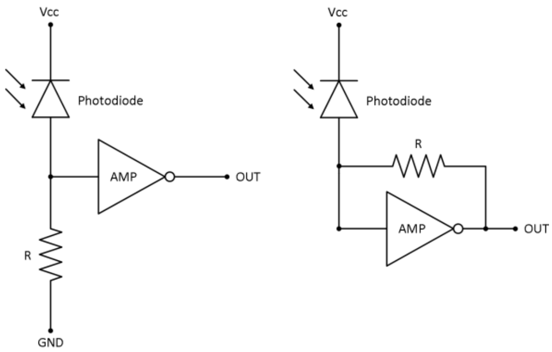


FIGURE 17: HIGH INPEDANCE AND TRANSIMPEDANCE AMPLIFIER DETECTOR CIRCUITS.

Most of the light sensors are built upon the photodiodes so they operate on photocurrent signal, which firstly is converted into voltage and then amplified. That makes the voltage conversion step very important in optical sensors' circuits. One of the methods of converting photocurrent into the voltage signal is to use a high impedance amplifier (Figure 17 on the left). It uses a resistor in order to develop the voltage, proportional to the light detector's current and then that voltage is amplified. Unfortunately, this circuit suffers from several weaknesses. First one is the saturation of the photodiode, if the resistance is too high it may prevent modulated signal from being detected. Saturation occurs when the voltage drop on the resistor, coming from the photodetector leakage current, approaches the voltage used to bias the diode. Additionally, while converting low current to voltage there is also a frequency response penalty when using simple high impedance detector circuit. This is because the photodetector capacitance and circuit wiring form a frequency filter, which cause the circuit to have lower impedance when used at higher frequencies.

An improved amplifier is the transimpedance amplifier (Figure 17 on the right). It is an amplifier that acts like a buffer and produces the voltage output signal, proportional to the input current. The biggest improvement of transimpedance amplifier over high impedance technique is lowering or even eliminating the effect of circuit wiring and diode capacitance, allowing transimpedance amplifier based circuits to work at higher frequencies.

After current to voltage conversion, the signal can be converted into square voltage signal using frequency modulation or given as a digital value. Nowadays, because of a very wide usage of microcontrollers, optical sensors with the digital output are becoming more and more popular. Instead of converting signal in microcontroller using ADC, we get the exact illumination given in binary code directly from the sensor, communicating with it by SPI, I^2C or SMBus communication standards.

2.4 INDUSTRIAL COMMUNICATION

Industrial communication systems are specially designed for deterministic communication between sensors, actuators, programmable logic controllers, monitoring systems and operator workstation. These systems were traditionally based on wired technology and deterministic medium access control. Nowadays, the emerging trend is the availability of wireless technology for industrial communication systems, since this leads to more flexible mobile equipment at reduced cost [17]. For industrial networks, wireless technologies provide several advantages such as cabling cost reduction, installation facility of equipment within hazardous areas and the flexibility of performing rapid plant reconfigurations. Other advantage is the possibility of creating truly mobile workstations. The human operator needs only a mobile hand-held device with wireless communication interface in order to perform data analysis or control on nearest equipment.

Although, wireless based industrial communication systems seems to be a good alternative to the traditional wired technology, they must ideally offer the same services [18]. Wireless technologies unfortunately are more error-prone and the packet losses in channel medium are inevitable, especially in high disruption areas. That is why using wireless technologies inside the industrial environment is generally restricted to fault-tolerant applications.

In this part, two of the most suitable communication standards for data collection from sensors will be described. The first is the RS–485 wired standard, used in industrial communication for many years, which ensures high communication reliability. The second one is quite new. A very promising wireless technology, specially designed for sensors and automation applications – the ZigBee standard.

2.4.1 RS – 485

RS-485, also known as EIA-485, is a standard, which defines the electrical characteristics of drivers and receivers for use in differential, multipoint communication systems. It was approved in 1983 by Electronics Industries Association (EIA) and after a short time it found widespread acceptance and usage in industrial, medical and customer applications. Till nowadays it is one of the most often used standard for industrial communications [19].

The RS-485 standard is based on RS-422 and RS-232, also approved by the EIA. Comparing these standards, RS-485 adds improvements, like possibility to connect multiple transmitters, enhancement of the transmitter drive capability and conflict protection features. It also extends the bus common mode range. It was designed to work with balanced transmission and reception in order to ensure reliable communication over noisy environments. The transmission distance is highly dependent on data transmission rate. Faster transmission rates, shorten the distance between equipment. It does not support neither star nor ring network topologies. Its topology is a terminal matched bus structure (daisy-chain).

RS-485 key features:

- differential interface
- multipoint operation
- -7V to +12V bus common mode range
- up to 32 transceivers
- 10Mbps maximum data rate at 6m
- 1200m maximum cable length at 90kbps

Despite RS-485 was especially designed to operate in half-duplex mode, it can also be made full-duplex by adding two additional differential wires. To operate in half-duplex mode it requires only two wires terminated with resistors (Figure 18).

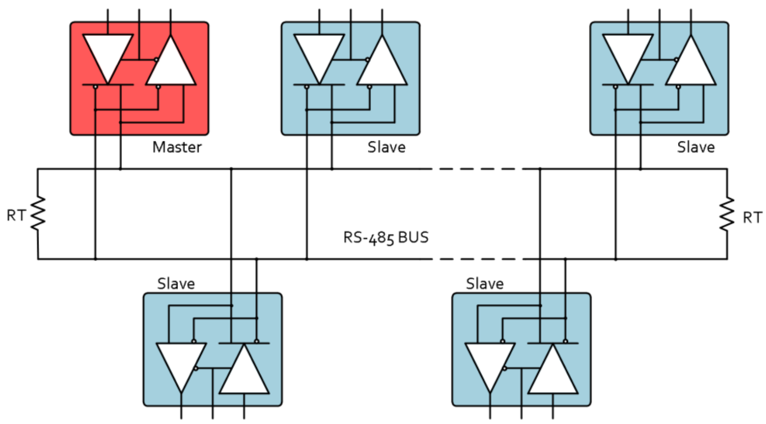


FIGURE 18: HALF-DUPLEX RS-485 BUS STRUCTURE.

Because it is possible to connect many devices to the RS-485 bus line, it has to be made sure that only one driver is transmitting data in a specific period of time. This is done using one of two modes: Master-Slave mode or Alternative Master – Slave mode [20]. In the first case, one of the devices connected to communication bus is a master and the others are slaves. That means, the master device constantly checks whether the slave nodes ask for communication. If communication request is sent by the slave device, master node grants right to control the bus to that device until data transmission is accomplished. Only the master device can initiate the transmission. It can also send broadcast message to all devices. Moreover, if two slave nodes want to communicate with each other, then data transmission has to go through the master device.

Alternative Master-Slave mode allows any device attached to the RS-485 bus, to become the master node. Master device passes the bus control to the adjacent nodes after successfully finished data transmission. In this mode any device can communicate with other node directly.

In order to ensure sufficient voltage drop margin for reliable data transmission, even under high external disruptions, the RS-485 standard defines the driver's minimum differential output as 1,5V and conform receivers to detect a minimum differential voltage input of 200mV.

The RS-485 robustness relies also on differential signaling over twisted pair of wires, where any noise coming from external sources affects equally both signal cables as common-mode noise, which can be handled by a differential receiver. Usually, unshielded twisted pair UTP cables, with a characteristic impedance of 120Ω, are used to provide sufficient communication conditions. The RS-485 bus lines must be always terminated with properly matched terminating resistors R_T (Figure 18), to avoid signal reflections at the ends of the line. Usually, to match the high cable impedance, 120Ω resistors are used [21].

In order to define the output state in the absence of transmit signals, it is suggested to connect biasing resistors to the communication bus. Random values appearing on receiver's output can be caused by: wire break or disconnection of a transceiver from the bus; insulation fault separating the differential pair of wires and inactive state of all of the drivers available in the bus. Biasing resistors are connected between power supply, communication bus and ground. Their values can be calculated from the following equation:

$$R_B = \frac{V_{Bus-\min}}{V_{AB} \cdot \left(\frac{1}{375} + \frac{4}{Z_0} \right)}$$

where $V_{Bus\text{-}min}$ is the minimum bus voltage of 4.75 V (5 V – 5%), V_{AB}=0.25V and $Z_0=120\Omega$ is the impedance of a bus wire.

As it was mentioned in the beginning of this section, the maximum bus length is limited because of the transmission line losses and the signal jitter at a given data rate. The following figure shows the cable length versus data rate characteristic of a conventional RS-485 cable.

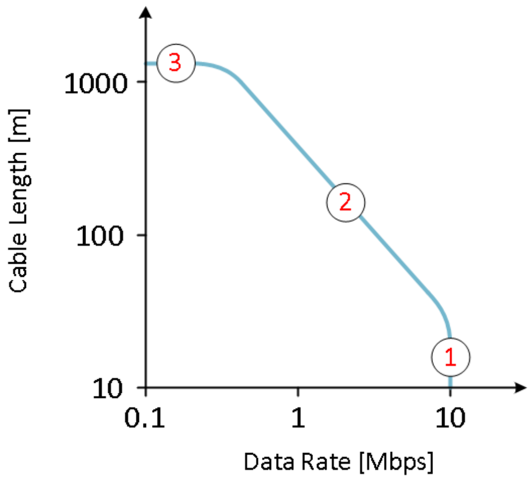


FIGURE 19: CABLE LENGTH VS. DATA RATE CHARACTERISTIC.

1) In this point high data rate is used over short cable's length. Transmission line losses can be neglected because data rate is mainly limited by the driver's rise time.

2) This part shows the transition from short to long data lines. The data line losses have to be taken into consideration. With growing cable length, the data rate must be reduced.

3) Here, lower data rate signals are used and the cable length limitation depends only on cable resistance.

2.4.2 ZIGBEE

What exactly is ZigBee? ZigBee is a wireless networking protocol, characterized with low data rate, low power consumption, low cost and targeted towards automation and remote control applications [22, 23]. ZigBee was designed to provide low cost and low power communication between devices, which demand high autonomy (up to several years) but do not require high data transfer rates. It was also designed to transmit data on relatively long distances, up to 100 meters (Figure 20).

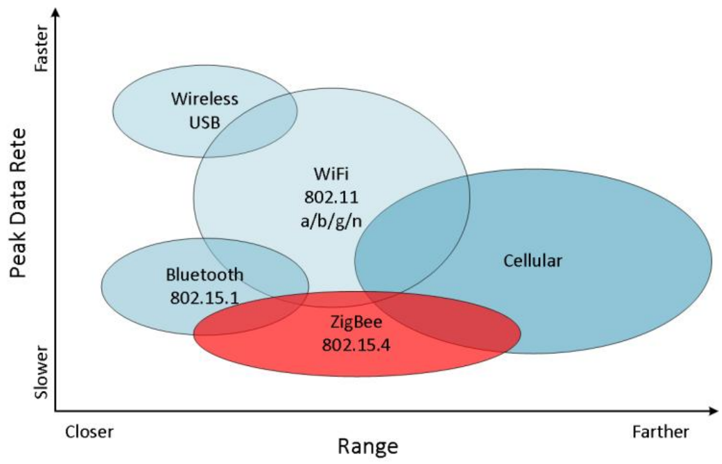


FIGURE 20: WIRELESS COMMUNICATION TECHNOLOGIES COMPARISON.

The ZigBee standard is maintained by the ZigBee Alliance, an association of companies, working together to enable reliable, cost-effective, and low-power wirelessly networked monitoring and control products based on an open global standard [22]. It is formed by different companies from all over the world like: Ember, Emerson, Freescale Semiconductor, Texas Instruments, Philips and many, many more.

ZigBee is a good alternative for wired communication systems, both for industry and also for home automation because of its very low power consumption and high reliability. The IEEE 802.15.4 standard takes care of power management in ZigBee devices through power saving modes, intelligent choice of beacon intervals, enable and disable status etc. In fact, power consumption in these wireless devices, happens only while transmitting some information to other node of the network and the interval between transmissions can be specified from the application profiles. In order to save even more energy, ZigBee devices can be set to send data only in case of emergency or status change of a sensor value.

Speaking about reliability, there are a lot of mechanisms implemented into the ZigBee standard in order to ensure the best, reliable communication. The first and the most important one is building whole ZigBee architecture upon the IEEE 802.15.4 standard. This is a modern and robust radio technology, which uses Offset-Quadrature Phase-Shift Keyring (O-QPSK) and Direct Sequence Spread Spectrum (DSSS), a combination of technologies that provides excellent performance in low signal-to-noise ratio environments. Also important is the Carrier Sense Multiple Access Collision Avoidance (CSMA-CA) mechanism [24]. Before transmission, the ZigBee device is listening to the channel and checking if it is clear and ready for the transmission to begin. It prevents devices from transmitting at the same time, causing data corruptions. ZigBee uses also 16-bit cyclic redundancy check (CRC) on each sent packet. If the received data bits are not correct, then data is transmitted again. Finally ZigBee support mesh topology networks (Figure 21), which provide automatic route discovery and self-healing.

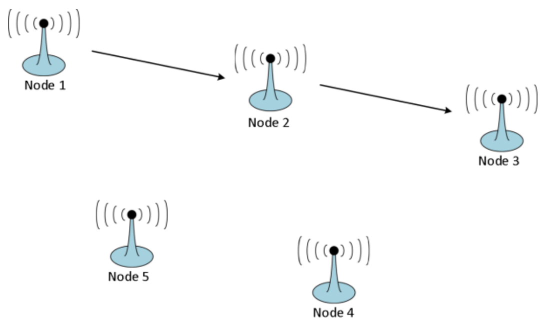


FIGURE 21: EXAMPLE OF THE ZIGBEE MESH NETWORK.

Within mesh network any node can communicate with another, no matter what the distance is, as long as there are some ZigBee devices between to pass the message along. It has to be mentioned, that the ZigBee standard allows building very complex networks, containing up to 65536 clients. Usually, the shortest path is chosen but sometimes, when one of the nodes necessary to pass the message (Node 2 in figure 22) is not responding or there is a barrier blocking the signal, then the message is transmitted through an alternative path.

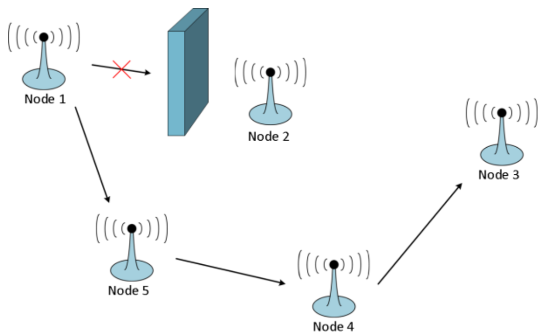


FIGURE 22: ZIGBEE'S ALTERNATIVE TRANSMISSION PATH.

Beside the mesh network, ZigBee supports also star and cluster-tree network topologies (Figure 23)[25]. The star topology is used for very simple applications, like home automation sensor reading. The cluster-tree topology is just a combination of star and mesh topologies.

In every type of the network, there has to be at least one device, which will start the network, that is, establish the connection between other devices and afterwards control the whole network. This device is called the PAN coordinator.

Usually, in order to ensure better reliability of the network, PAN coordinators are powered from the power sockets. Other devices are routers, which extend network area coverage, dynamically route messages around obstacles and provide backup routes in case of the network congestion or device failure. The third type of device in the ZigBee network is an end device. It can transmit or receive messages but cannot behave like the router or network coordinator. Usually, end devices are powered by batteries, allowing their mobility.

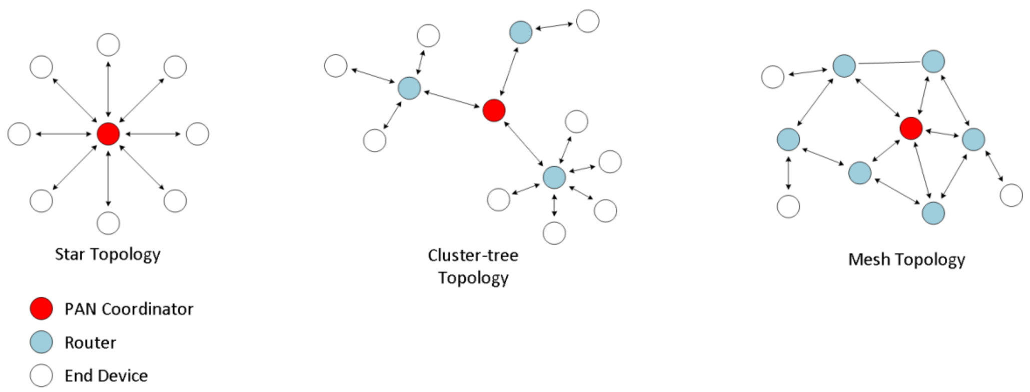


FIGURE 23: ZIGBEE NETWORK TOPOLOGIES.

Each transmitter working within this standard is built upon a layer architecture seen below (Figure 24) [26]. Each layer present in the stack behaves like an entity performing specific functions for the layer above. Layers, which are placed higher, perform more sophisticated operations, using abilities of those placed lower in the stack model. Between each layer, there is Service Access Point (SAP) placed, which provides an API that isolates the inner operations from other layers. The ZigBee architecture is based on the IEEE 802.15.4 specification, and therefore it uses two-SAP approach per layer – one for data and another one for layer management.

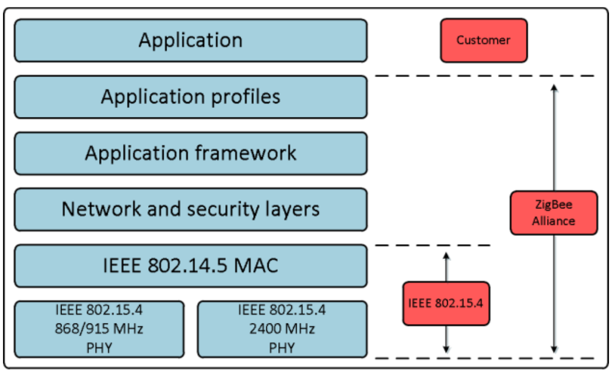


FIGURE 24: ZIGBEE STACK ARCHITECTURE.

The two lowest layers – Physical (PHY) and the Medium Access Control (MAC) – are defined by the IEEE 802.15.4 specification [27]. The PHY layer provides two services for the MAC layer: PHY data service and PHY layer management service interface. Data service enables the transmission and reception of PHY protocol data units across the physical radio channel. To the physical layer tasks belong also: activation and deactivation of the radio transceiver, energy detection, link quality indication, channel selection, clear channel assessment and transmitting packets over the physical medium.

The ZigBee physical layer offers two options, considering available frequency bands in the area of usage: 868/915 MHz and 2400 MHz. There is a single channel available in 868 MHz public band covering Europe, ten channels in 915 MHz band covering North America and sixteen channels in 2.4 GHz public band available all over the world. Several channels in different frequency bands enable the ability to relocate within spectrum. Along with different frequency used, maximum data rate also varies. ZigBee frequency bands are summarized below (Table 2).

Frequency band	Public?	Geographic region	Data rate	Number of channels
868.3 MHz	Yes	Europe	20 kbps	1
902 - 928 MHz	Yes	North America	40 kbps	10
2405 – 2480 MHz	Yes	Worldwide	250 kbps	16

TABLE 2: ZIGBEE FREQUENCY BANDS AND DATA RATES.

The Medium Access Control (MAC) layer is one of the most important in whole ZigBee stack [28]. The main function of this layer is defining how multiple ZigBee devices, transmitting in the same area will share the physical medium. This includes coordinating transceiver access to the shared radio link, scheduling and routing of data frames. It is also responsible for:

- associating and disassociating nodes in the network.
- beacon generation if device is a coordinator
- implementing carrier sense multiple access with collision avoidance (CSMA-CA)
- synchronization
- data transfer services for upper layers

MAC layer allows the device to work in two modes: beacon - enabled (slotted) and non beacon - enabled (unslotted). In beacon - enabled networks, data can be transmitted periodicly – the device is asleep and wakes up only for a short time for the beacon, checks if there is a message addressed to it and then goes back to sleep. Using this mode, ZigBee device saves a lot of power. In non beacon – enabled networks, the transceiver has to be awake all the time in order to receive new messages.

Beacon frame is one of four frames provided by 802.15.4 specification. Other frames are the data frame, acknowledgement frame and command frame. The most important one – data frame, the payload possess source and destination addresses, a sequence number, frame control bytes and a frame check sequence for verification of a correct data transmission. After the data frame reception, receiver performs a CRC check to verify if data was sent without any errors. If check is positive then an acknowledgement frame is sent to confirm correct data transmission. The command frame is used to provide basic control between ZigBee nodes.

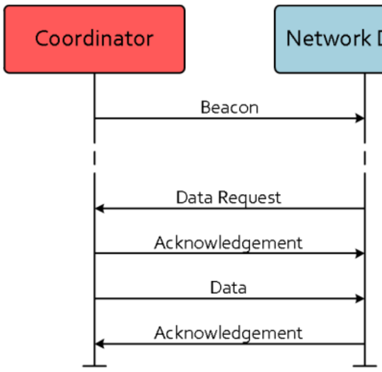


FIGURE 25: BEACON COMMUNICATION MECHANISM.

The network and security layers ensure correct operation of the underlying MAC layer and provide the interface to the application layer. In this layer the whole network is started, joined, left and discovered. The network layer responsibilities include addressing mechanisms, neighbor discovery and relay of frames to their destinations. If the PAN coordinator wants to establish the ZigBee network, firstly it has to make an energy scan in order to find the most suitable channel for new network. After that, the coordinator sets the logical network identifier (PAN ID), which will be assigned to all devices which will join the network. Also each node has a unique address assigned when it joins the network, which is used to address messages. This layer also provides security for the network, it is responsible for authentication, encryption and message integrity.

The application layer is composed of several sublayers: Application Support, Application Framework and ZigBee Device Object. APS layer is responsible for application meaning. It acts as a filter for the applications running above it on endpoints to simplify the logic in those applications. It understands what clusters and endpoints mean, and checks to see if the endpoint is a member of the Application Profile and group the message before sending. The APS layer also filters out duplicate messages that may have been sent up by the network layer. The APS layer keeps a local binding table, which indicates the nodes or groups in the network that this node wishes to speak to. The application framework is an execution environment for application objects to send and receive data. Application objects are predefined by the developer of the ZigBee device and in some way are application implementations, which can be a light bulb, a light switch, an LED etc. The application profile is run by the application objects. The ZDO layer (which includes the ZigBee Device Profile, ZDP), is responsible for local and over-the-air management of the network. It provides services to discover other nodes and services in the network and is directly responsible for the current state of the node in the network.

CHAPTER 3:
LIGHT CONTROL SYSTEM – GENERAL SPECIFICATIONS

This chapter discusses general specifications considering lighting control system. It acts as a main design guideline along with individual system components, defining different strategies to follow. It is important to provide several paths of system development, allowing the comparison of possible solutions leading to the selection of the best ones. It starts with general system overview which is followed by proposed designs of system components. Conclusions, concerning discussed solutions and the decisions of implementing them are presented eventually.

3.1 GLOBAL OVERVIEW

The task of this system is to control lighting installation switching on/off the contactors, in order to provide sufficient illumination inside the factory hall. To achieve this, control system has to be equipped with an optical sensor, control device, which will manage all operations, and switches controlling the contactors. The system is aimed to be flexible and at the same time easy to use. It may be accomplished by making it modular. The base of the system would be the control board, where the user would connect additional components (sensor and extension boards) in order to adjust the system configuration to the lighting installation. The number of sensor boards and extensions, controlling the contactors, would depend on lighting installation requirements.

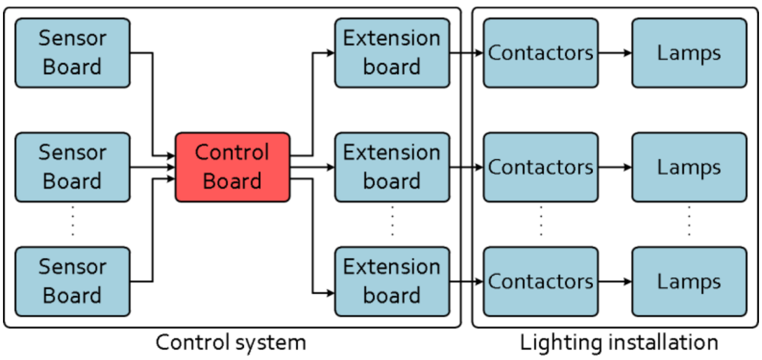


FIGURE 26: PROPOSED CONTROL SYSTEM STRUCTURE.

The system should also possess a mechanism used to reconfigure the system without interference into the lighting installation. Therefore, the user should have the possibility of assigning lamps to sensors using the control system. This way it will be possible to decide which lamps will be controlled according to the illumination level gathered from a specific sensor.

Other issues like choosing the type of optical sensor, way of controlling the contactors and communication between sensors and the control board has to be considered in order to provide wider range of possible strategies. Also economical aspect has to be taken under consideration to make the system competitive.

3.2 LIGHT SENSOR

The light sensors play an important role in the overall system. They are responsible for the correct acquisition of the illumination level. This is then used to control the light settings. Thus having fail safe operation is an important requirement for the light sensors. There are two problems that must be considered: incorrect readings and sensor obstruction due to dust or other environmental issues. This problems can be solved using redundancy on the sensors. Redundancy can be accomplished using three independent optical sensors in every sensor board. In this case, the values of light intensity measured by each sensor would be analyzed. Different values can be rejected and the exact illumination is given as an average of the other two values. This way one of sensors could be broken and the system would still work properly.

The sensor board can be designed using optical sensors with different output signals: analog or digital. The first type converts light into current or voltage signal. Usually dependence between light intensity and output signal is linear. The second group, converts illumination into a frequency modulated square signal (or into appropriate binary code).

Using optical sensors with analog voltage output gives the opportunity to detect if the illumination is within the range between maximum and minimum level with very simple circuit design, consisting of two Schmitt triggers, optical sensors, multiplexer and microcontroller (Figure 27). The main parts of this circuit are Schmitt triggers, which are ordinary comparators with additional positive feedback. Schmitt triggers eliminate the problem of false triggering due to the noise in sensor's output. Their task would be to compare the output signal coming from the optical sensors with voltages, which represents minimum and maximum illumination levels and at the same time prevent from unnecessary lamp switching because of the noise influence. If the voltage coming from the optical sensor is lower than minimum level set by the user, the outputs of both comparators is a logic zero. If it is higher than maximum level, then both comparators have logic one on their outputs. However, if output voltage of the optical sensor is between minimum and maximum level, then one of comparators have logic one and the other a logic zero on its output (Figure 28).

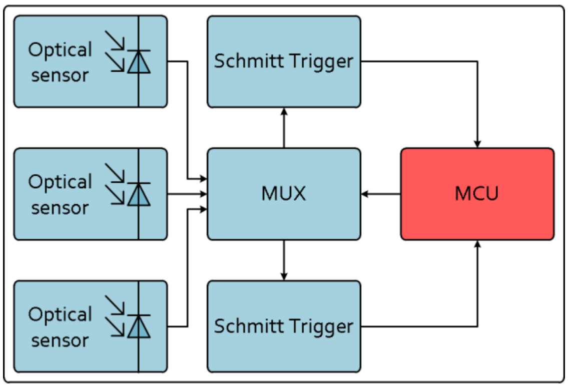


FIGURE 27: ANALOG BASED LIGHT INTENSITY SENSOR BOARD BLOCK DIAGRAM.

This solution is good, however, it has one serious disadvantage – the potentiometers used for generating voltages, which represent minimum and maximum level of illumination, would be placed on each sensor's board, thus demanding complicated procedures to set up the sensors.

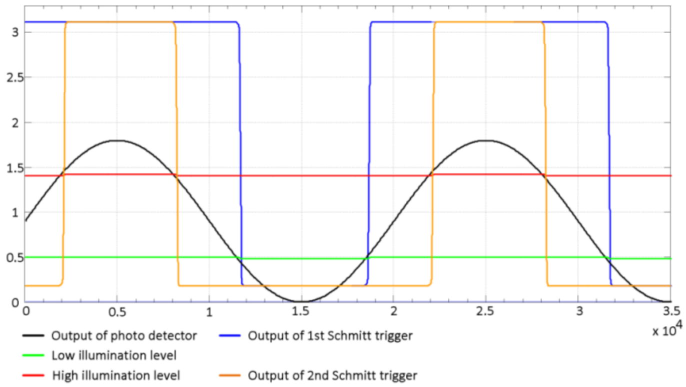


FIGURE 28: INPUTS AND OUTPUTS OF SCHMITT TRIGGERS.

Optical sensors with digital output have already built-in electronic circuits, able to convert the voltage signal to a digital form. This way, there is no need to compare the output signal of a sensor with reference voltage in order to check if illumination is within the specifications.

Among the optical sensors with digital output, there can be found devices, which convert light into frequency, or give the exact illumination in binary code. In the first option, getting the light intensity at the microcontroller is done by measuring the frequency of the output signal. In the second type, getting the illumination is even easier, because it is collected directly from an integrated circuit, communicating through SMBus or I^{2}C protocol.

Knowing the exact light intensity in the factory hall, gives an opportunity of better lighting control than using analog based sensor circuits. The system would know how fast light intensity is changing and what is the best strategy to apply. The system could even inform the user about the level of illumination in specific area by putting it on LCD or LED display.

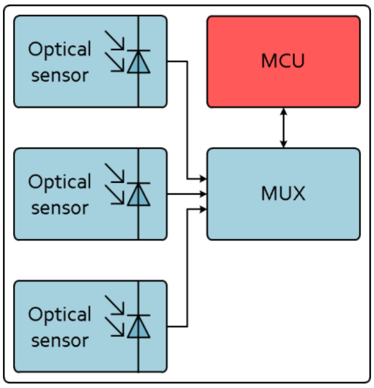


FIGURE 29: DIGITAL BASED LIGHT INTENSITY SENSOR BLOCK DIAGRAM.

Digital based sensor boards have also other advantages over analog based sensor boards. As long as all measurements and all calculations would be performed by the microcontroller, minimum and maximum levels could be set only in one place. This would be performed through a keypad as an interface, without requiring complex settings on each individual sensor.

3.3 SWITCHING BOARD CONNECTION

Choosing the way of connecting the system with lighting installation is another important issue. What needs to be done is overriding manual control of each contactor with automatic control. This can be achieved by using any kind of electronic switch like, a transistor, a triac, a relay or optical relay. These devices can be arranged into two groups: solid state switches (transistors and triacs) and relays. Like always, both groups have advantages and disadvantages. The first group characterizes with very low price but does not provide good galvanic isolation between switched signal and control circuit. Contactors, used to control lamps, are controlled by 230V AC signals, coming from the power lines. So working with such high voltages, demands a good separation between the power lines and the electronic circuit. The other group is more expensive but provides galvanic isolation between the control system and high voltage. While choosing between ordinary, coil relays and optical relays it is important to consider what current has to be handled. In this case it is about 100mA, so it was better to choose optical relay. The price would be similar to ordinary relays, but they are smaller and can switch faster.

This system is developed in order to provide lighting management system for already existing lighting installations, where usually two positions high voltage switches are used. Because those switches are quite expensive (around 6,5EUR, ABB C2SS3-10R-11 on pt.farnell.com), the system should be designed to fully cooperate with the existing installations. Manual switches, controlling the work of these contactors can be overridden with automatic control by placing the electronic switches in parallel with them. When the system is turned on and manual switches are off, the lamps are controlled automatically. However, if user wants to override automatic control and turn on one contactor independently from the lighting management system, then it suffices to turn on the manual switch, responsible for switching this particular contactor.

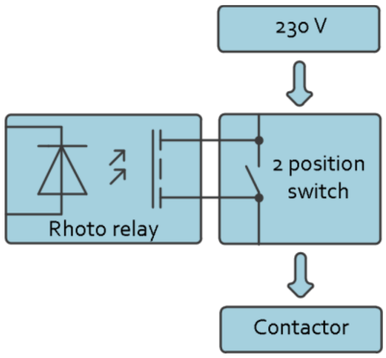


FIGURE 30: DIAGRAM SHOWING OVERRIDING TWO POSITIONS SWITCH.

The problem appears when the user would like to turn off one or more contactors and have the rest of them controlled automatically by the system. Using two position switches it is impossible. Turning off specific lamps is possible only when automatic control would be disabled and all lamps controlled manually.

However, in order to guarantee complete control on each lamp, three position switches can be used. This solution is better because provides the possibility of controlling each contactor either automatically or manually. However, considering the cost of changing the already existing installation is not profitable. The idea of this solution is to put an electrical switch in parallel with the manual switch in one of three positions so that the user has three options to control the contactor. The first switch position makes lighting controlled automatically, the second overrides automatic control and turns on the contactor and the last one overrides automatic control and turns off the lamps.

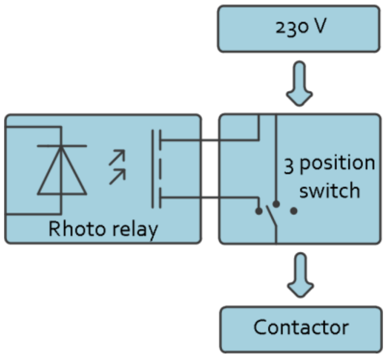


FIGURE 31: DIAGRAM SHOWING SYSTEM USING THREE POSITIONS SWITCH.

3.4 SYSTEM COMMUNICATION

Every electronic system has implemented some kind of communication, which allows to interact between different components. In electronics there are a lot of different types of communication used, depending on the requirements of data rates, the distance between devices, signal carrier type and the environment where it will be used. Without going into details, each communication type relays on or combines these basic types: serial, parallel, wired or wireless.

In this part, the advantages and disadvantages of the previously revised communication standards of RS-485 and ZigBee, will be presented allowing to choose the best suited communication type between control and sensor boards. Industrial environments are very demanding considering electronic communication, due to the presence of huge electromagnetic disruptions, temperature changes, presence of dust and long distances between electronic devices. The communication type has to be chosen precisely for the system requirements.

The most popular standard for the communication in factories is RS–485. This standard uses differential transmitters, two-wire transmission path and differential receivers in order to send data at long distances (up to 1200m). Implementing the RS–485 standard as the system communication fulfill system requirements, considering the distance between devices and that data rate is not high for the required application. Both, sensor boards and the control board should be equipped with one RS-485 transceiver in order to communicate with each other. Considering the price, it is a good solution. Also, using this type of communication solves the problem of powering the sensor board. Proper communication within this standard requires only two signal lines so using an UTC cable, which consists of 8 wires, gives the opportunity to power the sensor board with two of the unused wires.

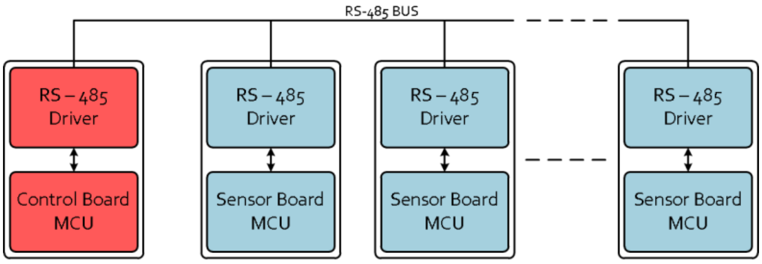


FIGURE 32: RS–485 BASED SYSTEM CONNECTION – DAISY-CHAIN TOPOLOGY.

There are two ways of implementing the RS-485 communication standard. The first one assumes connecting all used sensor boards and the control board to one bus and making use of RS-485 multiple devices handling (Figure 32). When one of the devices would like to communicate with another, it has to send a broadcast message with the ID of the target device, with which it wants to communicate and wait for getting permission to use the transmission line. When the transmission line is free and the master node grants access to the transmission medium, then the communication is initiated. It is a good solution because it reduces the length of necessary cable but each sensor available in the system would have to own a unique identification what could complicate the design and production process of the sensor boards.

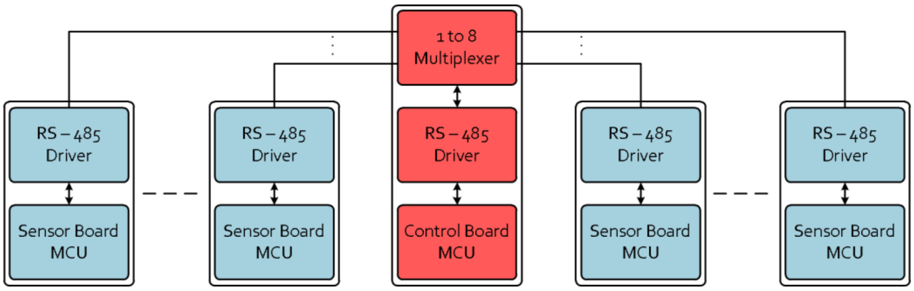


FIGURE 33: RS-485 BASED SYSTEM CONNECTION – “STAR TOPOLOGY”.

Other communication system based on the RS-485 standard, assumes independent signal line for each sensor board. It is similar to the star topology network and can be achieved by using an analog multiplexer after the RS–485 driver (Figure 33) to pick one of the sensor boards to communicate with. In this solution there would be only one sensor board on each bus line, thus assigning unique ID for every sensor board would not be necessary anymore. That would make communication easier. Unfortunately, using this solution would require more cable, since every sensor board would possess its own signal line.

It is also possible to use ZigBee wireless technology, which is a little bit more complicated but it does not require putting expensive cables in order to perform data transmission. From all wireless communication technologies available, ZigBee was considered due to its low power consumption, low bit rates (up to 250Kbps) and range up to 100m. Typical applications of this standard include sensor networks, home automation and alarm systems so it is exactly what is needed for designing this system.

The ZigBee network, proposed for this project, would consist of a network coordinator, which in this case would be placed on the control board and end devices placed on each of sensor boards (Figure 34). The control board starts the network, assigns its ID, allows the sensor boards to join the network and gather data directly from them.

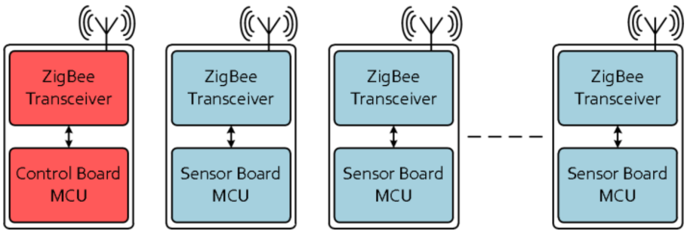


FIGURE 34: ZIGBEE BASED SYSTEM COMMUNICATION.

Typically, ZigBee transceivers consume around 20-30mA while communicating. This is too much if the sensor boards would be powered from batteries and required the transceiver to be active all the time. One of the solutions of this problem is to power the sensor boards from batteries and additionally charge them using photovoltaic cells. Unfortunately this solution is quite expensive because solar cells are addressed to generate energy from the sun light and when it comes to work within the building, it is not so efficient.

A second solution able to reduce power consumption consists of turning on the ZigBee module only when data between control and sensor boards needs to be transmitted. ZigBee transceivers, while in standby mode, consume negligible power. This can be done designing proper synchronization mechanism, able to manage ZigBee modules, present in different sensor boards, so that they would be active only for a while and not at the same time (Figure 35). Also a “beacon mechanism”, described in the second chapter, available in ZigBee modules can be used.

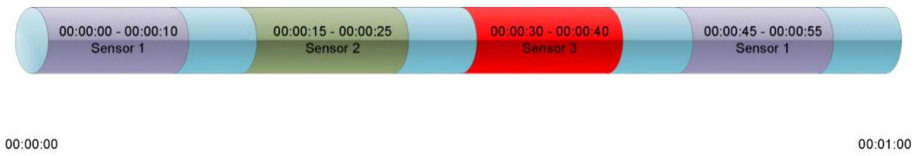


FIGURE 35: TIMELINE SHOWING ACTIVE SENSORS.

3.5 WORKING AREAS

There is a wide variety of factory halls, some are small, others are large, some have spots with daily light and others do not, thus it is incorrect to ensure uniform lighting conditions for every factory hall. In order to provide better precision of lighting control, the factory hall can be divided into few smaller areas, and provide independent control of the lights in these areas (Figure 36). Each area, which also can be called a sector, would possess its own sensor board, able to measure the illumination conditions on that particular sector.

The user should have an opportunity to choose the number of sectors, which would be most suitable for a specific factory hall. It is also adequate that the user should be able to choose which lamps belong to each sector. On the figure below there is an example of factory hall divided into five sectors with eight lamps each, controlled by four independent contactors. Overall system design must consider the specification of sectors and address light control adequately. This would make the system flexible, easy to use and interesting for future clients.

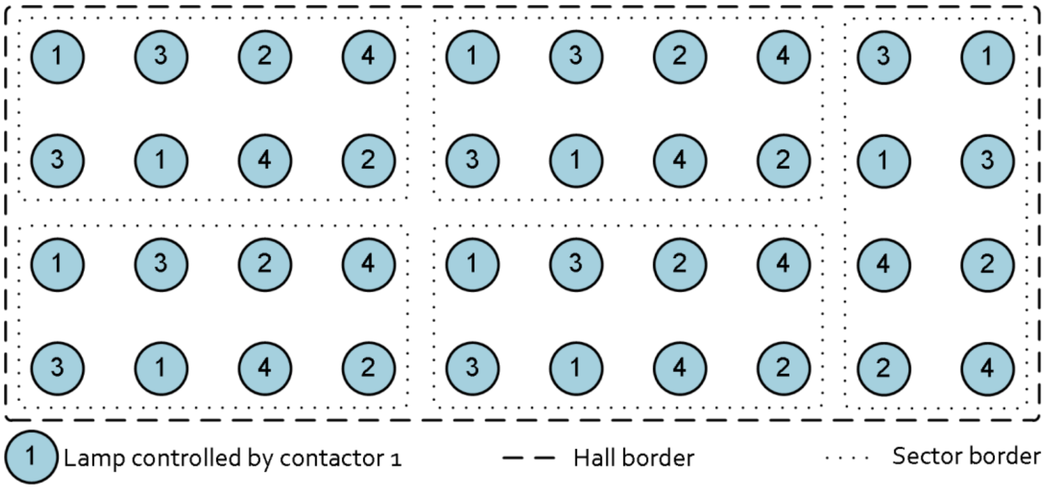


FIGURE 36: FIGURE SHOWING SECTORS IN A FACTORY HALL.

Providing the possibility of creating different working areas make sense only if the user has the possibility to set the preferred illumination level for each sector. One of the solutions of setting these levels assumes turning on the lamps in every sector gradually and letting the user choose the preferred illumination level by pressing the button when lighting intensity would be considered the most suitable (Figure 37). If the button would not be pressed until all lamps would be switched on, then the system would start the preferred illumination selection sequence again. However, this solution is good only when lamps turn on immediately, otherwise it would take a long time to configure the system.

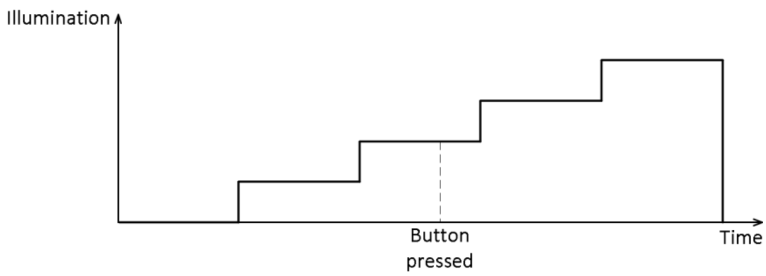


FIGURE 37: GRAPH SHOWING DESIRED ILLUMINATION LEVEL SELECTION.

In case of using lamps with long turn on time, the desired illumination level could be set by manually turning as many lamps as would be necessary to provide proper lighting conditions and then inform the system about it by pressing the button, for example. After waiting for lamps to reach full performance, the system would measure illumination and save it as a new level.

Preferred illumination level for each sector could be also set as a percentage of maximum illumination, provided by the lighting installation. In that case, the user has to set a number between 1 to 100 and then the system would handle measuring maximum lighting intensity and calculating preferred illumination range.

3.6 MODULAR BUILD

The flexibility of this system will be provided in part by the support to different and independent lighting sectors, but also number of supported contactors. Factories differ with production type, dimensions and lighting type. The quantity of used lamps for the majority of the factory halls is different. These specifications have a direct influence on the number of contactors. In order to provide a system able to cope with a wide range of industrial lighting installations it is necessary to consider modularity as an important feature.

A system, consisting of as many elements as it would be required for a large lighting installation can be designed. However, this solution would not be profitable because it would contain many electronic components, which would not be used in other installations. That is why the system should be designed in such a way that the user could change parts of it depending on actual needs. This would minimize the number of electrical elements used for the management system and therefore the final price.

There are two solutions for making the system modular, considering number of supported contactors. The first one is to divide the control board into two separate parts. One would consist of a power supply, a controller and the communication device to communicate with the sensor boards. On the second board there would be a multiplexer, several latches and photo relays, in a quantity that would depend on the client needs. These boards would be connected with two sockets (Figure 38), which would connect the microcontroller with the multiplexer and the latches and also provide the information of how many lamps and areas would be controlled by the system. The first 4 bits of the extension information connector would be used to provide information of the number of sectors and the other 4 bits would be used to provide information of the number of contactors used to control lamps in each sector. This information would be passed to the control device in a fixed binary code set at the extension board. Every relay would be related with one sensor board and it would be fixed. If the user would choose four sectors and four contactors operating in every sector, then the first four relays would belong to sector one, another four to sector two, etc…

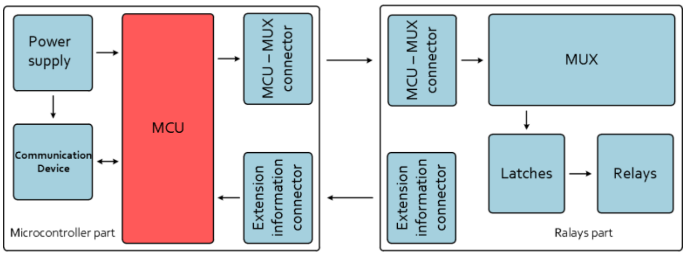


FIGURE 38: BLOCK DIAGRAM SHOWING THE CONNECTION BETWEEN CONTROL BOARD AND EXTENSION BOARD.

Another solution is able to make the system even more flexible by using multiple extension boards. Instead of connecting just one extension board with a different number of relays on it to the control board, multiple boards with smaller but fixed number of relays would be used. On the control board there would be several connectors where the extension boards could be attached. The number of plugged extension boards would rely on the number of contactors, controlling the lighting installation.

All the extension boards would be connected with the microcontroller, using one dedicated bus line. Operations on the extension board would be performed after sending an enable signal to one of the extensions (Figure 39). The system should also be able to detect if each extension board is plugged into the socket or not and adapt to that configuration. Detecting the presence of the extension may be accomplished by checking if enable signal coming from the decoder on the control board, would appear on microcontroller's pin after doing a short–circuit between two pins of extension board's connector.

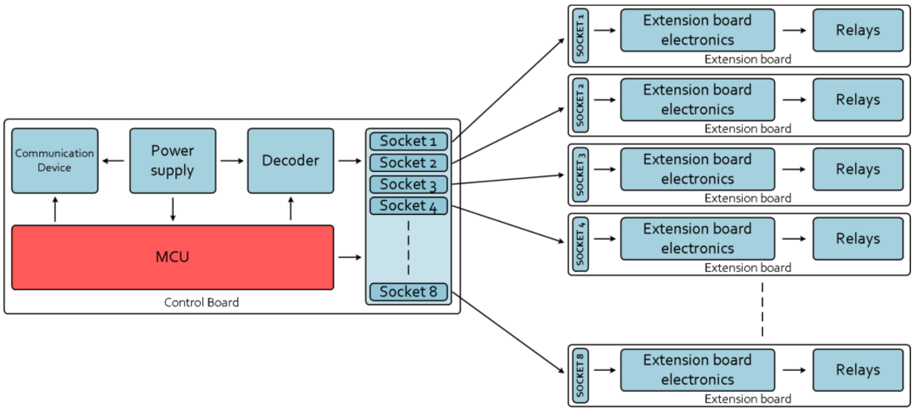


FIGURE 39: BLOCK DIAGRAM SHOWING THE CONTROL BOARD AND EXTENSIONS.

A system designed in this way, should also provide the possibility of assigning each relay to one of the sectors. There are two possibilities to do that: one based on software and the other based on hardware. Using the first one, the user would have to choose the number of sectors controlled by the system first and then pick the lamps which would belong to each sector, using the user interface. The system would light one of the lamps in turn and then the user would have to set the sector to which a given lamp belongs to. In case of using lamps with long turn on time, every relay could be related with one LED, which would indicate which lamp is currently turned on so that the user would be able to assign it, without obligation of turning on the corresponding lamp.

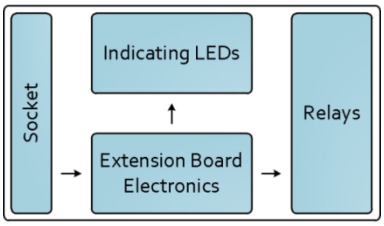


FIGURE 40: EXTENSION BOARD'S BLOCK DIAGRAM – RELAY ASSIGNING BY SOFTWARE.

In order to assign relays to sectors by hardware, each extension board should be equipped with one DIP switch, where the user would set its ID. Also each sensor board would have to possess its own identification circuit so that the user could set the same ID on their DIP switches in order to link the relay with sensor board. Extension boards with hardware ID assign would be working in two modes, depending on the signal sent by the microcontroller. When enabled, extension would operate on photorelays, after sending the WR signal. It would read the ID when RD signal would be sent. Assigning relays to sectors, using hardware solution would be much easier than doing it by software, less time consuming but slightly more expensive.

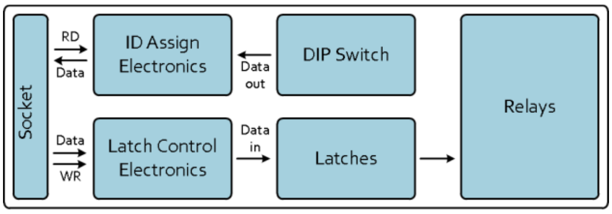


FIGURE 41: EXTENSION BOARD'S BLOCK DIAGRAM – RELAY ASSIGNING BY HARDWARE.

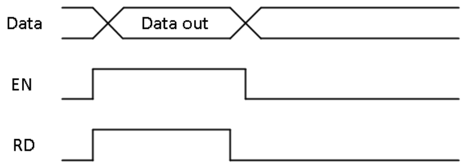


FIGURE 42: TIMING DIAGRAM FOR READING EXTENSION'S BOARD ID.

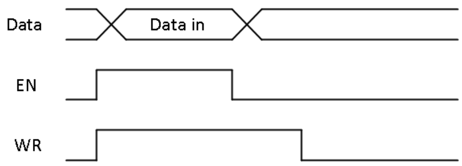


FIGURE 43: TIMING DIAGRAM FOR ENABLING RELAYS CONTROL.

Assigning by:	Advantages	Disadvantages
Software	- system configuration may be changed many times	- additional LED for every relay should be used in case of using long turn on lamps
Hardware	- system configuration may be changed many times - everyone will be able to configure system without technical knowledge (easier to use)	- user can set the same ID for two sensors and make system work unstable - it is more expensive than software solution

TABLE 3: COMPARISON OF ASSIGNING RELAYS TO SENSORS BY SOFTWARE AND BY HARDWARE.

3.7 USER INTERFACE

The user interface has to be very simple so that everyone would be able to configure the system without any technical knowledge. It may consist of micro switches and LEDs. One diode would have green color and it would be turned on when the system would be powered and work properly. Other ones would be the control LEDs. Their task would be to inform the user about system status and providing information during the system configuration. The number of LEDs would depend on how many sectors maximum are going to be supported (Figure 44).

FIGURE 44: USER INTERFACE WITH LED DIODES.

Also in order to make the system more "user friendly", instead of using simple LED diodes, the system can be designed to provide user interface based on 7 segment LED displays (Figure 45). From a technical point of view it would be almost the same solution but from aesthetic and practical side, it would be much easier to control the system and it would look better.

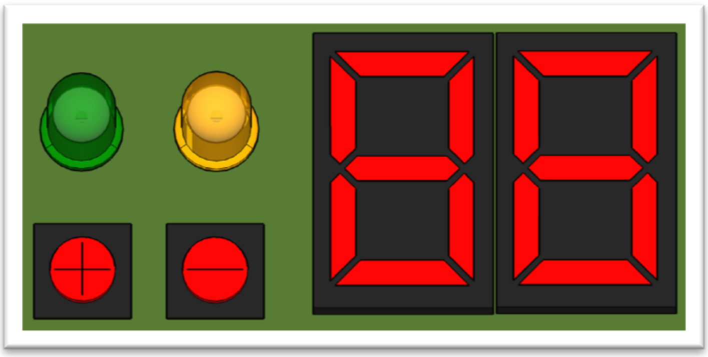


FIGURE 45: USER INTERFACE WITH 7 SEGMENT LED DISPLAY.

3.8 SELECTED DEVELOPMENT STRATEGY

Study of presented strategies allowed to get familiar with their strong and weak points and choose the best possible solutions. Flexibility of the system will be provided by the modular build. The user will be able to choose how many sectors will be supported by connecting adequate number of sensor boards. Also number of contactors will have influence on the system structure. They will be switched, using extension boards, which will be connected to the control board. Each extension board will support small but fixed number of contactors, so to control large quantity of contactors the user will have to attach several extension boards. Main reason of choosing this solution is giving the possibility of adjusting the system configuration precisely for lighting installation requirements.

The user will be able to configure the system by assigning extension boards to sensors using DIP switches. This solution is easier to implement and also requires less effort from the user. Configuration of preferred illumination level will be done using the user interface which will contain two push buttons, two seven segment LED displays and a control LED. It was chosen because it is will provide sufficient interaction between the system and the user and will make system configuration more intuitive.

Considering system communication and the type of the optical sensor, none of proposed solutions will be implemented. Instead of using RS-485 and ZigBee standard to gather illumination level from the sensor board, illumination will be measured directly by the microcontroller, placed on the control board. It will gather illumination level from the light to frequency converter, placed on the sensor board measuring the frequency. This way the price of the sensor board will be lowered because communication modules and microcontroller on the sensor board will not be necessary.

CHAPTER 4:
LIGHT CONTROL SYSTEM – DESIGN AND TEST

The main objective for the development of this project was to create cheap, reliable and universal lightning management system for the industry. There are already some similar control systems available on the market and they were described before (Chapter 2) in order to evaluate their advantages and disadvantages. Also available technologies and devices were reviewed to have better knowledge, what can be improved in those systems to provide a more competitive product. The main ideas of how to design a new system were presented in the previous chapter.

In this chapter, design and implementation details will be described. The reader will have an opportunity to learn the principle of operation of the developed system, which blocks of the system are responsible for specific functions and also get familiar with technologies and components, which were used to develop the project and why.

4.1 SYSTEM ARCHITECTURE

The system architecture was dictated that this system should be able to cooperate with already installed lighting infrastructures. Learning the general scheme of these installations allowed to develop the system, which fulfill all of the demands for industrial lighting management. This very simple scheme, assumes using high power lamps in order to provide sufficient lighting intensity. Usually, there are few single lamps related in groups, which are turned on together and placed in that way to provide equal lighting distribution in specific area. Lamps belonging to one group are controlled by single contactor, which is turned on or off by high power switches, manipulated by human. Depending on the hall dimensions and lamps configuration, the lighting installation may consist from very few to over a dozen contactors.

The goal of making the system flexible so that it would cope with both simple and complex installations was achieved by making it fully modular. The user can decide what parts, in what quantity are required to fulfill the lighting installation requirements. The system was designed to support from 4 up to 32 contactors, used for controlling the lamps. The number of supported contactors can be changed by attaching up to seven extension boards.

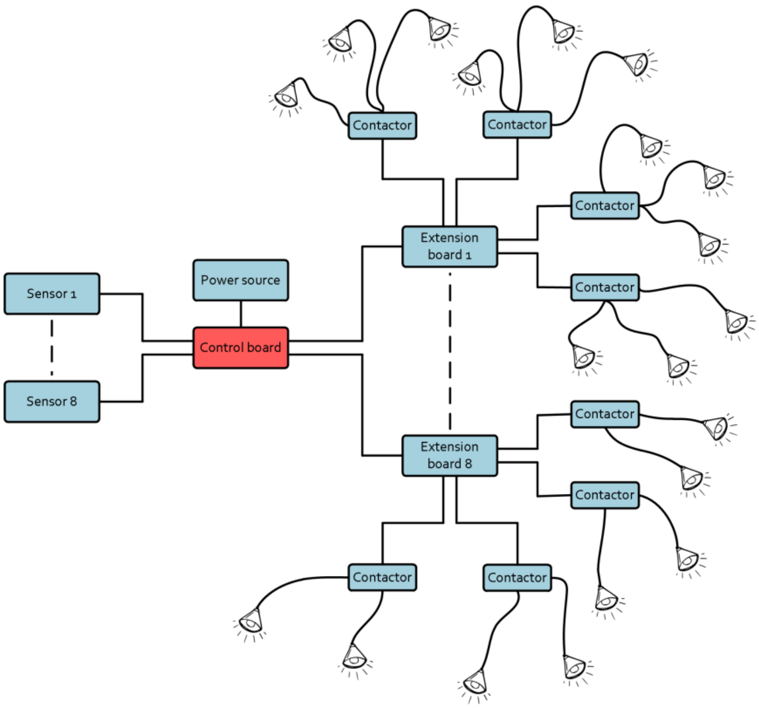


FIGURE 46: LIGHTNING MANAGEMENT SYSTEM ARCHITECTURE.

The user can also decide if all the contactors will be controlled as they would belong to one sector or can assign them to different sectors. Taking into consideration that some sectors can be very large, we can conclude that the illumination in the most distant spots will not be measured precisely and therefore lighting intensity will be regulated incorrectly. Dividing the hall workspace into smaller areas (sectors), and providing independent control, makes possible to have different illumination conditions in every sector, but also improves lightning management precision. The number of sectors is set automatically by reading the number of connected sensor boards.

Assigning extensions to sensor boards is very simple and demands activity as easy as setting the same combination on DIP switches, belonging to both sensor and extension boards. It is possible to assign more than one extension to a sensor board by giving the same ID to sensor board and few extensions. However, it is very important not to set the same ID to more than one sensor board because it may make system unstable. Also setting the ID for both, sensor and extension boards as "0" is forbidden because when there is no external board connected to the control board, the system considers its ID as "0". In that case, setting "0" ID for sensor board or extension will make it invisible for the system.

The system installation example was modeled on the figure below (Figure 47). It is based on wired communication between system's parts, using the ethernet cable, connected with RJ-45 sockets, what makes the system configuration very easy. Control parts (control board and extensions), are supposed to be placed in a control box, together with manual switches, what will provide one control interface for the whole lighting installation. Sensor board's placing depends on the number of sectors but it should be placed in the middle of the sector at height as low as possible.

FIGURE 47: EXAMPLE OF FACTORY HALL, USING DEVELOPED SYSTEM.

The system is powered with one, external 9V or 12V power supply. In order to provide information, allowing to choose the most suitable power supply for given system configuration, power consumption measurements were done for each part of the system. The power consumption for the base system is presented in the following table but along with the increase of used parts (sensor and extension boards), current consumption is growing also so that maximum supported current flow for external power supply have to be recalculated for every system configuration.

Part:	Power consumption: [W]
Control Board	2,276
Extension Board	0,820
Sensor	0,651
TOTAL:	**3,747**

TABLE 4: TOTAL POWER CONSUMPTION FOR THE BASE SYSTEM.

The total cost of the used components also depends on used configuration. For the base system, the price is presented in the following table but along with increase of used parts, the user will have to deal with higher prices. Maximum price for the full system, containing eight sensor boards and extensions is about 110EUR.

Part:	Price: [EUR]
Control Board	26,54
Extension Board	6,49
Sensor	4,60
TOTAL:	**37,63**

TABLE 5: TOTAL PRICE FOR THE BASE SYSTEM.

4.2 OPERATION PRINCIPLE

Properly connected and configured system starts its work with the system initiation. The microcontroller sets necessary registers and change pins to either input or output mode. The system turns on all of the available lamps, waits till they will get the maximum performance and afterwards gets values necessary for further operations like IDs of connected sensors and extensions and maximum attainable illumination. If normalized sector areas used for generation of minimum and maximum levels of illumination were not set before then system asks to do it, otherwise it reads them along with preferred illumination levels from EEPROM memory so that it does not have to be set with every system restart (Figure 48).

Afterwards, the system enters the loop, which is executed for each of active sensor boards. Firstly it checks if buttons on the control board were pushed and hold, in order to perform system settings change and if this condition was fulfilled, the user will be asked to choose the sector in which the preferred illumination level will be changed. Sector choice is confirmed by holding both buttons again. If chosen sector ID does not exist in the system, the user will be informed about that by displaying "--" sign on the seven segment LED displays. Otherwise, the user will be asked to set preferred illumination level and confirm it by holding both buttons again.

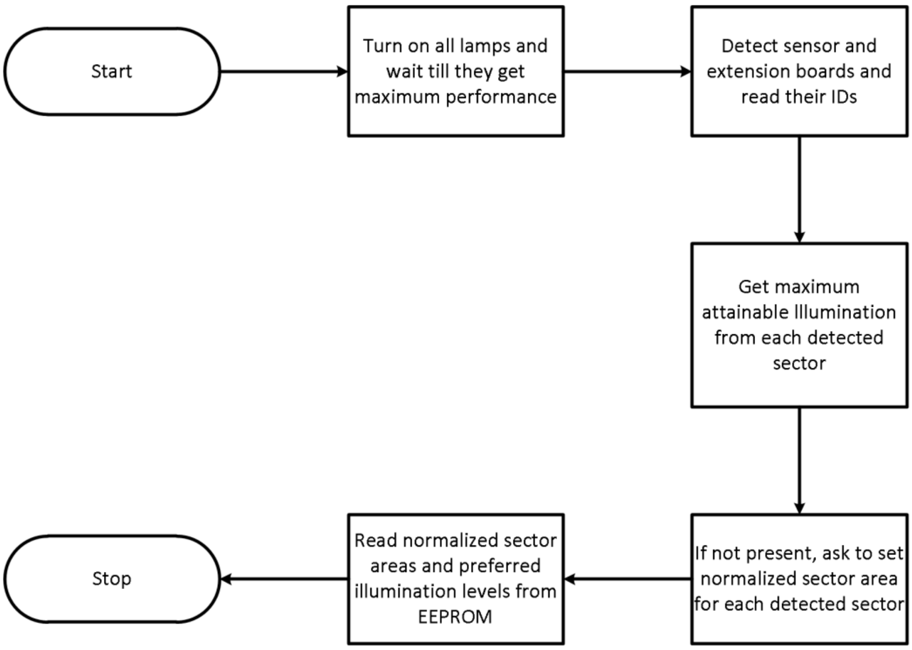


FIGURE 48: BLOCK DIAGRAM OF INITIATION PROCEDURE.

Actual lighting management starts at this point. The system measures illumination for currently selected sensor board and compares it with minimum and maximum levels, calculated as described in the control board's section. If detected lighting intensity is lower than minimum level then system searches for an extension board, with the same ID as sensor's and turns on one relay. However, if there is more than one extension board linked with the sensor board, the system switches a relay on the board with the smallest quantity of relays turned on, providing equal lighting distribution. After that, actual measured illumination is compared with maximum preferred level and if it is higher, then system turns off one of relays linked with currently operated sensor board, also using mechanism providing equal illumination distribution but this time it searches for board with higher quantities of turned on relays and turns off one of them. If the actual illumination is between maximum and minimum levels, then system considers it as proper lighting intensity and does not perform any actions.

When the system terminates the execution of the procedure for one sensor, it moves to another, until it will reach the last one. After performing operations for all sensor boards, operation is repeated from the first sensor.

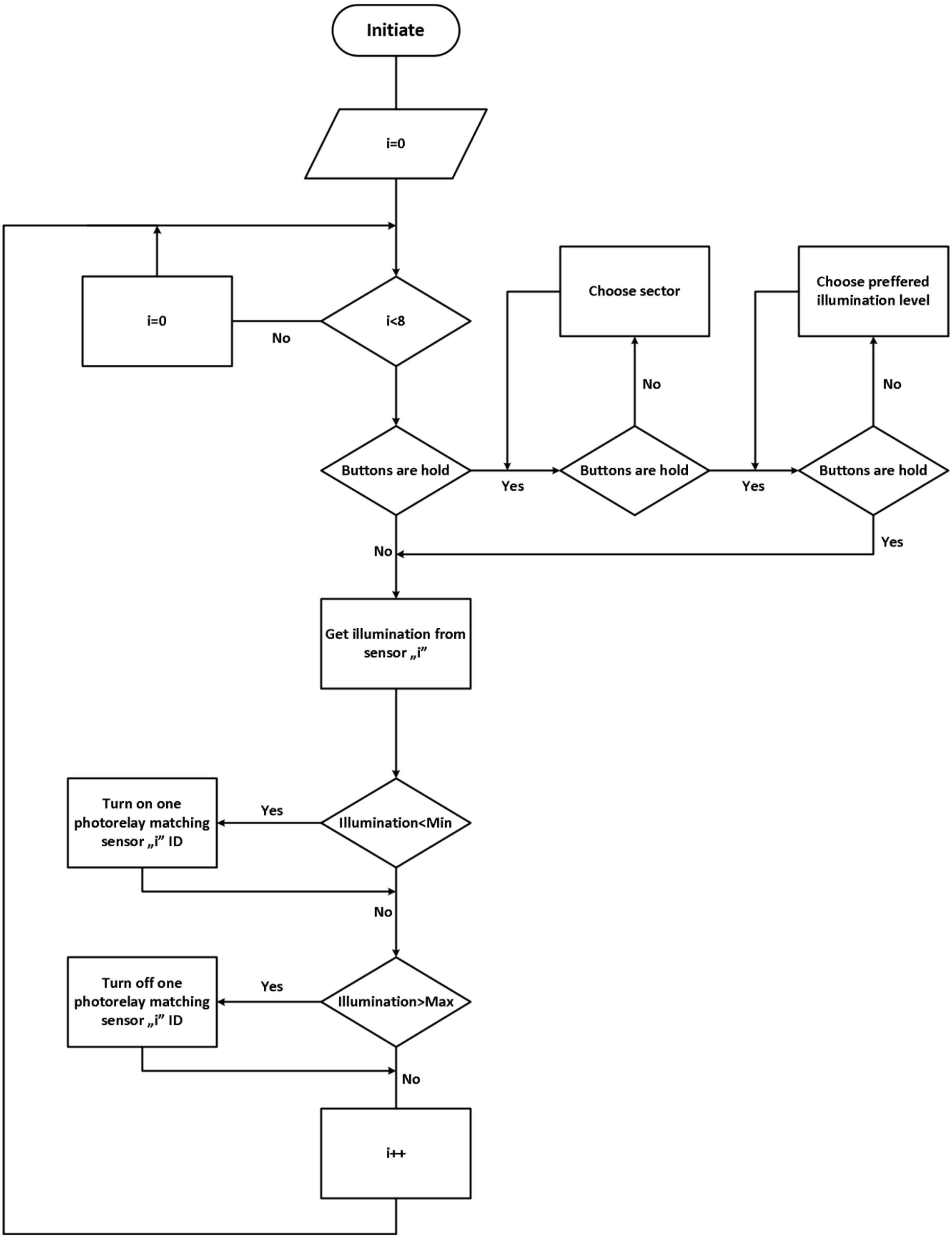


FIGURE 49: BLOCK DIAGRAM OF IMPLEMENTED ALGORITHM.

4.3 CONTROL BOARD

The control board is the heart of this system. It is responsible for the system initiation, collecting illumination levels from sensors, controlling extension boards and providing the user interface for system configuration. It consists of a power supply circuit, the microcontroller and its peripherals, the user interface, sockets used for connecting sensors and extensions and one extension board built-in.

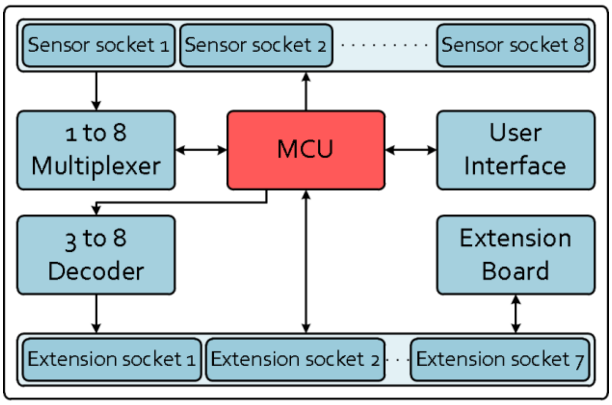


FIGURE 50: CONTROL BOARD'S BLOCK DIAGRAM.

The system operates on a 5V power supply, which is built upon the UA7805 voltage regulator. Despite it is a quite old technology, it is still very popular. It has relatively high voltage drop of 2V but it can handle input voltages up to 25V and 1.5A of current, flowing through it. The 1N4007 diode was used to protect the circuit from connecting it to the opposite polarity and C3, C4, C5 condensators were used to smooth any voltage signal fluctuations (Figure 51). When the system is turned on, this is indicated by the green LED (D2), connected directly to the power supply.

The brain of whole system is a PIC16F877A-I/P microcontroller from Microchip. It was chosen because it has many I/O pins, large program (14.3KB) and data (368B) memory available. Besides, it has three timers, EEPROM memory and external interrupt on RB0/INT pin, which are necessary to this project. It is clocked from an external crystal oscillator with 20MHz frequency, which is the maximum speed available for this microcontroller. However, depending on the type of lamps controlled by this system, the crystal oscillator can be changed to slower the clock frequency, in order to save energy. The control board contains also a programming interface to set up the system. The connection between the programmer and the microcontroller is done by the six pin connector, marked on the circuit (Figure 51) as P3.

The user interface, present on the control board, consists of two micro switches, two seven segment LED displays and one yellow LED as it was presented on Figure 45. The micro switches (uS1 and uS2) enable to interact with the microcontroller. They are connected to the power supply by 10KΩ pull-up resistors. When the micro switch is pressed, the logic state changes from one to zero on the appropriate input pin of the microcontroller.

The seven segments LED displays and the diode are used by the microcontroller to communicate with the user. While building the prototype, common anode, red, Kingbright SA56-11HWA displays were chosen but also different versions of SA56-11 can be used in order to get different color or better luminous intensity.

The user interface is used to set the preferred illumination level for any of eight supported sectors. While the system is performing normal actions, both yellow LED indicator and 7 segment displays are off. The user starts the preferred illumination level change sequence by pressing and holding both micro switches at the same time. The system will wait for the user to input the ID of the sector for which the changes will be performed. During this process the system will turn on yellow LED, which will start flashing slowly indicating the sector choice step. The user changes the sector ID by pressing plus or minus button. After setting the appropriate sector ID on the seven segment display, the user has to confirm it by pressing and holding both micro switches again. In this point yellow LED indicator will start flashing faster and the actual preferred illumination level for the selected sector will be read from the EEPROM memory and presented on the displays. After selecting a new level, the user has to push and hold buttons once more to enter the new settings, which will be set and written to the EEPROM. After the system restart, the illumination levels will be restored.

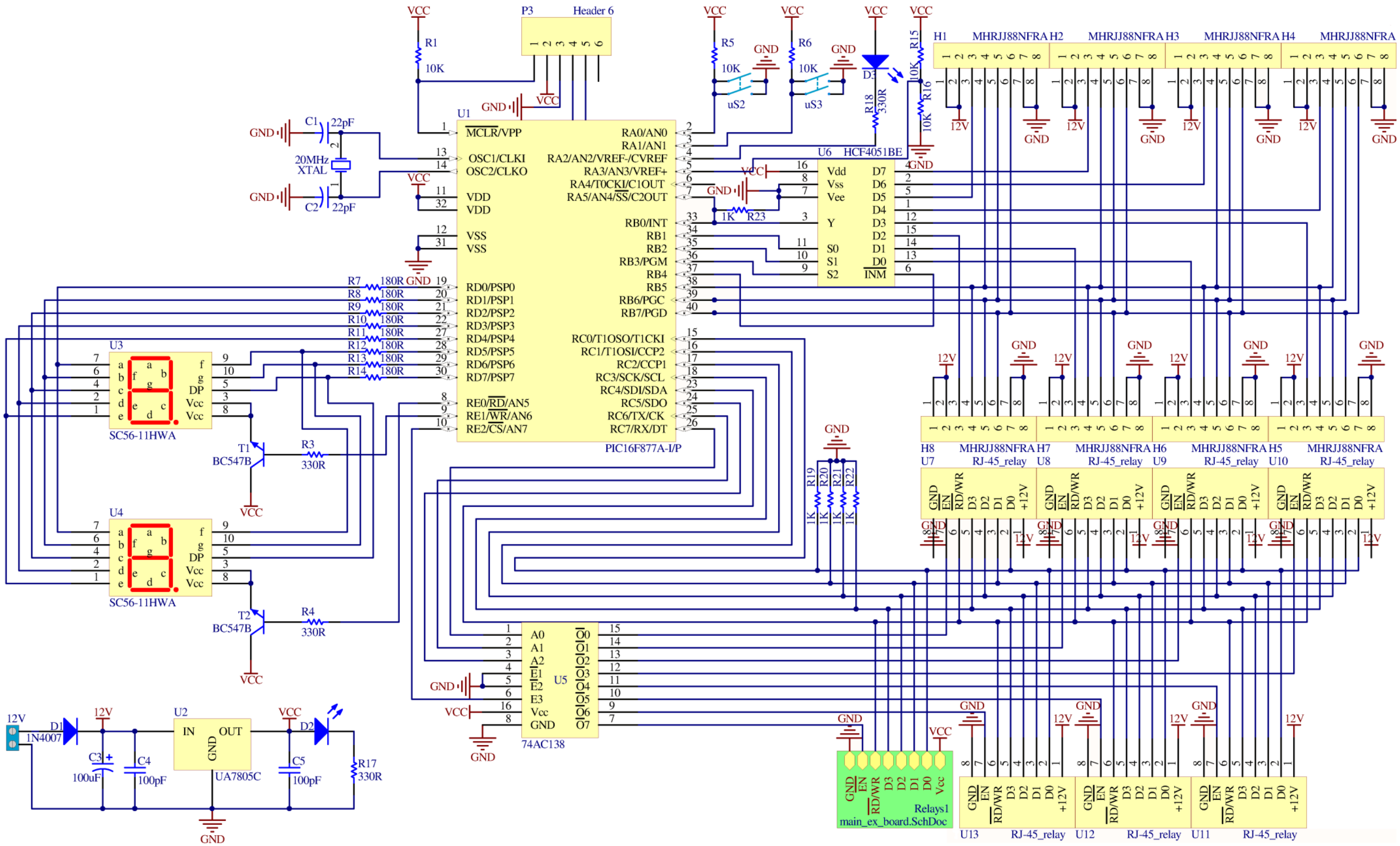


FIGURE 51: CONTROL BOARD'S CIRCUIT.

The preferred illumination level is expressed as a percentage of the maximum illumination which can be detected when all lamps are shining. This value is used to generate minimum and maximum levels between which lighting intensity may oscillate. The space between these levels has to take under consideration the area of each specific sector. If this space is too large then the system will not be accurate. However, if it is too small then lamps will be switched continuously causing damage to the lighting installation. On Figure 52 we can see an example of operation with incorrect generated levels, for a preferred illumination level set at 50%. We can see that for some periods of time, lights are toggling. This happens because opening just one relay circuit, changes the illumination in the hall so drastically that the illumination surpasses the control levels. The system will try to regulate lighting intensity but it will cause only instability. In the case, presented on the figure below, lamps were switched only few times but if the illumination would be constant, then lamp toggling would last longer.

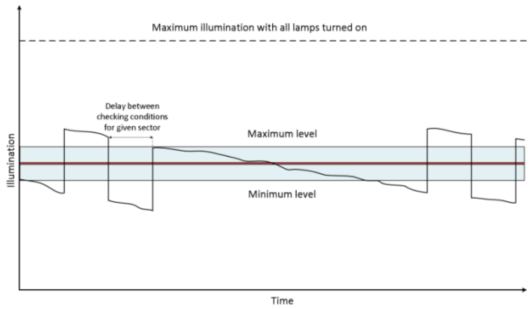


FIGURE 52: INCORRECT LEVELS GENERATION.

To avoid these undesired toggling, the system calculates (assuming uniform illumination) the values of maximum and minimum illumination accordingly to the percentage relation between sector and hall area ($A = \frac{Sector\ Area}{Hall\ area} * 100\%$). In order to achieve more accurate minimum and maximum levels, they are generated basing on area factor (Figure 53), preferred level and maximum attainable illumination level:

$$ML = PL + (MI - PL) * F(A)$$

$$mL = PL - PL * F(A)$$

, where:
A - is the normalized sector area
ML - maximum threshold
mL - minimum threshold
MI - maximum illumination
F(A) - area factor

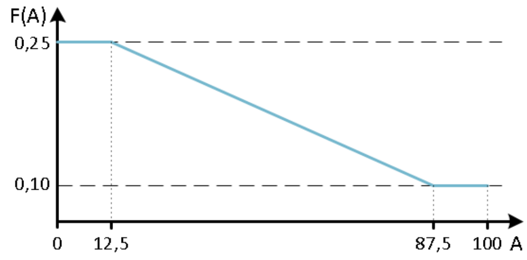


FIGURE 53: CHART OF AREA FACTOR FUNCTION.

This way, implying equal light distribution, when the illumination is lower than the minimum level it will not reach a illumination higher than maximum level, immediately after turning on one relay circuit. This will protect the system from being unstable, what can cause inconvenience for the employees and risk of damage of the lighting infrastructure.

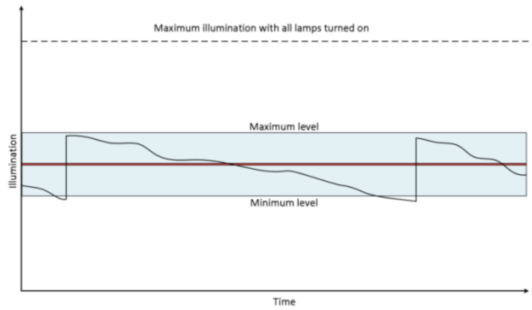


FIGURE 54: CORRECT LEVELS GENERATION, CONSIDERING AREA OF THE SECTOR.

The system was designed to support up to eight different sectors. Each sector will have one sensor board, so that eight RJ-45 sockets were used for sensor connection. Each socket is connected to the power supply, 3-wire control bus (responsible for controlling the sensor circuit), and one individual wire responsible for collecting data from the specific sensor board. Selecting a target board is done by choosing the adequate input of 8-channel multiplexer (HCF4051BE) marked as U6 on the control board circuit.

To provide flexible system for different sizes of lighting installations, the control board is equipped with seven sockets, where other extension boards can be attached, thus allowing to enlarge the number of relays used for controlling the contactors. One of the extensions was built into the control board to provide only a base system for simple lightning infrastructures, containing up to four lighting control circuits. The system can choose on which extension board wants to operate by sending an enable signal, which comes from a 1 of 8 decoder (74AC138) (marked as U5 on the control board circuit).

The control board PCB was designed in order to fit into Series 1570 DIN rail enclosure from Bernic (Figure 55). The board has dimensions of 151x82mm with two 10x1mm cut outs for snap on the sides and two mounting holes. PCB prints of bottom layer, top layer and drill drawings can be found in Appendix B. More details about board shape and enclosure can be found in product datasheet [29].

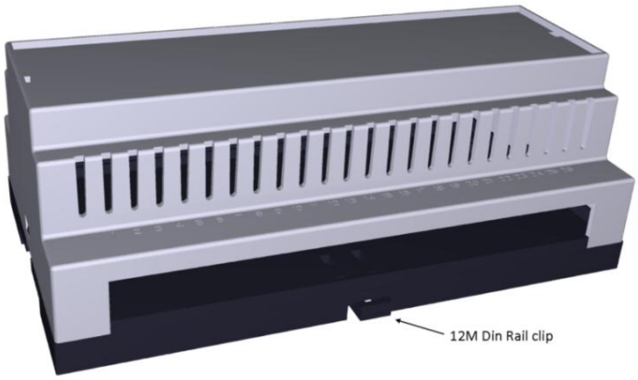


FIGURE 55: BERNIC SERIES 1570 DIN RAIL VENTILATED ENCLOSURE FOR PLUGABLE TERMINALS [30].

One of the goals of this project was to develop a low cost lighting management system, so this was one of the priorities during components selection. In order to provide the final cost of the project, prices of components used for building each part of the system will be presented. Components like resistors, capacitors or inexpensive connectors were not taken under consideration because their price is irrelevant considering other elements. Since electronic parts, used for devices' manufacturing are usually purchased in a bulk, each component's price is given for 100 or more units.

Part name:	Part number:	Unit Price: [EUR]	Price: [EUR]	Source:
MICROCHIP 8BIT FLASH MCU, DIP40	PIC16F877A-I/P	3,610	3,610	pt.farnell.com
LED DISPLAY, 0.56", HE-RED	SA56-11EWA	0,580	1,160	pt.farnell.com
LED, 5MM	HLMP-1503	0,094	0,188	pt.farnell.com
SINGLE 8-CHANNEL ANALOG MULTIPLEXER	HCF4051BE	0,360	0,360	pt.farnell.com
1-LINE TO 8-LINE DECODER	74AC138	0,197	0,197	pt.farnell.com
LINEAR VOLTAGE REGULATOR 5V	UA7805C	0,440	0,440	pt.farnell.com
XTAL, 20.000MHZ	9B-20.000MEEJ-B	0,320	0,320	pt.farnell.com
TACTILE SPST SWITCH	MC32828	0,064	0,128	pt.farnell.com
RJ45 SOCKET	MHRJJ88NFRA	0,910	13,650	pt.farnell.com
EXTENSION BOARD	-	6,490	6,490	-
		TOTAL:	**26,54**	

TABLE 6: CONTROL BOARD'S COMPONENTS COST, WHEN BUYING 100+ UNITS.

Because of modular build approach, power consumption of each part has to be considered. That will allow choosing the external power supply's current efficiency, adequate for the system needs. The control board's power consumption is presented in the following table.

Part name:	Part number:	Power consumption: [W]
MICROCHIP 8BIT FLASH MCU, DIP40	PIC16F877A-I/P	0,075000
LED DISPLAY, 0.56", HE-RED	SA56-11EWA	1,190000
LED, 5MM	HLMP-1503	0,150000
SINGLE 8-CHANNEL ANALOG MULTIPLEXER	HCF4051BE	0,000750
1-LINE TO 8-LINE DECODER	74AC138	0,000200
LINEAR VOLTAGE REGULATOR 5V	UA7805C	0,040000
EXTENSION BOARD	-	0,820110
	TOTAL:	**2,276060**

TABLE 7: CONTROL BOARD COMPONENTS' POWER CONSUMPTION.

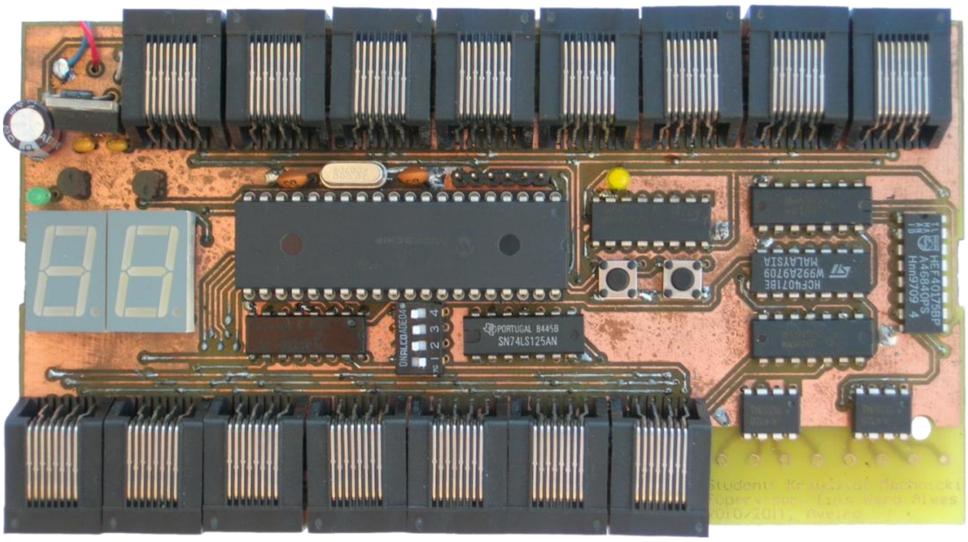


FIGURE 56: CONTROL BOARD'S PHOTOGRAPH.

4.4 EXTENSION BOARD

The system was designed to be universal and therefore can be modified without any special, technical knowledge. Its flexibility relays on being built from many parts which can be attached, only when installation conditions require it. The extension board, as the name suggests, was developed in order to extend system's capabilities. When we are dealing with small working areas, where only few lamps are used, then probably the base system, containing one extension board would be enough. Things look different, when the system has to control huge factory halls with a large number of lamps. In that case, the user attaches extension boards, thus allowing to control more lamps.

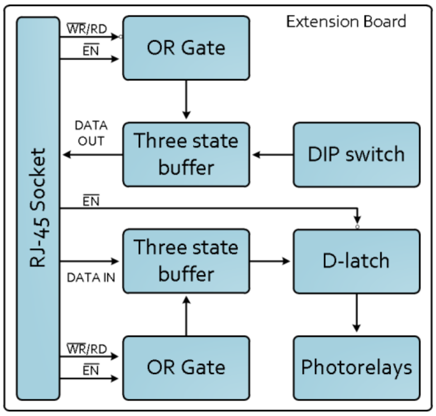


FIGURE 57: EXTENSION BOARD'S BLOCK DIAGRAM.

Each extension board has its own voltage regulator, similar to the one present on the control board. It was designed that way, in order to minimize the cost of the base system. The system could have only one voltage regulator on the control board and power all other parts but in that case it should support high current flow. It would not be profitable for the base system or systems with small amount of extensions because power consumption would be relatively small, comparing to the voltage regulator's capabilities. The price of voltage regulators heavily depends on maximum supported current and in that case, the user would pay for capabilities which would not be used.

As it was mentioned previously, each extension board contains four photorelays (ASSR-1228-002E), which control four contactors. Each photorelay can handle 400V output voltage and 100mA of average output current. Relays are manipulated by the microcontroller, located on the control board. Considering that only one board can be controlled at the same time, D-latches were used to keep other photorelays in the proper state. If the control unit wants to operate on relays placed on specific extension boards, then firstly it has to send a zero logic state on $\overline{WR}/RD$ signal to choose the write mode, send information, to the relays that needs to turn on using DATA IN bus, and then activate the board by sending an $\overline{EN}$ signal from 1 of 8 decoder placed on the control board (Figure 57). After that sequence, the OR gate (CD4071BE) will "open" the three state buffer (SN74LS125AN), passing the DATA IN on the D-latch (CD40175BE) inputs, which will be locked by the $\overline{EN}$ signal, coming through several inverters (SN74HC04N), in order to delay the $\overline{EN}$ signal, coming to the D-latch sufficiently, so that three state buffers will manage to pass the DATA IN information to the latches.

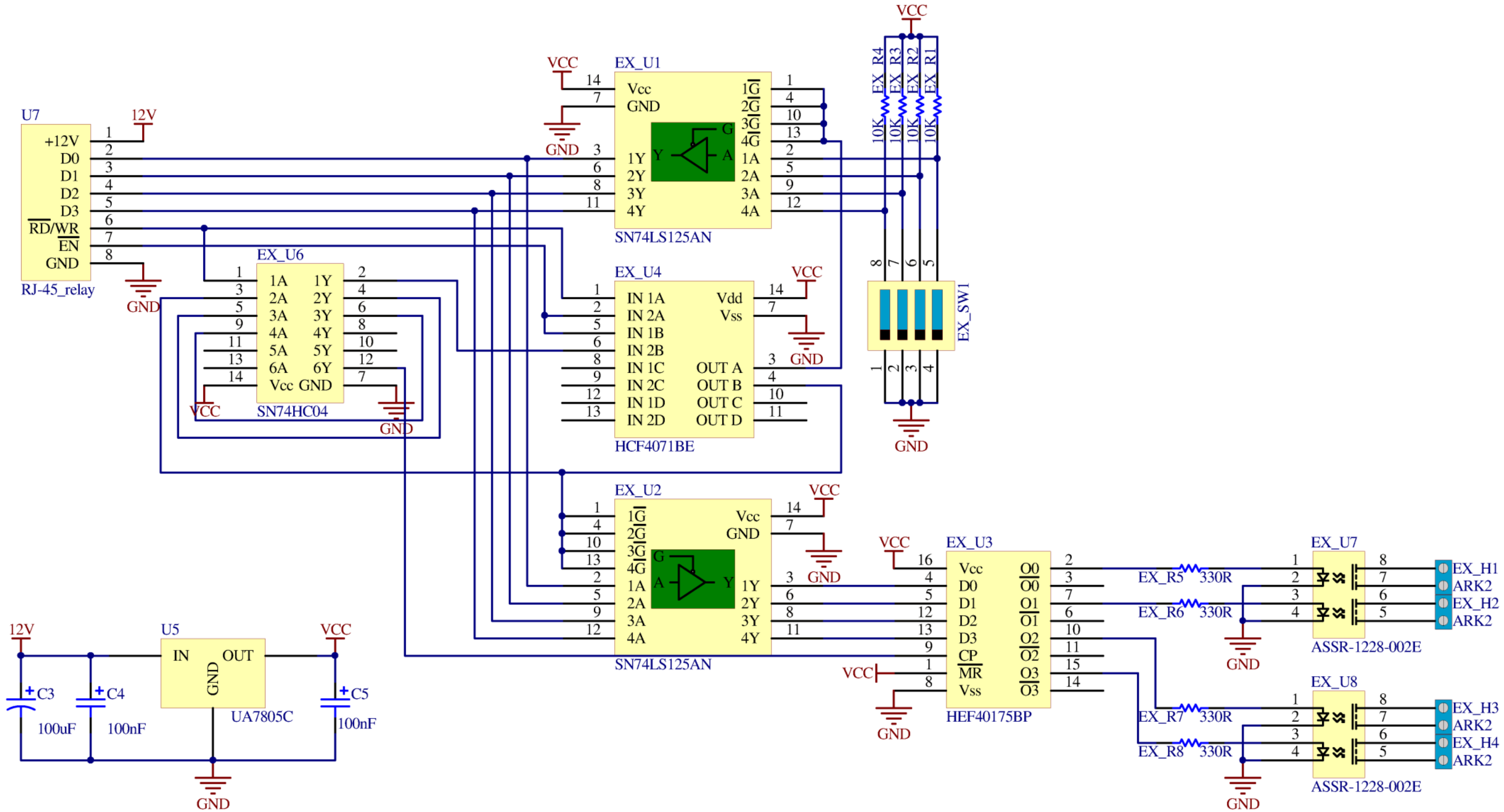


FIGURE 58: EXTENSION BOARD'S CIRCUIT.

Every board has to possess its own ID so that there is a four way DIP switch (MCNDI-04S) placed on each extension board. This unique identification is used to link extensions with sensor boards. Reading the DIP switch information procedure is similar to operating on photorelays. To read the ID information, firstly the microcontroller choose the extension by sending an $\overline{EN}$ signal to one of the boards and after that sends $\overline{WR}/RD$ signal as logic one. This signal combination, coming through extension's board electronics will "open" the three state buffer, passing the ID to the microcontroller's pins. Using the same signal to choose between write and read modes, gives the protection from short circuit between DIP switch and photorelays parts of the extension board.

Part name:	Part number:	Unit Price: [EUR]	Price: [EUR]	Source:
QUAD D-TYPE FLIP-FLOP	CD40175BE	0,21	0,21	pt.farnell.com
QUAD CMOS OR GATES	CD4071BE	0,31	0,31	pt.farnell.com
QUAD BUS BUFFERS	SN74LS125AN	0,36	0,72	pt.farnell.com
HEX INVERTER	SN74HC04N	0,17	0,17	pt.farnell.com
4 WAY DIP SWITCH	MCNDI-04S	0,50	0,50	pt.farnell.com
LINEAR VOLTAGE REGULATOR 5V	UA7805C	0,44	0,44	pt.farnell.com
PHOTO RELAY	ASSR-1228-002E	1,61	3,22	pt.farnell.com
RJ45 SOCKET	MHRJJ88NFRA	0,91	0,91	pt.farnell.com
		TOTAL:	**6,49**	

TABLE 8: EXTENSION BOARD'S COMPONENTS COST, WHEN BUYING 100+ UNITS.

Part name:	Part number:	Power consumption: [W]
QUAD D-TYPE FLIP-FLOP	CD40175BE	0,000005
QUAD CMOS OR GATES	CD4071BE	0,000005
QUAD BUS BUFFERS	SN74LS125AN	0,270000
HEX INVERTER	SN74HC04N	0,000100
4 WAY DIP SWITCH	MCNDI-04S	0,010000
LINEAR VOLTAGE REGULATOR 5V	UA7805C	0,040000
PHOTO RELAY	ASSR-1228-002E	0,500000
	TOTAL:	**0,820110**

TABLE 9: EXTENSION BOARD'S COMPONENTS POWER CONSUMPTION.

The extension board's PCB was also designed to fit into similar DIN rain enclosure as the control board. In this case, Series 520 DIN rail enclosure from Bernic was chosen [31]. The PCB has dimensions of 82x46,7mm with two 11x1mm cut outs on the sides and two mounting holes. PCB prints and design details can be found in Appendix B.

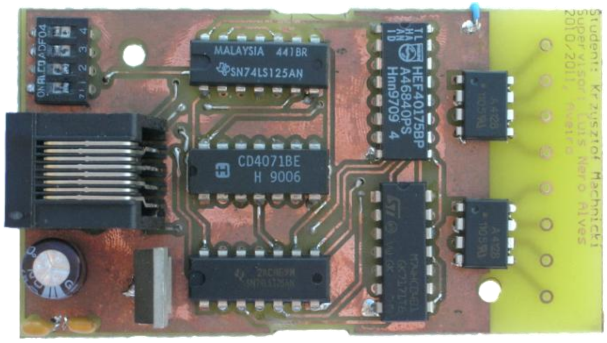


FIGURE 59: EXTENSION BOARD'S PHOTOGRAPH.

4.5 SENSOR BOARD

The sensor board is a very important part of the system. It collects the illumination from the environment and passes it to the control board, enabling to decide if lighting intensity is sufficient or not. It also possesses its unique ID, which allows the microcontroller to link it with extension boards.

Similar to the extension boards, each sensor board has its own voltage regulator. This is also due to price considerations, but there is also another reason. Sensors are connected to the control board with long wires, above 10m. With this cable length, the voltage drop can be a significant factor. The solution for this problem is to power the sensor board with higher voltage, (like 9V or 12V) and regulate it locally to 5V. Even if there will be small voltage drop on the line, the voltage should still be enough for the regulator to provide 5V on its output.

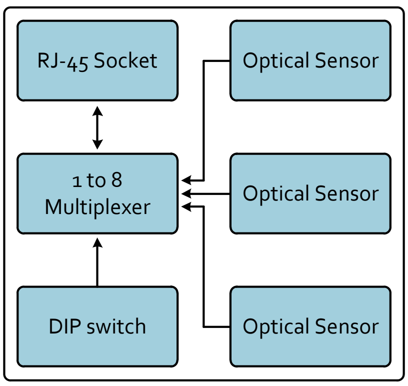


FIGURE 60: SENSOR BOARD'S BLOCK DIAGRAM.

The main sensor board's function is passing the actual illumination level to the microcontroller. Moreover, in order to ensure high reliability of the lighting management system, every sensor board is equipped with three, independent optical sensors. The possibility of measuring illumination level using three optical sensors, improves credibility of the measurements. Before the system will get the final value, the illumination is measured by all optical detectors and the most different one is rejected. The lightning intensity is then given as an average of the remaining values. This procedure ensures correct measurement, even if one of the optical sensors is damaged.

The communication between the control board and sensor boards is a key issue. As it was already mentioned, sensors will be placed far away from the control board what can cause some inconveniences for proper communication. The idea of solving this problem was using one of the communication standards RS-485 or ZigBee. Implementing one of these methods, would improve reliability on the communication, but it would be relatively expensive. Each sensor board should be additionally equipped with the RS-485 or ZigBee transceiver. The less expensive RS driver found on Farnell (SP485RCP-L), cost around 1EUR and the less expensive ZigBee transceiver from Microchip (MRF24J40MA-I/RM) cost over 7,50EUR. Therefore, even though the ZigBee standard, gives the possibility of reliable communication in industrial environments without wires, using it would drastically raise the cost of the system. Searching for low cost solutions brought the idea of using the simplest method – using a digital sensor with frequency modulated output signal, which is much more resistant to external disruptions than analog signals. That led to designing the sensor board, using the TSL220 light to frequency converter, which is a very simple device, representing lighting intensity with frequency modulated, square signal of 4V amplitude. With the illumination increase, the output signal frequency rises proportionally (Figure 62). Small voltage drop do not affect the signal integrity, enabling reliable illumination measurements.

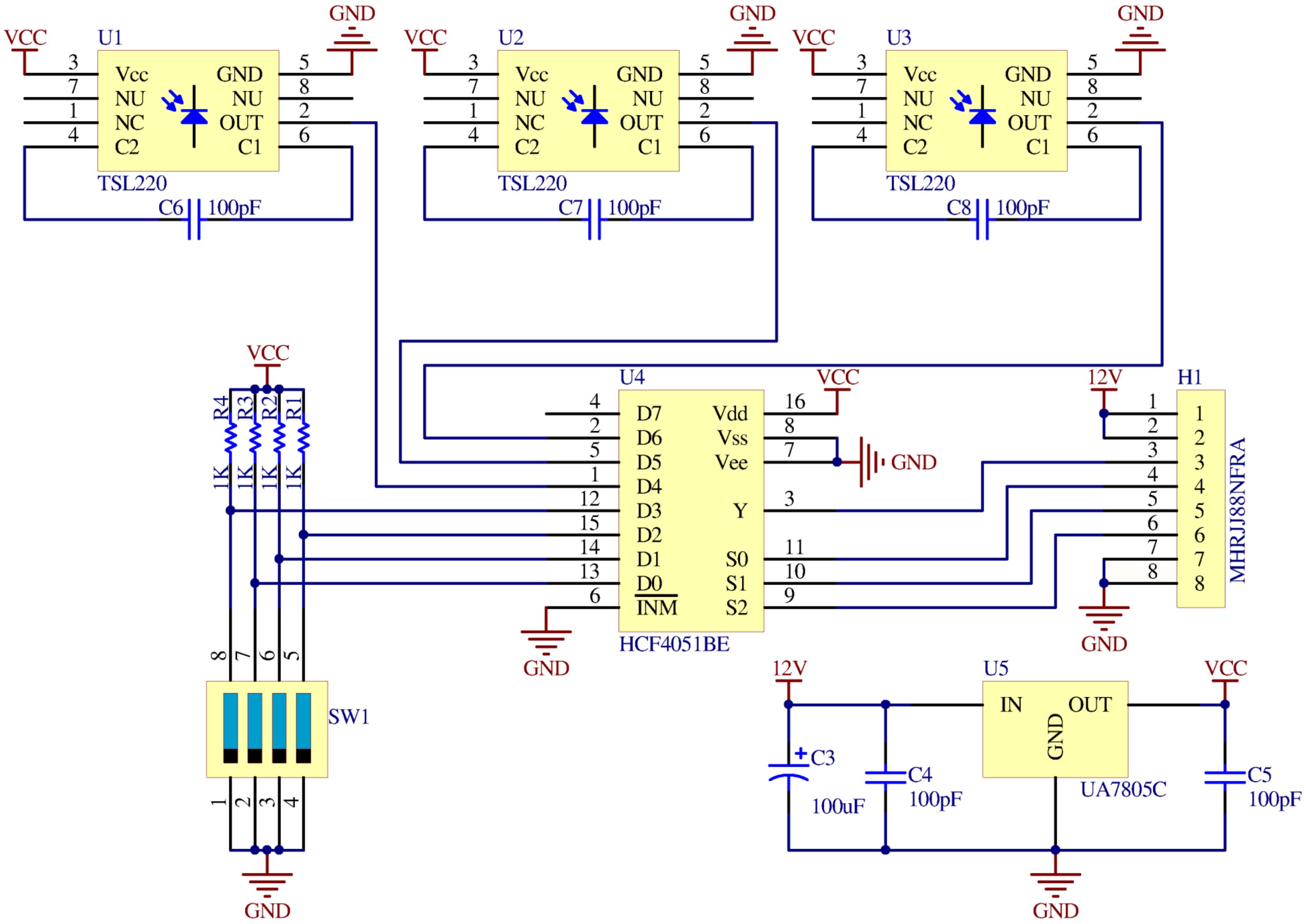


FIGURE 61: SENSOR BOARD'S CIRCUIT.

The TSL220 light to frequency converter can measure irradiance from 1 to 1000 μW/cm² and covers human eye responsivity quite good. However, the maximum measured irradiance is limited by the minimum and maximum output frequency range between 10Hz and 750 kHz. The output frequency range can be regulated by external capacitor connected to pin 4 and 6 of the device. Using capacitance values smaller than 100pF allows measuring lighting energy with better precision. Using too high capacitance values is not good, because the device cannot detect low irradiance levels. In order to cover the maximum irridance range which can be detected by the device and provide good precision, 100pF capacitors were chosen.

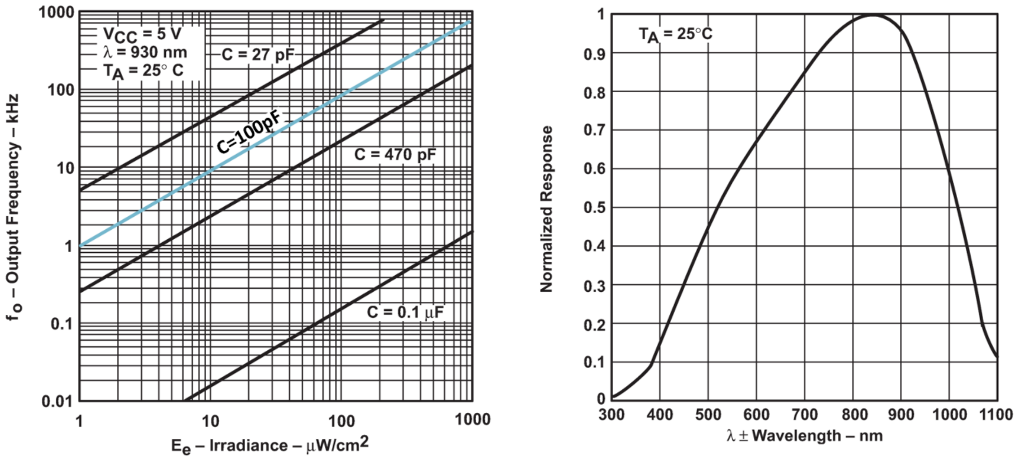


FIGURE 62: CHARACTERISTICS OF THE TSL220 LIGHT OF FREQUENCY CONVERTER[32].

Usually, illumination is described in the SI unit – lux (1lx = 1lumen/m²). However, there is no simple conversion factor between lux and irradiance because for every wavelength there is a different factor and it is not possible to make a conversion, unless the spectral composition of the light is known. In order to provide illumination range given in lux, which can be detected by TSL220 optical sensor with 100pF capacitor, illumination vs. frequency characteristic was made using HD450 Heavy Duty Light Meter from Extech Instruments (Figure 63). From this chart, minimum and maximum values of measured illumination can be red and they are in the range from 0 to around 1200 [lx], partly fulfilling industrial lighting recommended values.

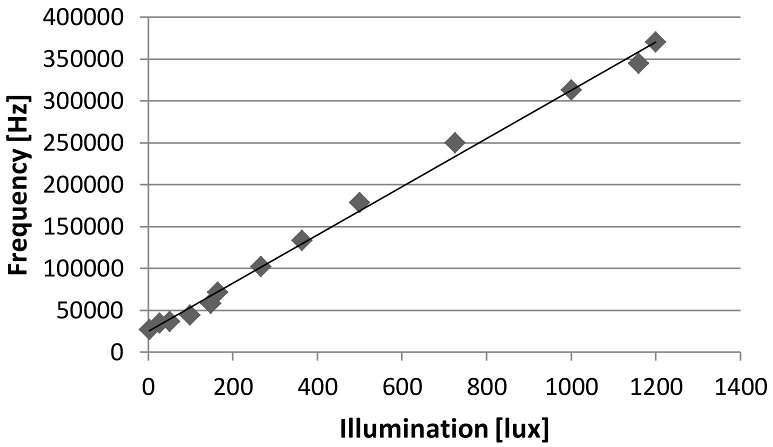


FIGURE 63: ILLUMINATION VS. FREQUENCY CHARACTERISTIC OF THE TSL220 OPTICAL SENSOR.

Each sensor board has a 4 way DIP switch ID circuit, like the one implemented on the extension boards. By manipulating the switches, the user is able to set 16 different configurations, which firstly are read by the system and then compared with those set on the extension boards in order to link them in a group.

Part name:	Part number:	Unit Price: [EUR]	Price: [EUR]	Source:
LINEAR VOLTAGE REGULATOR 5V	UA7805C	0,44	0,44	pt.farnell.com
SINGLE 8-CHANNEL MUX	HCF4051BE	0,36	0,36	pt.farnell.com
RJ45 SOCKET	MHRJJ88NFRA	0,91	0,91	pt.farnell.com
4 WAY DIP SWITCH	MCNDI-04S	0,50	0,50	pt.farnell.com
LIGHT TO FREQUENCY CONVERTER	TSL220	3,50	10,50	www.inelcocomponents.com
		TOTAL:	**12,71**	

TABLE 10: SENSOR BOARD'S COMPONENTS COST.

Part name:	Part number:	Power consumption: [W]
LINEAR VOLTAGE REGULATOR 5V	UA7805C	0,040000
SINGLE 8-CHANNEL ANALOG MULTIPLEXER	HCF4051BE	0,000750
4 WAY DIP SWITCH	MCNDI-04S	0,010000
LIGHT TO FREQUENCY CONVERTER	TSL220	0,600000
	TOTAL:	**0,650750**

TABLE 11: SENSOR BOARD'S COMPONENTS POWER CONSUMPTION.

Sensor PCB board was designed to fit into Series 1000, type 1061 sealed enclosure from Bernic [33]. It has dimensions of 77,5x72,5mm and it consists of two mounting holes. PCB prints and design details can be found in Appendix B.

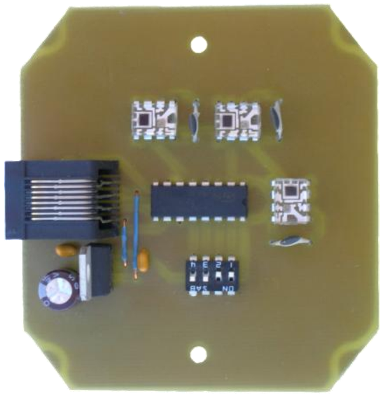


FIGURE 64: SENSOR BOARD'S PHOTOGRAPH.

The sensor board based on the TSL220 light to frequency converter met system requirements, nevertheless, another approach has been taken. The main reason for this was the relatively high price of the TSL220 light to frequency converter and manufacturer's decision of ceasing the production of this device. Taking the opportunity that sensor board will be redesigned, another improvement was also implemented. In order to enhance accuracy of the measuring procedure, the decision of separating optical sensors was made. The old sensor board had all three optical sensors concentrated in one place. This solution provided redundancy, considering possibility of breaking one of the sensors but it did not guarantee correct measurement in case of light blocking. The new sensor was divided into three independent boards, which would be placed in different locations so that even if one of the sensor boards will be covered by some obstruction, the remaining boards will handle with correct illumination measurement. There is one main sensor board, which is a kind of concentrator, where power supply, multiplexer, optical sensor and ID electronics are placed. Getting the advantage of one unused input of the multiplexer, placed on the main sensor board, it was possible to make the "concentrator" as the base sensor and the other two boards as optional, which can be connected in order to provide redundancy. This way system flexibility was improved because it is now up to the customer to decide if redundancy is required or not and if it is necessary to pay more in order to obtain it. The mechanism for this solution is very simple. As it was already mentioned, there is one unused multiplexer input on the sensor board, where after redesigning, pull-up resistor and signals coming from two optional sensor boards were connected. When there are no additional sensor boards connected, there is logic one on that input, caused by the pull-up resistor presence. Signal lines coming from additional sensor boards are connected to the ground so if at least one additional sensor board will be connected, it will force logic zero on the multiplexer's input. The microcontroller will detect the logic level on the multiplexer's input and adapt to that configuration. In case of using only the main sensor board (concentrator), measured illumination will be exactly as the one measured by this particular sensor. In case of using two sensor boards, illumination will be given as an average of these two boards, and in case of using three boards, the most different value of measured illumination will be rejected and average of other two values will be given as a result.

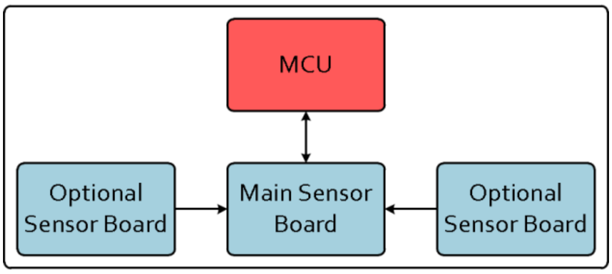


FIGURE 65: IMPROVED SENSOR DESIGN BLOCK DIAGRAM.

Besides changes in sensor board's structure, the light detecting device was also modified. In order to provide less expensive light to frequency converter, a lot of devices were considered but the results were not satisfying. In that case, the decision of developing a new light to frequency converter was made. After doing a search of available solutions for building this kind of device, it was decided to develop a new sensor based on the 555 timer and a photodiode. The 555 timer is a simple yet powerful device for generating Pulse-Width Modulated (PWM) signals, using two comparators and a RS latch (Figure 66). There is a voltage divider built in, made up from three resistors, which provide reference voltages for comparators. These comparators compare the reference voltages with the external signals and control the RS latch adequately. If the voltage signal connected to the THRES input is higher than reference voltage (usually 3.3V for 5V power supply), on the output pin there will appear logic zero, and if voltage connected to the TRIG input is lower than the reference (usually 1.65V for 5V power supply), on the output pin will appear logic one.

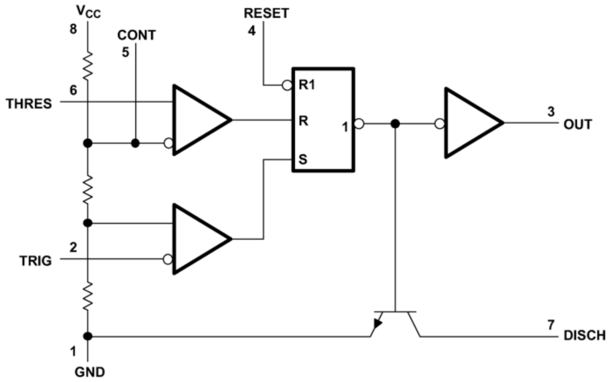


FIGURE 66: THE 555 TIMER FUNCTIONAL BLOCK DIAGRAM [34].

In order to build simple light to frequency converter, using the NE555 timer, a photodiode and capacitor, were used as displayed on Figure 67. Assuming that in the beginning C1 is discharged, and that on TRIG/THRES pins there is a voltage below 1.65V, the output of the 555 timer is forced to logic one. Because the diode is connected in the way that the anode is connected to the out pin and the cathode to TRIG/THRES, its resistance for current flowing to capacitor is minimal, what cause almost instant charging of the C1 capacitor. When the voltage, which is common for the capacitor and TRIG/THRES pins will increase above 3.3V, the 555 timer will change output state from one to zero and the capacitor discharging till value of 1.65V will begin. In this case diode's resistance depends on the lighting intensity coming on its surface. According to the time constant equation $\tau = R \times C$, the time of charging/discharging the capacitor is proportional to the values of capacitance and resistance. Summarizing, with higher illumination, coming on photodiode's surface, the resistance of the diode, in a reverse bias, is decreasing and therefore the time needed for the capacitor discharging is reducing, what makes output signal frequency higher.

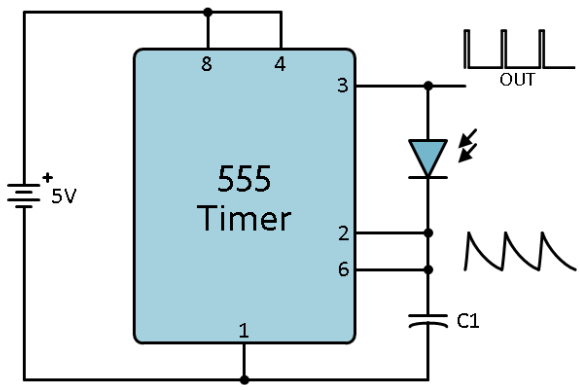


FIGURE 67: LIGHT TO FREQUENCY CONVERTER, BASED ON NE555 TIMER.

In the prototype, the SFH213 photodiode from Osram was used for lighting detection. It characterizes with good coverage of visible light spectrum, linear current output [35] and is relatively low-cost. In order to ensure better visible light detection any other photodiode can be used.

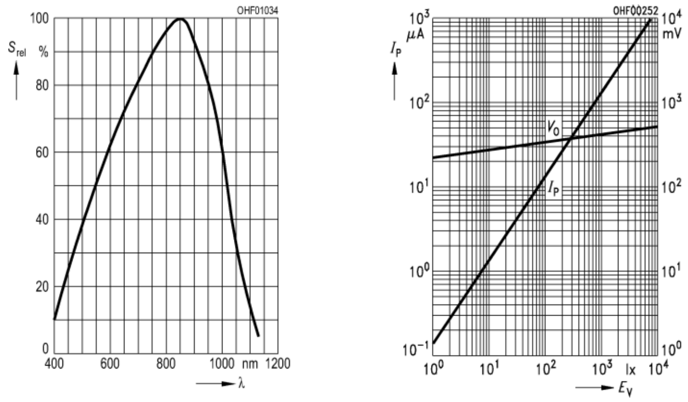


FIGURE 68: SPECTRAL SENSITIVITY, PHOTOCURRENT AND OPEN-CIRCUIT VOLTAGE CHARACTERISTICS OF SFH213.

In order to test if proposed circuit will meet the system requirements, circuit's performance was measured using a lux meter and an oscilloscope. As it is presented on Figure 69, light to frequency converter based on the NE555 timer can measure the illumination and converting it into frequency even better than previously used TSL220 integrated circuit. Because SFH213 output current is proportional to the illumination, output frequency of the 555 timer also has to be proportional to the illumination. Besides that, this sensor can measure the illumination from few lux up to about 5000 lux. There is also space left to solder optional resistor R6 in order to change illumination vs. frequency characteristic.

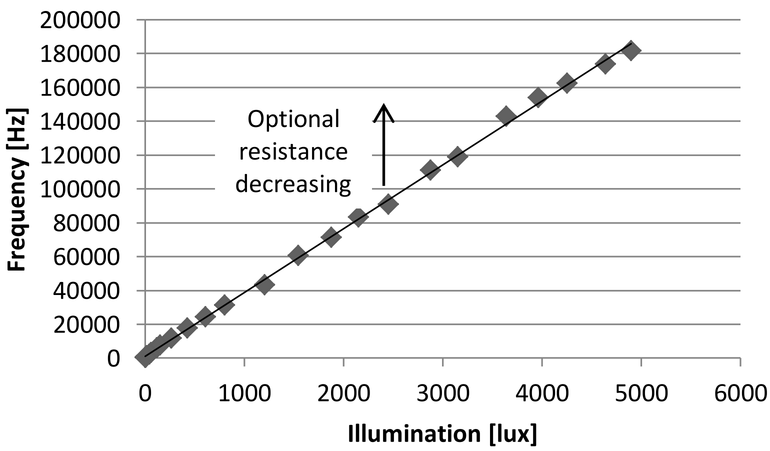


FIGURE 69: ILLUMINATION VS. FREQUENCY CHARACTERISTIC OF THE NE555 TIMER BASED OPTICAL SENSOR.

Considering the price of this sensor, it also presents better. For the TSL220 light to frequency converter we should pay around 3,5EUR, while for this sensor it would be around 0,8EUR (0,3EUR for the NE555P timer and 0,5EUR for the SFH213 photodiode on pt.farnell.com), what gives around 4,6EUR for complete sensor solution, containing three sensor boards.

Each board was designed to fit into G250C small enclosure with clear lid from GAINTA [36]. The PCB has dimensions of 46,5x44,5mm and its prints and design details can be found in Appendix B.

CHAPTER 5: CONCLUSIONS

In the introduction, it was stated that the main objective of this thesis was to design and implement a flexible lighting management system for industrial environments so that it would cooperate with most of existing lighting installations. At the same time this system should be less expensive than other advanced solutions addressed for industrial customers. This was achieved by revising already existing lighting management systems for the industry and available technologies, what allowed developing a system able to manage industrial lighting installation in most of the cases without obligation of modifying them. It is very important because industrial lighting installations are very expensive and modifying them would stop the production.

During the system design process, reliability and price were taken under consideration as the most important aspects. Nowadays, successful products have to be designed taking into consideration the maximization of the quality to price ratio. That is why during the planning phase of the system architecture, some good solutions had to be dropped because of their higher cost. This was the cause of dropping ZigBee as the system communication protocol.

The design process of this system was based on accurate data, which was provided by the Diferencial Company, and discussions about the development of this system. Unfortunately, access to the real industrial lighting installation to perform some tests and therefore improvements in the system was not feasible. However, the provided information was enough to build a complete system, which after few tests and improvements should become a final product, ready to be installed in factory halls.

Developing a system addressed for industrial clients, allowed to improve my knowledge of industrial electronics and know better the habits and requirements, occurring in this field. Moreover, I learned a lot about designing from very beginning a control system, which use sensors and industrial communication protocols.

5.1 FUTURE WORK PROPOSED

It has to be emphasized that the currently developed solution is just the prototype and before it can be considered as a final product, a lot of work has to be done. First of all, it has to be tested with real industrial lighting installation in order to check if it is working as it is supposed to work, without any faults. During the testing process, it will be easier to notice things, which can be improved and in consequence provide a more reliable product.

As for now there are already some suggestions, considering future work. During the programming of the user interface, there was revealed problem of holding two buttons in order to confirm new settings. In present system configuration, there are two push buttons, which are used to decrease and increase the number, showed on seven segment display. These buttons are also used for entering the configuration step and confirming new settings, by holding them at the same time. The problem occurs when the user wants to confirm settings by pressing and holding two buttons but they are not pressed exactly at the same time. This problem was partly solved using software by inserting a short delay, while detecting if both buttons were pressed. It could be eliminated by putting longer delay but it would cause using the user interface uncomfortable. The other solution of this problem assumes changing hardware configuration by adding one pushbutton, which would be used to start the configuration sequence and confirm new settings.

Other improvements concern the price of components, used for building the prototype. Usually the lowest price solutions were used but there are still components, which can be changed in order to lower the price of the system. Revising the prices and the quantity of used components, comes the conclusion that RJ45 sockets (MHRJJ88NFRA) and photo relays (ASSR-1228-002E) bring the highest costs. RJ45 sockets were used because they provide very easy connection between the board and ethernet cable. There are less expensive connectors that can be used. Photorelays can be replaced by TRIACs (Triode for Alternating Current), which perform the same function and are less expensive (around 0,1EUR on pt.farnall.com). Their disadvantage is a fact that they do not provide galvanic isolation, so this solution has to be considered very wisely.

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APPENDIX A: CIRCUIT DESIGNS

All circuit presented below were made using the trial version of Altium Designer. This software, based on the DXP platform, is a single application that offers a complete set of tools to implement PCB or FPGA projects and embedded software for microprocessor systems, ensuring full integration with the tools and project management functions. The program is an advanced and modern tool, which allows shortening the duration of the project both for large companies and small works done by students.

Considering number of system blocks, few different projects were created: control board, extension board and sensor boards. Schematics of these boards are presented below. Most of components' libraries were designed from scratch because they were not present in Altium's standard library. Besides, it required more work and was more time consuming, it allowed to know better the dimensions and features of used components, what resulted with better PCB design.

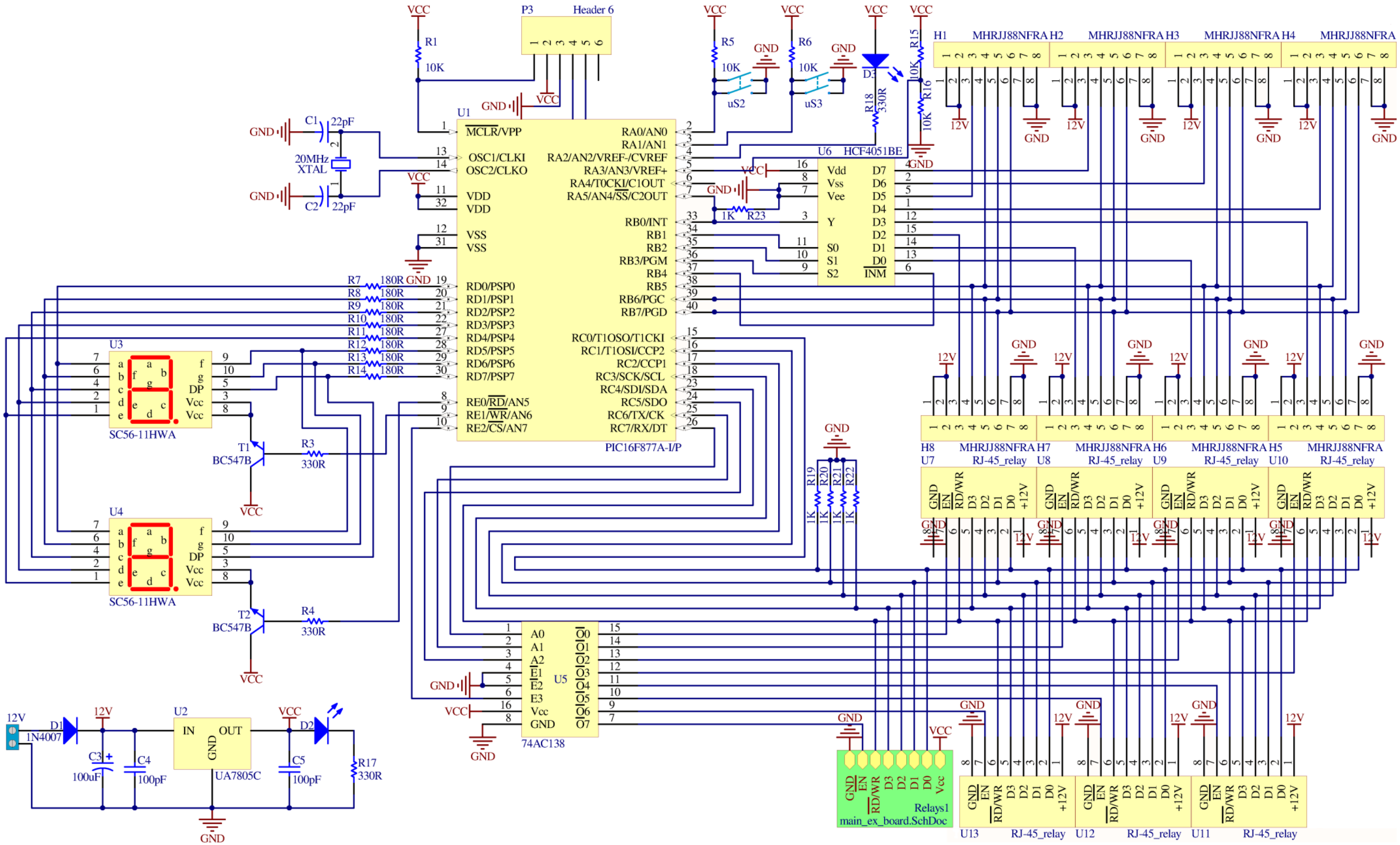


Figure 70: Control board's circuit.

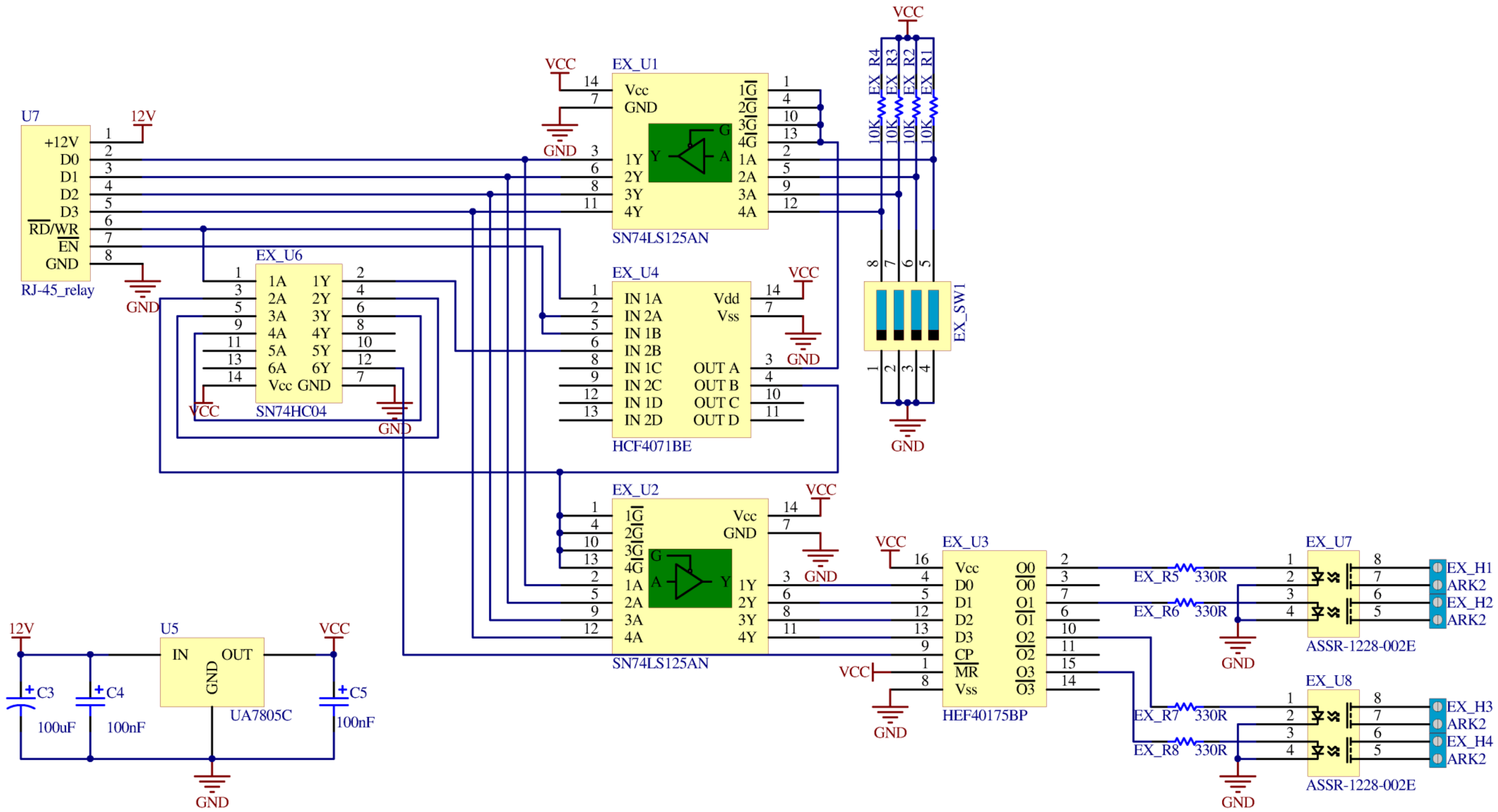


FIGURE 71: EXTENSION BOARD'S CIRCUIT.

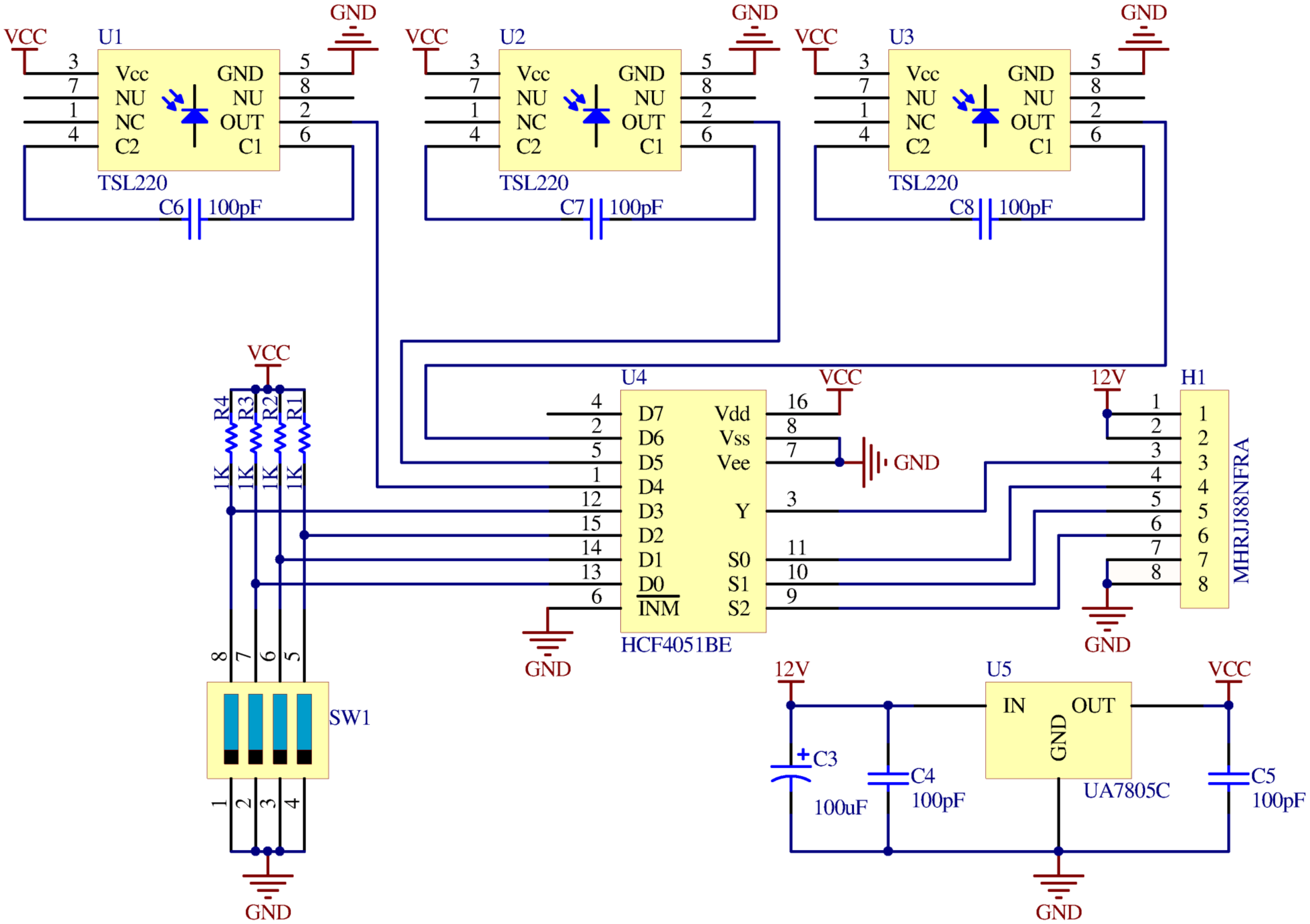


FIGURE 72: SENSOR BOARD'S CIRCUIT.

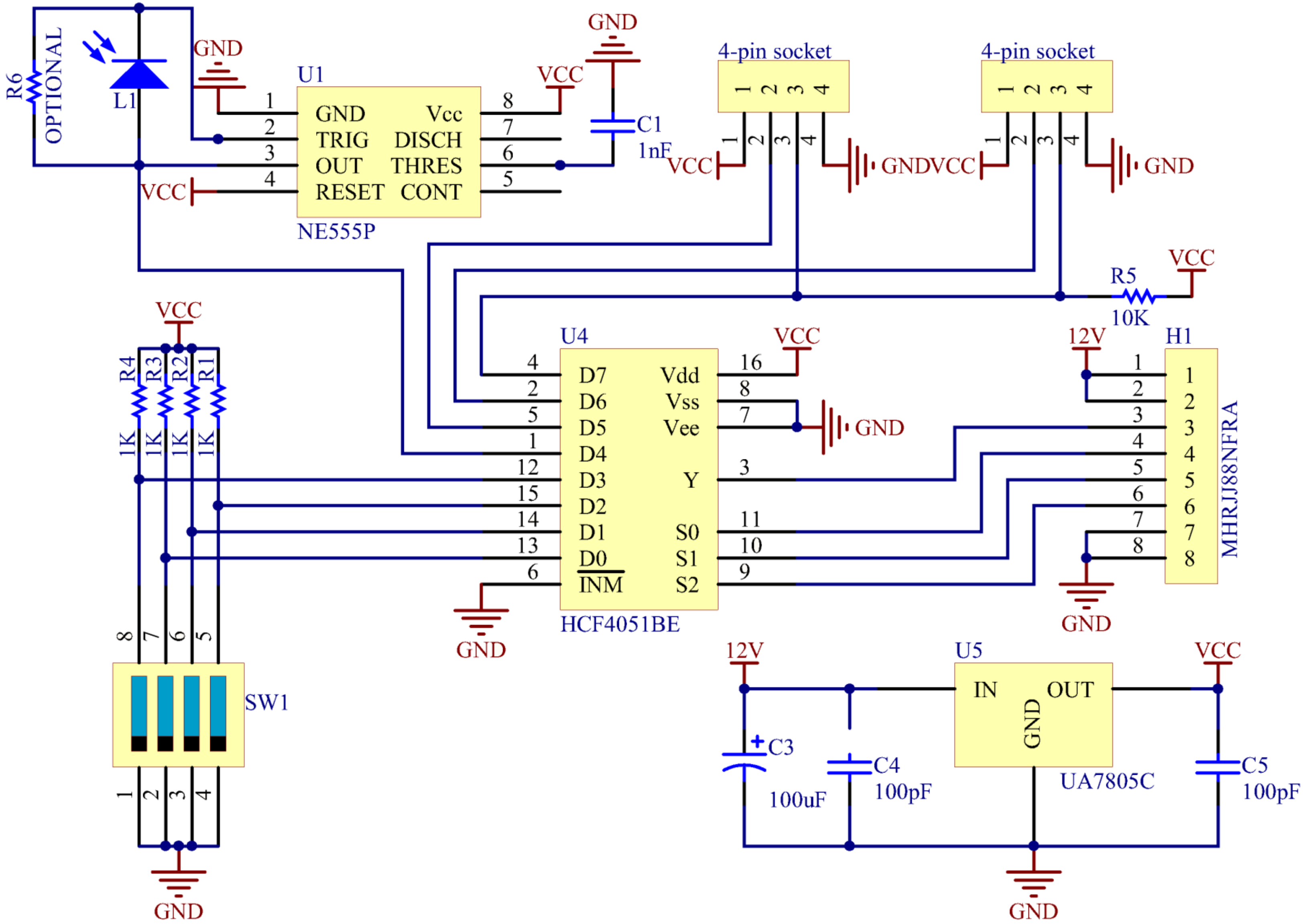


Figure 73: New sensor's main board circuit.

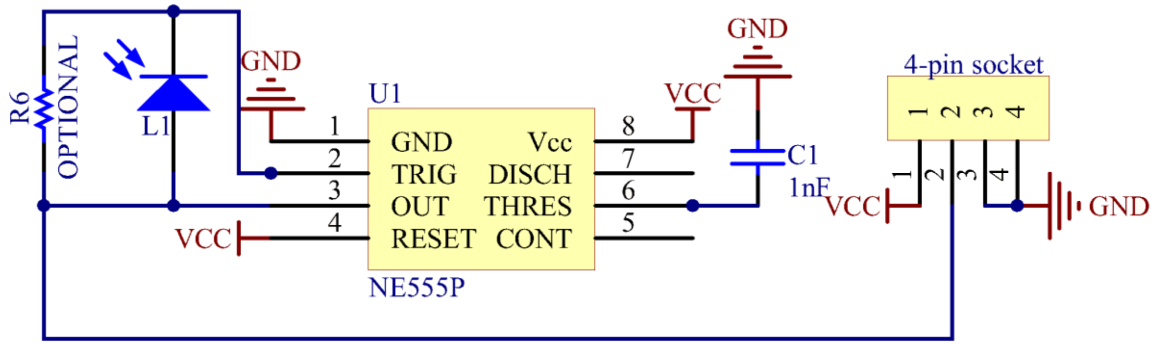


Figure 74: New sensor's extension board circuit.

APPENDIX B:
PCB DESIGNS

Boards used in this project were also designed in Altium Designer, what made the design process faster and easier due to the previous knowledge of this development tool. Designed PCB boards were produced at the university, using simple etching method so there had been some restrictions concerning width of the tracks and space between them. Imposed rules were set in Altium Designer and allowed the minimum track width of 20 mils and space between them of 15mils. Also minimum hole size was restricted to 0.8mm so PCB layout was designed to meet this condition.

Because each via, present on the boards had to be soldered by hand, tracks were designed in the way to minimize their number. However, a lot of them were used to connect polygons together, which belong to ground signal net.

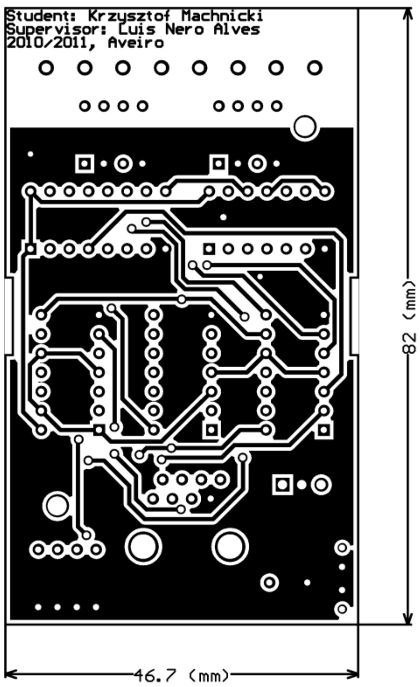


FIGURE 75: EXTENSION BOARD'S TOP LAYER.

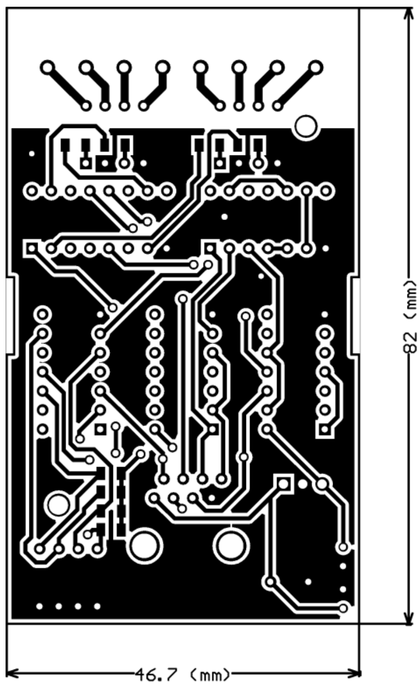
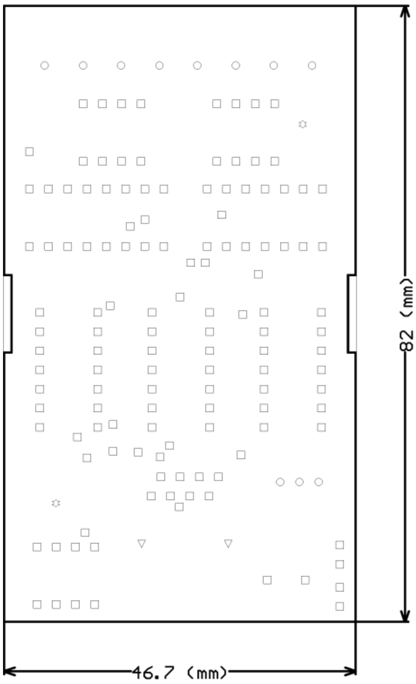


FIGURE 76: EXTENSION BOARD'S BOTTOM LAYER.



Symbol	Hit Count	Tool Size	Plated	Hole Type
□	130	0.8mm (31.496mil)	PTH	Round
○	11	1.2mm (47.244mil)	PTH	Round
☼	2	2.5mm (98.425mil)	PTH	Round
▽	2	3.25mm (127.953mil)	PTH	Round
	145 Total			

FIGURE 77: EXTENSION BOARD'S DRILL DRAWING LAYER.

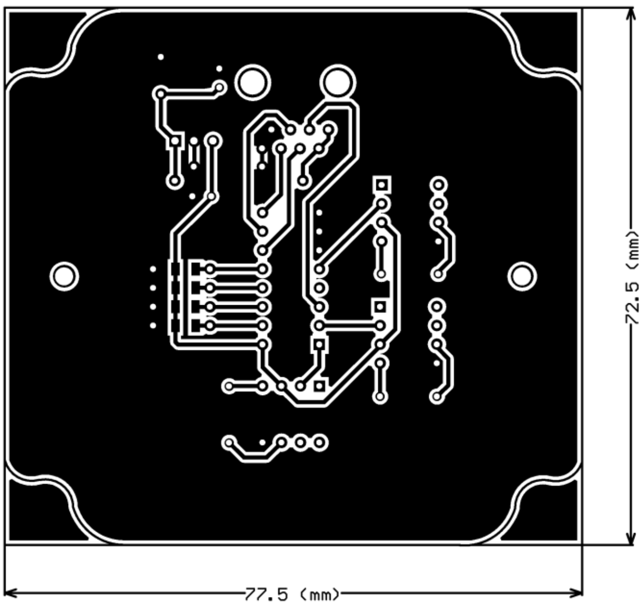


FIGURE 78: SENSOR BOARD'S BOTTOM LAYER.

Symbol	Hit Count	Tool Size	Plated	Hole Type
□	72	0.8mm (31.496mil)	PTH	Round
○	3	1mm (39.37mil)	PTH	Round
▽	2	2.4mm (94.488mil)	PTH	Round
☼	2	3.25mm (127.953mil)	PTH	Round
	79 Total			

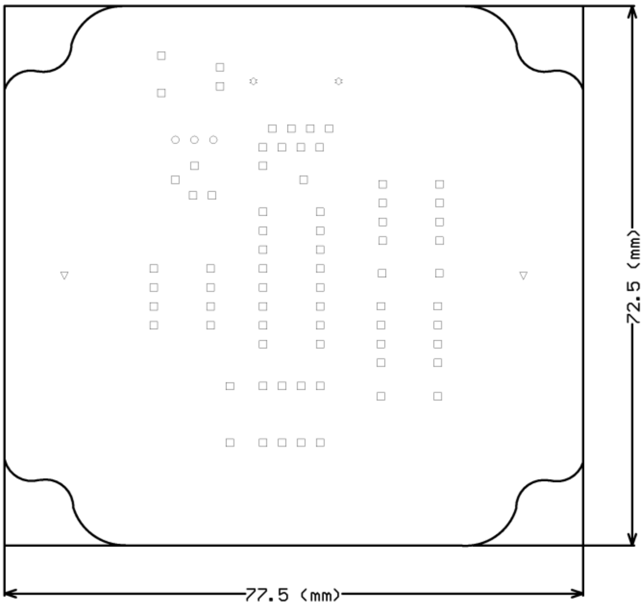


FIGURE 79: SENSOR BOARD'S DRILL DRAWING LAYER.

Symbol	Hit Count	Tool Size	Plated	Hole Type
□	512	0.8mm (31.496mil)	PTH	Round
▽	15	1.2mm (47.244mil)	PTH	Round
☼	2	2.5mm (98.425mil)	PTH	Round
○	30	3.25mm (127.953mil)	PTH	Round
	559 Total			

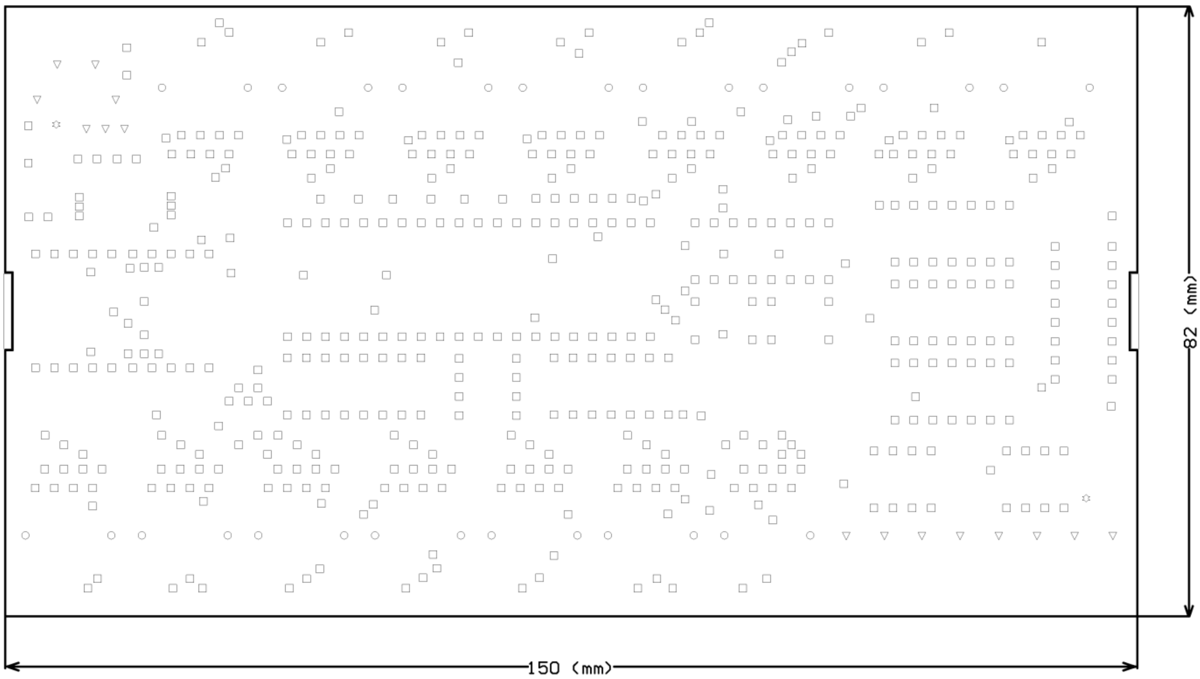


FIGURE 80: CONTROL BOARD'S DRILL DRAWING LAYER.

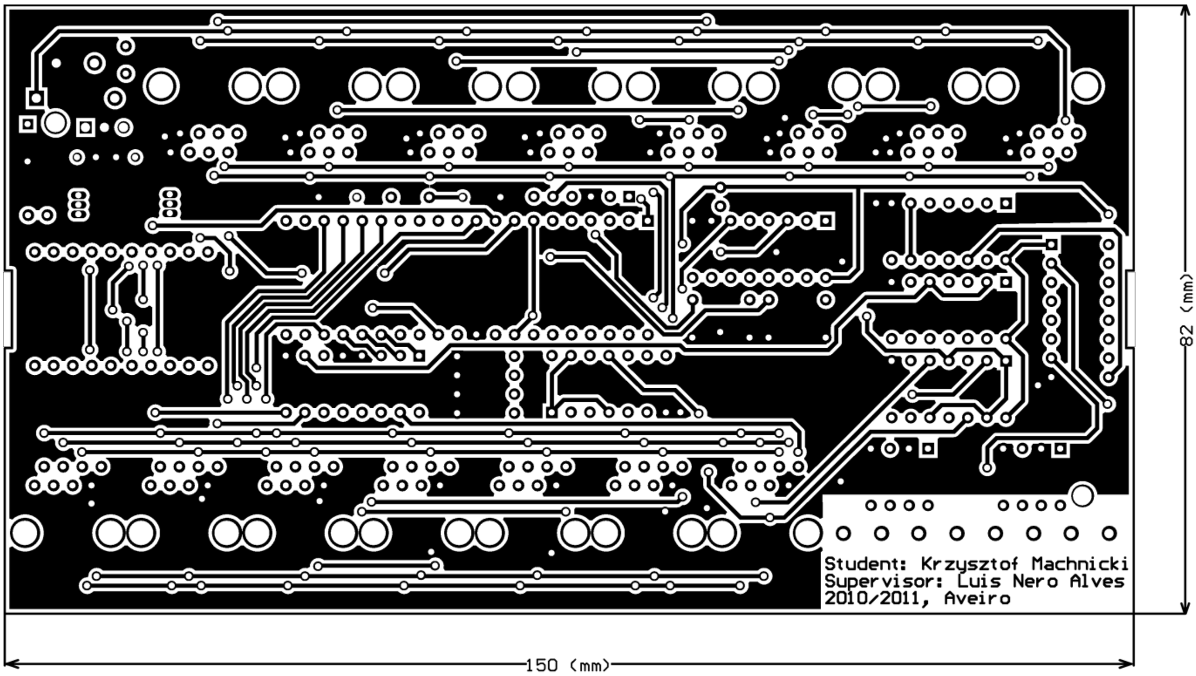


FIGURE 81: CONTROL BOARD'S TOP LAYER.

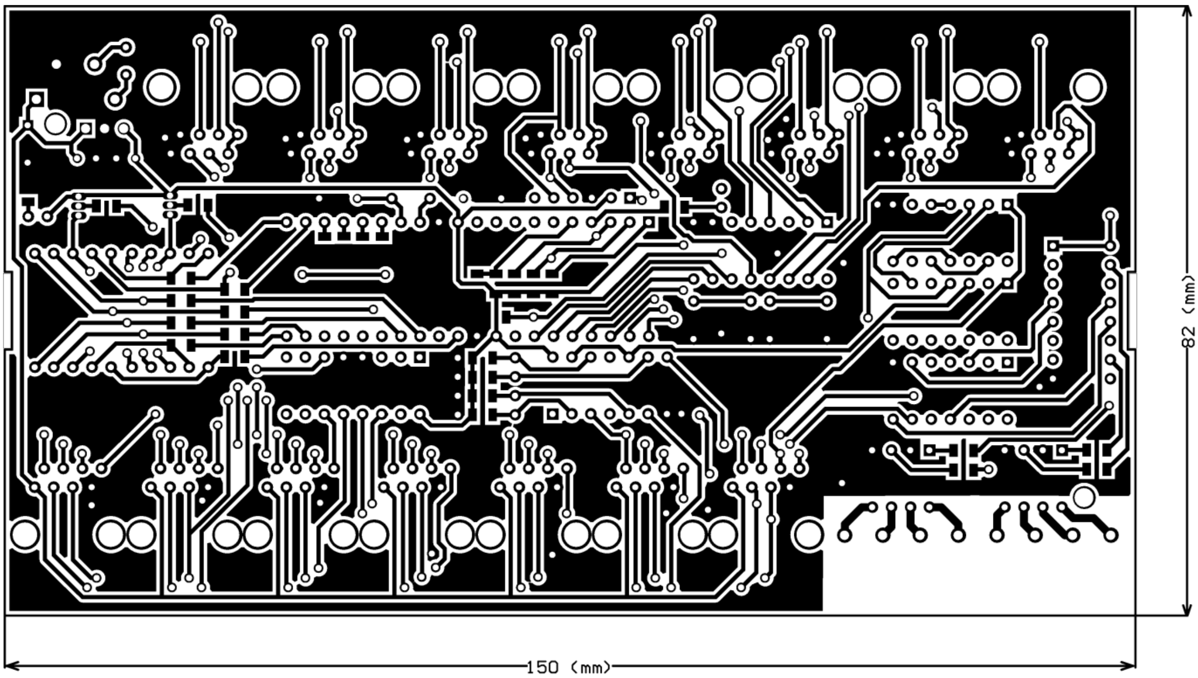


FIGURE 82: CONTROL BOARD'S BOTTOM LAYER.

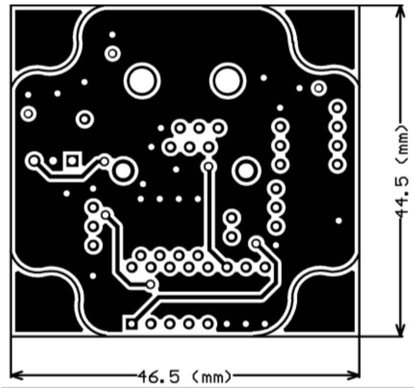


FIGURE 83: NEW SENSOR'S MAIN BOARD TOP LAYER.

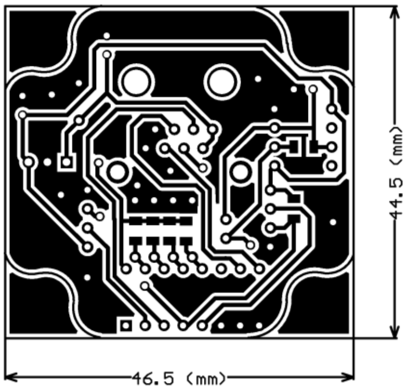


FIGURE 84: NEW SENSOR'S MAIN BOARD BOTTOM LAYER.

Symbol	Hit Count	Tool Size	Plated	Hole Type
□	70	0.8mm (31.496mil)	PTH	Round
○	3	1mm (39.37mil)	PTH	Round
☼	2	2mm (78.74mil)	PTH	Round
▽	2	3.25mm (127.953mil)	PTH	Round
	77 Total			

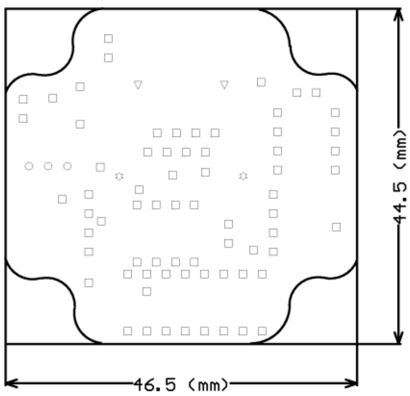


FIGURE 85: NEW SENSOR'S MAIN BOARD DRILL DRAWING LAYER.

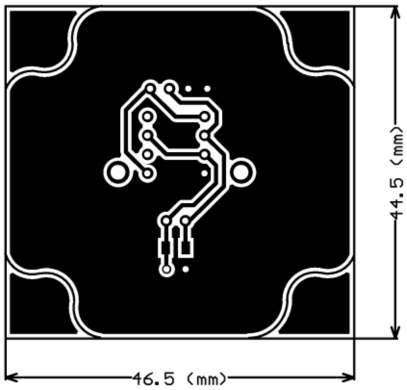


FIGURE 86: NEW SENSOR'S EXTENSION BOARD BOTTOM LAYER.

Symbol	Hit Count	Tool Size	Plated	Hole Type
□	16	0.8mm (31.496mil)	PTH	Round
○	2	2mm (78.74mil)	PTH	Round
	18 Total			

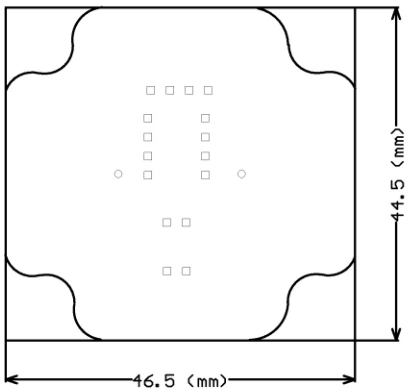


FIGURE 87: NEW SENSOR'S EXTENSION BOARD DRILL DRAWING LAYER.

APPENDIX C: SOFTWARE DESIGN

Microcontroller was programmed in C language, using PICkit 3 Programmer and MPLAB Integrated Development Environment ver. 8.66. Configuration Bits were set as follows:

Field	**Category**	**Setting**
FOSC	Oscillator Selection bits	HS oscillator
WDTE	Watchdog Timer Enable bit	WDT disabled
PWRTE	Power-up Timer Enable bit	PWRT disabled
BOREN	Brown-out Reset Enable bit	BOR disabled
LVP	Low-Voltage In-Circuit Serial	Programming RB3 is digital I/O, HV on MCLR must be used for programming
CPD	Data EEPROM Memory Code Protection bit	Data EEPROM code protection off
WRT	Flash Program Memory Write Enable bits	Write protection off; all program memory may be written to by EECON control
CP	Flash Program Memory Code Protection bit	Code protection off

Source code used to program PIC16f877A microcontroller occupy 72,4% of program space and 64,9% of data space and is presented below:

```
#include <htc.h>
#ifndef _XTAL_FREQ
   #define _XTAL_FREQ 20000000
#endif

//############################## GLOBAL VARIABLES ###############################//

bit leftPressed=0, rightPressed=0, leftHold=0, rightHold=0, leftHoldState=0, rightHoldState=0, leftLastState=0,
rightLastState=0;
int timer0=0, buttonCount=0, buttonTemp=100, leftHoldTemp=0, rightHoldTemp=0, freq=0, flash=0,
sensorID[8], relayID[8], relays[8];
float level[8], illuminationMax[8];

//########################### FUNCTION DECLARATIONS ###########################//

int absolute(int a);
void initiate();
void onDisplay(char number);
void notAvailable();
void buttonPressed();
void flashingDiodeOn(int diodeMode);
void flashingDiodeOff();
int getExID(int board);
```

```
int getSensorID(int sensor);
void setExRelay(int board, int on);
int getIllumination(int sensor);
void writeEEPROM(int address, int data);
int readEEPROM(int address);
void interrupt isr(void);

//################################## MAIN ##################################//

void main(void)
{
   int i=0, j=0, x=0, y=0, a=0, b=0, target=0, sector=0, exist=0, av=0;
   float exLevelMax=0, exLevelMin=0, illumination=0;
   initiate();                                  // Invoking initiating function
   while(1)                                     // Main program loop
   {
      for(i=0;i<8;i++)                          // For loop changing sensor boards
      {
         relayID[i]=getExID(i);                 // Getting extension boards ID
         buttonPressed();                       // Checking if button were pressed
         if(leftHold==1&&rightHold==1)
         {
            leftHold=0;
            rightHold=0;
            buttonCount=1;
            a=1;
            flashingDiodeOn(1);                 // Turning on yellow diode in slow flashing mode
            while(a)
            {
               buttonPressed();                 // Checking if button were pressed
               onDisplay(buttonCount);          // Displaying actual selected sector ID
               sector=buttonCount;
               if(buttonCount>15)
               buttonCount=15;
               else if(buttonCount<1)
               buttonCount=1;
               if(leftHold==1&&rightHold==1)
               {
                  exist=0;
                  leftHold=0;
                  rightHold=0;
                  b=1;
                  for(j=0;j<8;j++)              // Searching for extension with the same ID as sensor
                  {
                     if(sensorID[j]==sector)
                     {
                        exist=1;
                     }
                  }
                  if(exist==0)                  //If extension was not found, software start skip config
                  {
                     a=0;
                     b=0;
                     flashingDiodeOff();        // Turning off the flashing diode
                     for(av=0;av<30000;av++)
                     {
                        notAvailable();         // Displaying "—" sign
                     }
                  }
                  else
                  {
                     buttonCount=readEEPROM(sector);   // Restoring current preferred level from EEPROM
                     flashingDiodeOn(0);        // Turning on yellow diode in fast flashing mode
                  }
                  while(b)
                  {
```

```
                buttonPressed();                          // Checking if button were pressed
                onDisplay(buttonCount);                   // Displaying actual preferred lighting level
                if(leftHold==1&&rightHold==1)
                {
                   leftHold=0;
                   rightHold=0;
                   a=0;
                   b=0;
                   flashingDiodeOff();                    // Turning off the configuration diode
                   for(j=0;j<8;j++)
                   {
                      if(sensorID[j]==sector)
                      level[j]=buttonCount;
                   }
                   writeEEPROM(sector, buttonCount);      // Writing new settings into EEPROM
                }
             }
          }
       }
    }
    illumination=getIllumination(i);                      // Getting actual illumination from sensor "i"
    x=0;
    exist=0;
    for(j=0;j<8;j++)
    {
       if(sensorID[i]==relayID[j])
       x++;                                               // Counting extension boards, connected with sensor
    }
    exLevelMin=(((illuminationMax[i])*((level[i])/100))-(illuminationMax[i]/(x*8)));
    exLevelMax=(((illuminationMax[i])*((level[i])/100))+(illuminationMax[i]/(x*8)));
    if(illumination<exLevelMin)                           // Activities executed if illumination is too high
    {
       y=4;
       for(j=0;j<8;j++)
       {
          if(sensorID[i]==relayID[j])
          {
             if(relays[j]<=y)
             {
                y=relays[j];
                target=j;
             }
          exist=1;
          }
       }
       if((relays[target]<4)&&exist==1)
       {
          relays[target]++;
          setExRelay(target, relays[target]);
       }
    }
    if(illumination>exLevelMax)                           // Activities executed if illumination is too low
    {
       y=0;
       for(j=0;j<8;j++)
       {
          if(sensorID[i]==relayID[j])
          {
             if(relays[j]>=y)
             {
                y=relays[j];
                target=j;
             }
          exist=1;
          }
       }
```

```
            if((relays[target]>0)&&exist==1)
            {
               relays[target]--;
               setExRelay(target, relays[target]);
            }
         }
      }
   }
}

//##################################### ABS #####################################//

int absolute(int a)
{
   if(a<0)
   return a*(-1);
   else
   return a;
}

//#################################### DELAY ####################################//

int __delay_s(int s)
{
   for(int i=0; i<s;i++)
   __delay_ms(1000);
}

//#################################### INITIATE ##################################//

void initiate()
{
   int i=0;
   ADCON1=0b00000110;                          // Setting ADCON1 register and available ports
   TRISA=0b00111011;
   TRISB=0b00000001;
   TRISD=0b00000000;
   TRISE=0b00000000;
   PORTA=0b00000100;
   PORTB=0b00000000;
   PORTD=0b00000000;
   PORTE=0b00000000;
   for(i=0;i<8;i++)                            // Turning on all available lamps in order to measure
                                               maximum illumination levels
   setExRelay(i,4);
   __delay_s(60);                              // Waiting till lamps will get maximum performance
   for(i=0;i<8;i++)
   {
      sensorID[i]=getSensorID(i);              // Getting sensors ID
      illuminationMax[i]=getIllumination(i);   // Measuring maximum illumination for every sector
      relayID[i]=getExID(i);                   // Getting extension boards ID
      relays[i]=4;                             // Storing information that all lamps are turned on
      level[i]=readEEPROM(sensorID[i]);        // Reading desired illumination levels from EEPROM
      if(level[i]>99)                          // If there is no information about illumination levels
                                               in EEPROM, set maximum
      {
         writeEEPROM(sensorID[i], 99);
         level[i]=99;

      }
   }
}
```

```
//################################## DISPLAY  ###################################//

void onDisplay(char number)
{
   GIE=0;                                          // Disabling global interrupts
   char numbers[10]={0b11000000, 0b11111001, 0b10100100, 0b10110000, 0b10011001, 0b10010010,
   0b10000010, 0b11111000, 0b10000000, 0b10010000};
   RE0=1;                                          // Activation of decades 7 - segment LCD
   PORTD=numbers[number/10];                       // Sending number of decades
   RE0=0;                                          // Deactivation of decades 7 - segment LCD
   RE1=1;                                          // Activation of unities 7 - segment LCD
   PORTD=numbers[number%10];                       // Sending number of unities
   RE1=0;                                          // Deactivation of unities 7 - segment LCD
   GIE=1;                                          // Enabling global interrupts
}

void notAvailable()
{
   GIE=0;                                          // Disabling global interrupts
   RE0=1;                                          // Activation of decades 7 - segment LCD
   PORTD=0b10111111;                               // Sending number of decades
   __delay_us(10);
   RE0=0;                                          // Deactivation of decades 7 - segment LCD
   RE1=1;                                          // Activation of unities 7 - segment LCD
   PORTD=0b10111111;                               // Sending number of unities
   __delay_us(10);
   RE1=0;                                          // Deactivation of unities 7 - segment LCD
   GIE=1;                                          // Enabling global interrupts
}

//################################## BUTTONS #################################//

void buttonPressed()
{
   if(RA0==0||RA1==0)                              // Checking if one of the switches is pressed
   {
      GIE=1;                                       // Enable global interrupts
      OPTION_REG=0b0111;                           // Prescale Timer0 with 256
      T0CS=0;                                      // Select internal clock
      TMR0IE=1;                                    // Enable Timer0 interrupt
   }
}

//#################################### DIODE #################################//

void flashingDiodeOn(int diodeMode)
{
   flash=0;                                        // Clearing temp
   T2CON=0xff;                                     // Setting Timer2 options
   if(diodeMode)                                   // Checking if user wants diode flashing slowly or fast
   PR2=255;
   else
   PR2=50;
   TMR2IE=1;                                       // Enabling Timer2 interrupt
   PEIE=1;                                         // Enabling peripherals interrupt
   GIE=1;                                          // Enabling global interrupt
}

void flashingDiodeOff()
{
   TMR2ON=0;                                       // Disabling Timer2
   TMR2IE=0;                                       // Disabling Timer2 interrupt
   RA2=1;
}
```

```
//######################### READING EXTENSION BOARD ID  #########################//

int getExID(int board)
{
   GIE=0;                              // Disabling global interrupts
   TRISC=0b00001111;                   // Setting port bits as outputs and inputs
   TRISE2=0;                           // Setting Port E as output
   RC4=0;                              // Sending RD signal to extension boards
   RC7=board%2;                        // Selecting which extension board should be enabled
   RC6=(board/2)%2;
   RC5=(board/4)%2;
   RE2=1;                              // Enabling decoder and sending EN signal to one of
                                       extension boards
   __delay_us(5);
   int ID=(RC0+RC1*2+RC2*4+RC3*8);
   RE2=0;                              // Disabling decoder
   GIE=1;                              // Enabling global interrupts
   return ID;                          // Return extension board ID
}

//############################## READING SENSOR ID  ##############################//

int getSensorID(int sensor)
{
   GIE=0;                              // Disabling global interrupts
   int a=0, b=0, c=0, ID=0;            // Declaration of help variables
   RB3=(sensor/4)%2;                   // Selecting MUX input to read from specific board
   RB2=(sensor/2)%2;
   RB1=sensor%2;
   RB4=0;                              // Enabling MUX
   RB5=0;                              // Setting MUX address bits
   RB6=1;
   RB7=0;
   __delay_us(5);                      // Delay is needed for MUX to change its inputs
   a=RB0;
   RB5=1;
   RB6=0;
   RB7=0;
   __delay_us(5);
   b=RB0;
   RB5=0;
   RB6=0;
   RB7=0;
   __delay_us(5);
   c=RB0;
   RB5=1;
   RB6=1;
   RB7=0;
   __delay_us(5);
   ID=(a+(b*2)+(c*4)+(RB0*8));
   RA4=1;                              // Disabling MUX
   GIE=1;                              // Enabling global interrupts
   return ID;                          // Return sensor ID
}

//####################### SETTING EXTENSION BOARD RELAYS  #######################//

void setExRelay(int board, int on)
{
   GIE=0;                              // Disabling global interrupts
   TRISC=0b00000000;                   // Setting Port C bits as outputs
   TRISE2=0;                           // Setting Port E bit as output
   RC4=1;                              // Sending WR signal to extension boards
   RC7=board%2;                        // Selecting which extension board should be enabled
   RC6=(board/2)%2;
   RC5=(board/4)%2;
```

```
  RE2=1;                              // Sending EN signal to specific board
  if(on==0)                           // Checking how many relays should be turned on
  {
    RC0=0;
    RC1=0;
    RC2=0;
    RC3=0;
  }
  if(on==1)
  {
    RC0=0;
    RC1=1;
    RC2=0;
    RC3=0;
  }
  if(on==2)
  {
    RC0=1;
    RC1=1;
    RC2=0;
    RC3=0;
  }
  if(on==3)
  {
    RC0=1;
    RC1=1;
    RC2=0;
    RC3=1;
  }
  if(on==4)
  {
    RC0=1;
    RC1=1;
    RC2=1;
    RC3=1;
  }
  RE2=0;
  __delay_us(5);
  RE2=1;                              // Enabling decoder and sending EN signal to one of
                                      extension boards
  __delay_us(5);
  RE2=0;
  GIE=1;                              // Enabling global interrupts
}

//########################## READING ILLUMINATION LEVEL #########################//

int getIllumination(int sensor)
{
  GIE=0;                              // Disabling global interrupts
  int freq1=0, freq2=0, freq3=0;
  TRISB0=1;
  PEIE=1;                             // Enabling peripheral interrupts
  freq=0;                             // Clearing freq
  RB3=(sensor/4)%2;                   // Selecting MUX input to read from specific board
  RB2=(sensor/2)%2;
  RB1=sensor%2;
  RB4=0;                              // Enabling MUX
  TMR1IE=1;                           // Enabling Timer1 interrupts
  T1CON=0b00110000;                   // Setting Timer1
  INTEDG=1;                           // Selecting rising edge as INT interrupt trigger
  RB5=1;                              // Setting MUX address bits
  RB6=1;
  RB7=1;
  if(RB0==1)
  {
```

```
    RB5=0;                                  // Setting MUX address bits
    RB6=0;
    RB7=1;
    TMR1IE=1;                               // Enabling Timer1 interrupts
    TMR1ON=1;                               // Turning on Timer1
    INTE=1;                                 // Enabling INT interrupts
    GIE=1;                                  // Enabling global interrupts
    while(TMR1ON==1);                       // Waiting till previous measuring will get completed
    GIE=0;                                  // Disabling global interrupts
    freq1=freq;
    return freq1;
  }
  else
  {
    RB5=0;                                  // Setting MUX adress bits
    RB6=0;
    RB7=1;
    TMR1IE=1;                               // Enabling Timer1 interrupts
    TMR1ON=1;                               // Turning on Timer1
    INTE=1;                                 // Enabling INT interrupts
    GIE=1;                                  // Enabling global interrupts
    while(TMR1ON==1);                       // Waiting till previous measuring will get completed
    GIE=0;                                  // Disabling global interrupts
    freq1=freq;
    freq=0;
    RB5=1;                                  // Setting MUX adress bits
    RB6=0;
    RB7=1;
    TMR1IE=1;                               // Enabling Timer1 interrupts
    TMR1ON=1;                               // Turning on Timer1
    INTE=1;                                 // Enabling INT interrupts
    GIE=1;                                  // Enabling global interrupts
    while(TMR1ON==1);                       // Waiting till previous measuring will get completed
    GIE=0;                                  // Disabling global interrupts
    freq2=freq;
    freq=0;
    RB5=0;                                  // Setting MUX adress bits
    RB6=1;
    RB7=1;

    TMR1IE=1;                               // Enabling Timer1 interrupts
    TMR1ON=1;                               // Turning on Timer1
    INTE=1;                                 // Enabling INT interrupts
    GIE=1;                                  // Enabling global interrupts
    while(TMR1ON==1);                       // Waiting till previous measuring will get completed
    freq3=freq;
    RB4=1;                                  // Disabling MUX
    if((absolute(freq3-freq1)>absolute(freq2-freq1))&&(absolute(freq2-freq1)>absolute(freq3-freq2))
    ||(absolute(freq2-freq1)>absolute(freq3-freq1))&&(absolute(freq3-freq1)>absolute(freq3-freq2))
    ||(freq3==freq2==freq1)||(freq2==freq3)||freq1==0)// Rejecting most different freq value
    return (freq3+freq2)/2;                 // Returning average of two most similar freq values
    else if((absolute(freq3-freq2)>absolute(freq1-freq2))&&(absolute(freq1-freq2)>absolute(freq3-freq1))
    ||(absolute(freq2-freq1)>absolute(freq3-freq2))&&(absolute(freq3-freq2)>absolute(freq3-freq1))
    ||(freq3==freq2==freq1)||(freq1==freq3)||freq2==0)// Rejecting most different freq value
    return (freq3+freq1)/2;                 // Returning average of two most similar freq values
    else if((absolute(freq3-freq1)>absolute(freq3-freq2))&&(absolute(freq3-freq2)>absolute(freq2-freq1))
    ||(absolute(freq3-freq2)>absolute(freq3-freq1))&&(absolute(freq3-freq1)>absolute(freq2-freq1))
    ||(freq3==freq2==freq1)||(freq1==freq2)||freq3==0)// Rejecting most different freq value
    return (freq1+freq2)/2;                 // Returning average of two most similar freq values
    else
    return (freq1+freq2+freq3)/3;
  }
}
```

```
//################################## EEPROM ##################################//

void writeEEPROM(int address, int data)
{
  GIE=0;                                    // Disabling global interrupts
  while(WR==1);                             // Waiting until writing finished
  while(RD==1);                             // Waiting until reading finished
  EEADR=address;
  EEDATA=data;
  EEPGD=0;                                  // Clearing EEPGD bit
  WREN=1;                                   // Enabling write to EEPROM
  EECON2=0x55;                              // Required sequence
  EECON2=0xAA;
  WR=1;                                     // Writing to EEPROM memory
  GIE=1;                                    // Enabling global interrupts
  WREN=0;                                   // Disabling write to EEPROM
}

int readEEPROM(int address)
{
  GIE=0;                                    // Disabling global interrupts
  while(WR==1);                             // Waiting until writing is finished
  while(RD==1);                             // Waiting until reading is finished
  EEADR=address;                            // Setting address
  EECON1=0;                                 // Clearing CFGS and EEPGD bit
  RD=1;                                     // Enabling read from EEPROM
  GIE=1;                                    // Enabling global interrupts
  return EEDATA;                            // Returning data from EEPROM
}

//################################# INTERRUPTS #################################//

void interrupt isr(void)
{
  GIE=0;                                    // Disabling global interrupts
  if(INTF)                                  // Checking if INT interrupt flag is on
  {
    freq++;                                 // Incrementing freq variable
    INTF=0;                                 // Clearing INT interrupt flag
  }

  if(TMR1IF)
  {
    TMR1ON=0;                               // Turning off Timer1
    TMR1IF=0;                               // Clearing Timer1 interrupt flag
    TMR1IE=0;                               // Disabling Timer1 interrupts
    INTE=0;                                 // Disabling INT interrupts
    INTF=0;                                 // Clearing INT interrupt flag
  }

  if(TMR0IF)                                // Checking if Timer0 interrupt flag is on
  {
    timer0++;
    if(RA1==0&&leftHoldState==0)            // Checking if left button is pressed and if it was hold
                                            before
    {
      leftHoldTemp++;                       // Incrementing holdTemp
      if(leftHoldTemp==40)
      {
        leftHold=1;
        leftHoldState=1;
        leftHoldTemp=0;
      }
    }
    if(RA0==0&&rightHoldState==0)           // Checking if right button is pressed and if it was hold
                                            before
```

```
{
   rightHoldTemp++;                                   // Incementing holdTemp
   if(rightHoldTemp==40)
   {
      rightHold=1;
      rightHoldState=1;
      rightHoldTemp=0;
   }
}
if(RA0==0&&rightLastState==1&&rightHoldState==1)  // Checking if right button is pressed and if it was
                                                   pressed before
buttonTemp++;
if(RA1==0&&leftLastState==1&&leftHoldState==1)    // Checking if left button is pressed and if it was
                                                   pressed before
buttonTemp--;
if(buttonTemp==105)
{
   if(buttonCount<99)
   buttonCount++;
   buttonTemp=100;
}
if(buttonTemp==95)
{
   if(buttonCount>0)
   buttonCount--;
   buttonTemp=100;
}

if(timer0==7)
{
   timer0=0;
   if(RA0!=0||RA1!=0)
   {
      if(RA1==0&&leftLastState==0)                 // Checking if left button is pressed and if it was not
                                                   pressed before
      {
         leftPressed=1;
         leftLastState=1;
         if(buttonCount>0)
         {
            buttonCount--;
            buttonTemp=100;
         }
      }
      if(RA0==0&&rightLastState==0)                // Checking if right button is pressed and if it was
                                                   not pressed before
      {
         rightPressed=1;
         rightLastState=1;
         if(buttonCount<99)
         {
            buttonCount++;
            buttonTemp=100;
         }
      }
   }
}
if(RA0==1)                                         // Checking if right button is released
{
   rightPressed=0;
   rightLastState=0;
   rightHoldState=0;
   rightHoldTemp=0;
   rightHold=0;
   T0IE=0;
}
```

```
    if(RA1==1)                          // Checking if left button is released
    {
      leftPressed=0;
      leftLastState=0;
      leftHoldState=0;
      leftHoldTemp=0;
      leftHold=0;
      T0IE=0;                           // Disable Timer0 interrupt
    }
  T0IF=0;                               // Clear Timer0 interrupt flag
  }

  if(TMR2IF)                            // Checking if Timer2 interrupt flag is on
  {
    flash++;                            // Incrementing flash, which is used to slower
                                        interrupt appearance
    if(flash==50)                       // If flash equals 50 then toggle diode
    {
      RA2=!RA2;
      flash=0;
    }
    TMR2IF=0;                           // Clear Timer2 interrupt flag
  }
  GIE=1;                                // Enabling global interrupts
}
```