Development of a novel Intelligent Lighting Control system with Imaging Sensor for optimum daylight exploitation and energy saving (ILCIS)

1. Introduction

Harvesting daylight can be considered as a very important strategy to reduce artificial lighting consumption in buildings. Thus, the use of photosensors is significant and a chance for energy savings. The basic operation of a photosensor is the production of a unique signal that is related to the average amount of lighting in a space (in which it is placed), using its spatial and spectral response. This specific signal forces ballasts in luminaires to reduce the output power at the same level for all luminaries, while these should be regulated separately for an optimum operation. Namely, a conventional lighting control system does not have the capability of distinguishing the areas that are darker or brighter than the others inside the control zone. Thus, this system, among other problems, is unable to dim the light in the brighter areas and light up the darker one simultaneously. In other words, it is impossible for the system to avoid optical discomfort and consume less energy due to the exploitation of the daylight.

This research project proposes an innovative daylight responsive system with a CCD sensor instead of a photosensor in order to control optimally the light levels. The new CCD sensor would be able to capture and process images that include all or the most of the room space and calculate the photometric parameters in thousands of points in the room simultaneously. The proposed system will be developed in order to control luminaries individually and to be designed to work with the open source Digital Addressable Lighting Interface (DALI) protocol.

Main problems with current technology

Generally, while there are many case studies documenting energy benefits of lighting control with photosensors, building contractors are rather reluctant to install such systems, not only due to the increased cost but also due to their hypothetical unreliability in achieving predicted energy savings. The key component is the photosensor, whose behavior defines the whole system's efficiency when it is placed on the ceiling. A stand-alone photosensor placed on the ceiling corresponds to the incident radiation on the ceiling (for one point only) and converts this radiation to a proportional control signal (according to the illuminance values on the ceiling) for all the luminaries on the control zone. Furthermore, the ratio of ceiling/workplace illuminance is not constant because of the variation of the light distribution caused mainly by changes in the amount of daylight entering the room. Thus, it is difficult for a photosensor placed at a specific point on the ceiling to track illuminance chances for all the area it controls. As a result, the control of the light level on multiple working planes is complicated.

In some cases, the control of the lighting fixtures is actualized with multiple photosensors. Installations with multiple photosensors have not been examined at all by scientists. There is a lack of operational equations of photosensor control algorithms and their commissioning procedure that are necessary for the proper function of a daylight responsive system. As a result, their function hasn't been tested and their performance is unreliable. Thus, the efficiency of the responsive daylight systems in real case studies, using multiple photosensors placed on the ceiling for each luminaire, differs considerably from hypothetical cases when a sensor controls each luminaire separately. Actual energy savings are lower than the calculated ones and the performance according to designed light levels and visual comfort is poor.

Furthermore, the spectral response of photosensors is wider than what the human eye sees. Thus, UV and IR filters are fitted in front of photodiodes, but in most cases their response is still wider than the photopic human eye sensitivity $V(\lambda)$. As a result, photosensors perceive a greater quantity of light than the human eye can see and artificial lighting is erroneously dimmed creating visual discomfort.

The proposed solution

This research proposes the development of a new lighting control system based on a digital CCD imaging sensor and intelligent control algorithms. The proposed research aims to: a) the minimization of the limitations of the conventional technology of photosensors, b) the development of a reliable system that uses new control algorithms based on image processing technics.

A brief description of the workflow of the proposed system can be summarized in the following basic steps:

- The new sensor is placed anywhere on the ceiling and aims to the control zone. The CCD sensor captures images of the room with a wide field of view (as wider as possible). The captured images are converted to real luminance images using image-processing routines. The light level on one or more parts of the room is calculated and compared to the desired levels (set-points).
- The new control algorithm will calculate the proper conversions of the CCD output regarding its position. An algorithm will also correct illuminance values taking into account daylight and artificial light spectra and a model that calculates the proper function of a photosensor with respect to the adequacy of light and users' behavior.
- The corresponding light levels on one or more surfaces of the room will be calculated from the new operational equations and from the illuminance values according to the desired light levels. The illuminance values will be calculated from the luminance maps. The installed luminaires (that will use DALI EDBs) will be dimmed individually at the appropriate light level through a multi-signal output.

As a result, the new system will be able to control the light levels properly and create comfort lighting conditions and visual comfort for all users of the room.

It should be pointed out that there are very few publications on the application of photosensors with CCD camera for lighting control in the international bibliography.

2. State of the art

Conventional daylight responsive control systems

Nowadays, exploitation of daylight is mainly achieved by using conventional photosensors (based on photodiodes) placed on the ceiling. The photosensor detects luminous flux and converts it to a signal sent to the controller, which, on its turn, processes this signal and defines the desired dimming level. Because of the fact that the estimation of energy savings depends on the illumination values on the working plane, while the photosensor is placed on the ceiling, the convergence between the calculated energy savings and the real one is not satisfactory.

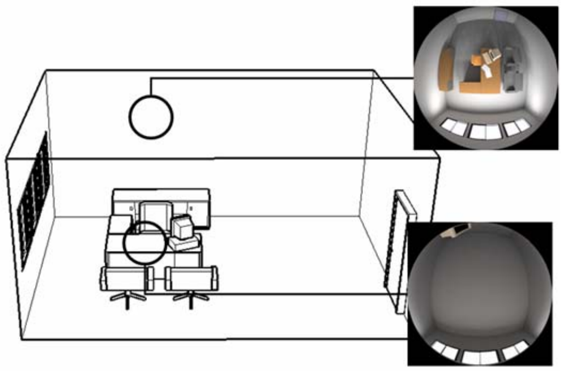

Fig 1. - The estimation of energy savings depends on the illumination values on the working plane while the photosensor is placed on the ceiling.

Most of problems are caused mainly by the way that conventional photosensors control the luminaries. A variety of controllers, software, sensors and devices are currently available, but there is a lack of information concerning the actual performance of these systems and their commissioning procedure. In order to fully exploit their capabilities and implement the most energy efficient control strategies, simulation software, reliable data from these components measured or provided from the manufacturers, official directives and guidelines are needed.

Many case studies have documented energy savings by exploiting daylight [1-3]. However, their object concerns the necessity of use of these systems. Neither the development of photosensors involving new technologies nor the choice of more efficient components have received the appropriate concern. Furthermore, for an optimum planning of a daylight responsive system are required both the selection of the most energy efficient components and accurate computations of daylight distribution and the position of the photosensor [4]. This on its turn will affect the commissioning procedures. [5].

Ignoring the spectral sensitivity of the photosensor in a daylight responsive system results to differences between the calculated energy savings. The broader spectral response of most commercial photosensors makes them respond differently from a photosensor with the CIE photopic luminous efficiency function

V(λ). Necessary developments regarding the spectral response of the photosensors must be done, such as optimizing an algorithm for the compensation of the spectral response of the photosensor for spectrally different light sources.

In addition, the field of view regarding the position of the sensor is a significant factor for the photosensor commissioning and its proper function. Changing only the position and the spatial response of the photosensor, great differences are observed in the energy savings and in the adequacy of light for the same room.

Last but not least, many problems are created with shadings. The existence of solar traces or reflections of the solar radiation on the sensor affects considerably the control of luminaries. Manufacturers of photosensors adopt special blinds for the sensors modifying their performance in their effort to solve this specific problem.

According to the above, development of a sensor using new technologies is necessary.

References

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Present level of knowledge for embodying new technologies

Recently, there has been an effort to embody new technologies by developing photosensors using CCD cameras or CMOS image sensors instead of photodiodes [6-9]. These sensors are quite promising, in the sense that they can measure luminance patterns [10] same as the human visual system and that they can replace multiple sensor systems. However, their capabilities are still rather limited. There are errors associated with the estimation of luminance from a scene image when deriving illuminance from luminance and during the calibration procedure and commissioning [7]. Except for these, their increased cost and size can create practical limitations during the installation. A conventional photosensor using a simple constant set point control algorithm (integral reset algorithm) can perform equally well with a CMOS sensor [9].

References

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Innovation of the project

The proposed research will exploit the up-to-date and innovative development in the field of CCD sensors. It is worth mentioning that there is not yet a commercial CCD sensor for the purpose of the project. Therefore, the sensor must be developed from an early stage. Namely, the full CCD photosensor must be built up from the beginning. After a thorough search of the market, a set of CCD sensors that meets the technical requirements of the project will be chosen. This kind of sensors is not incorporated in commercial cameras but is used in inquiring applications that develop new products. Practically the sensor will be acquired in a primitive stage along with the corresponding basic software. The extent of the development and tuning of a) the sensor and b) the application software depends on the user. In this case, the sensor will be assembled with suitable lens and V(λ) filters in order to correspond to the human visual system. The final product will be an outcome of procedures that involve research and measurements in the laboratory. Since any CCD photosensor does not exist in the market, the proposed one could be characterized as prototype. This gives an added value to the research, because it could be applied to real installations of lighting controls as an innovative component.

The image processing, in order to calculate the intensity of light in every pixel of the captured picture, will require original inquiring effort. The final result will be really innovating, because it will embody CCD sensors with state-of-the-art image processing in lighting control systems for daylight harvesting. For the control of the sensor an advanced controller (built up from an early stage for the purposes of the project like the CCD) will be used and the appropriate software and algorithm will be developed. This kind of research has been found in very few cases in the international bibliography but without development either of the image processing or of the controller.

As a result, the whole system will use prototype components, from the CCD sensor and the controller to the software (image processing and control algorithms). The combination of all the above-mentioned components creates an original and innovative final product (the final system) that can be used straightforward for the control of artificial lighting. The precise exploitation of daylight with the innovative system will result in a better energy saving, an optical comfort for the users and an unerring function of the dimming.

The main idea of the proposed research is original not only for the European region but also worldwide. As mentioned above, there is a lack of publications in international bibliography concerning similar research. This can be verified by the abundance of installations of control systems with conventional photosensors worldwide without anyone among them being based on sensors with CCD camera. An extensive search in the catalogues of the relative manufacturers will confirm the non-existence of this technology of lighting control.

3. Objectives

The main objective of this project is to help overcome the obstacles to the wide spread of the photosensors, offering a really simple but intelligent system. Furthermore, important objectives of the project are:

- The development of the new photosensor based on a calibrated CCD sensor.
- The setup of the experimental procedure for the calibration of the CCD photosensor.
- The development of the algorithm for the determination of the room luminance and the calculation of the illuminance map
- The development of the algorithm for the control of the lighting output of the individual luminaires
- The development of the system aiming to control the luminous flux of the individual luminaires of the artificial lighting system
- The comparison of the new system with a conventional one in real conditions.

The innovative CCD photosensor with the corresponding control system and commissioning procedure can be implemented into areas with high levels of daylight (offices, schools and non-residential buildings that are used mainly during daytime). The use of the innovative system can overthrow the obstacles to the poor performance of the conventional systems.

4. Research Methodology

WP1: Project coordination

WP2: Data collection of the existing technology on CCD photometry and lighting control algorithms.

The second WP of the proposed project will be an extensive investigation of problems created in rooms where a lighting control system with photosensors is installed. In addition, all the technical characteristics of a daylight responsive system (photosensors, controllers and electronic dimmable ballasts) will be recorded and analyzed.

More analytically, the first step of this WP is the survey of innovative systems that exploit daylight, using publications from international bibliography. This will direct the research to present concrete results. Afterwards, there will be an investigation of problems created in areas where a lighting control system with photosensors is installed. Information about the proper function of these systems will be gathered after an investigation in buildings in Greece. Details will be extracted through visits to selected buildings, after asking for the opinion of the users, along with the help of proper questionnaires. The content of these reports will reveal the problems that are associated with the use of photosensors in lighting control systems.

Leading companies associated with lighting control and photosensors will support the research with technical characteristics of the individual components that will imply a complete system. Photosensors and EDBs are widely used in many systems and their characteristics are well known.

Next step prior to the development of the system is the investigation of all parameters that influence its operation (user behaviour, spectral response of photosensor and spectral distribution of daylight and artificial lighting, operational equations for multiple photosensors, control strategy and communication of photosensor with lighting fixtures).

WP3: Development and calibration of a CCD sensor for photopic lighting measurements including luminance, illuminance and colour calibrations.

This workpackage includes all the laboratory/experimental work towards the development of the new CCD photosensor. Current standards define the desired lighting levels in a room, expressed in illuminance values (lux). The proposed photosensor will be calibrated in order to measure luminance values and then transform them to illuminance values with the highest possible accuracy in any conditions wherever it is placed. In addition, a colour version of CCDs will be calibrated in order to measure, as accurately as possible, the colours of scene objects. Moreover, the WP3 includes the experimental measurements of the operation and communication characteristics of the ballasts that use the DALI protocol. Following is a brief analysis of the designed work.

CCD sensors facts

CCD sensors (*Fig. 1a*) are widely used in many systems (e.g. digital cameras, camcorders, industrial machine vision, microscopy, spectroscopoy, etc) and their characteristics are well known. The pixels their images consist of are stimulated by light and produce a digital image. The final image is actually an array of corresponding saturation values of each pixel (*Fig. 1b)*.

(a) (b)

Fig. 1 – A typical CCD sensor. (a) and its output (b)

The spectral response of CCD is wider than the visible light (*Fig. 2*). Thus, UV and IR filters are fitted in front of CCD arrays in most cases.

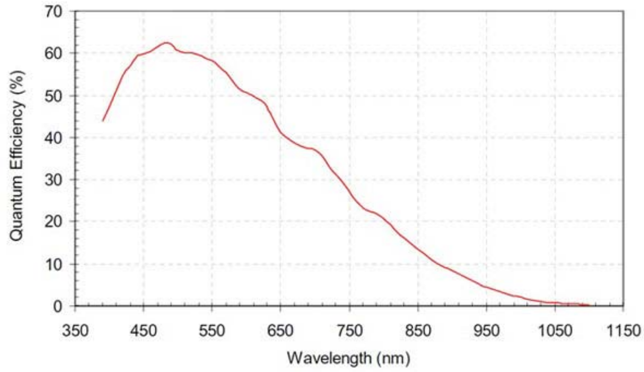


Fig. 2 – Typical CCD spectral response.

In case of a colour version of a CCD, a mask (filter) is placed in front of pixels filtering the light by primary colours (RGB). In most cases, the filter is the Bayer filter (Fig. 3). In this case, the output image is actually a set of three arrays, one for each colour. Figure 4 shows an example of colour CCD output and its spectral response curves.

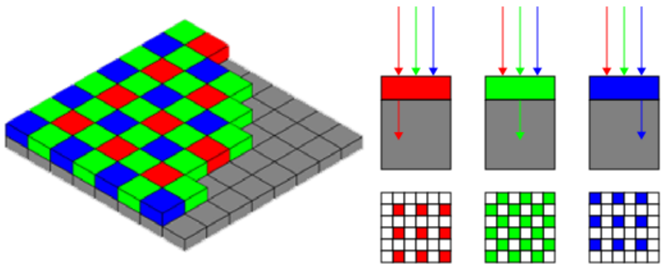


Fig. 3 – The Bayer filter of colour CCD sensors.

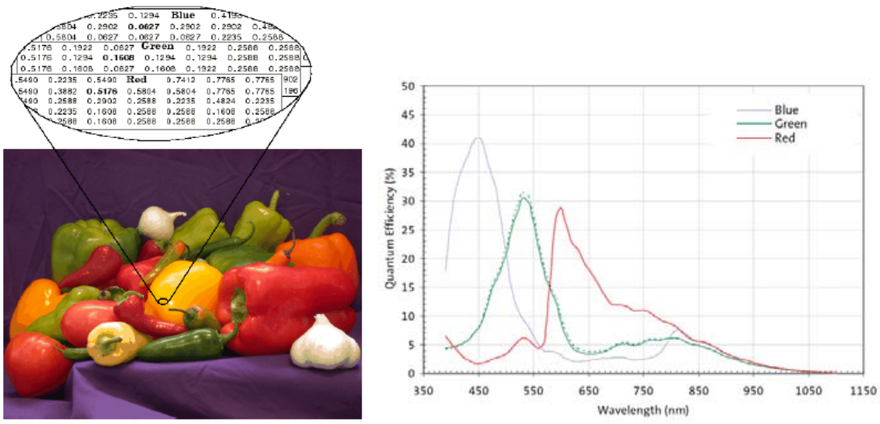


Fig. 4 – Example of the output of a colour CCD sensor and sensor's spectral response.

Photometric units (luminance, illuminance, luminous flux etc.) are based on human vision and thus on the spectral response of the human eye. For this reason, the proposed sensor will be equipped with a CIE V(λ) photopic filter (*Fig. 5*) which simulates the spectral response of the human eye.

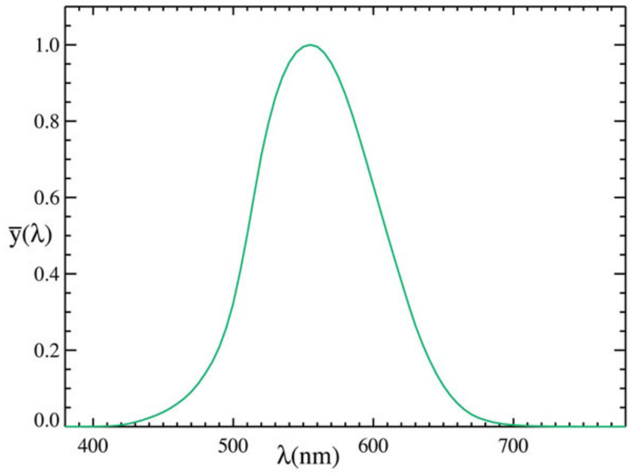


Fig. 5 – Spectral sensitivity on human eye - V(λ) photopic filter.

Photometric calibration of CCD

The first objective of this WP is to develop the calibration set-ups and the corresponding procedures in order to make the CCD sensor function as an imaging luminance and an illuminance meter. Both monochrome and colour CCD models will be tested. Three experimental set-ups are designed to be used for the calibration procedure.

The first one (*Fig. 6*) will be used for two reasons. Firstly, for the calculation and the elimination of the CCD lens' peripheral brightness reduction effect (vignetting). An example of vignetting calculation is presented in Figure 7. Secondly, it will be used in a series of measurements in order to calculate the dynamic range of the sensor, which in other words is the range of light levels that the sensor can capture at the same time in one single shot (image). This measurement will clarify the possible need to use multiply image merge (High Dynamic Range, HDR) in order to measure more light levels in a room. The main instrument of this set-up will be a uniform luminance source with the capability to obtain a wide range of luminance levels in its output port.

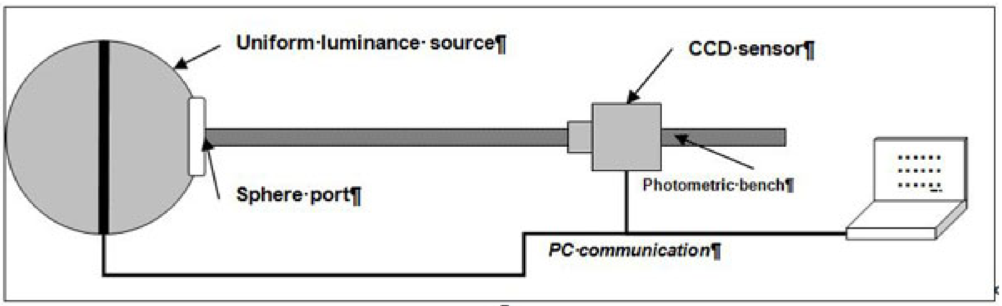
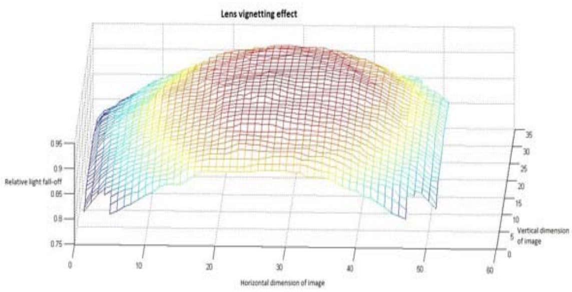


Fig. 6 – Proposed experimental set-up (No1)



A second set-up (*Fig. 7*) will be used to obtain the colour response of the CCD, using, among others, a monochromator and various standard light sources. With a series of measurements, an accurate spectral response will be calculated for both colour and monochrome CCD sensors.

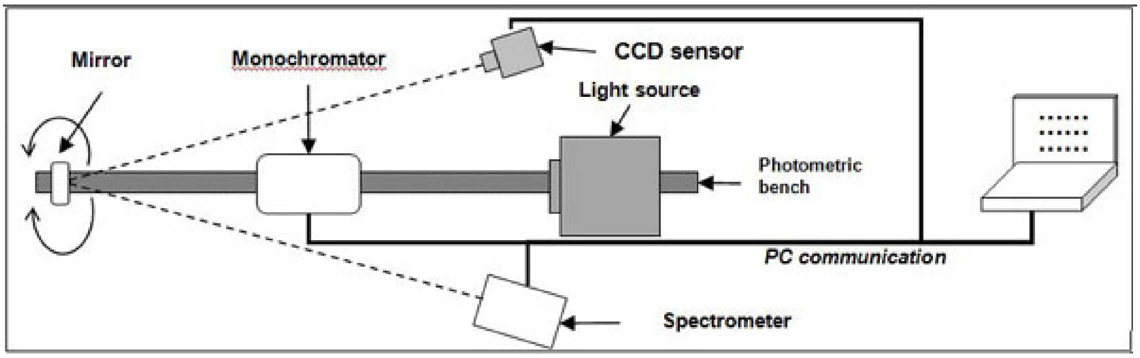


Fig. 7 – Proposed experimental set-up (No2)

The third proposed set-up (*Fig. 8*) will be used in order to test the accuracy of CCD measurements and to calculate correction factors, using chromatic targets of common materials and various light sources. These experimental procedures constitute one of the most critical tasks of the whole research project. In this way, the proposed CCD sensor would have the capability to measure and calculate illuminance values and lighting levels in a room, minimizing the error caused by the variety of materials and colours of room's elements.

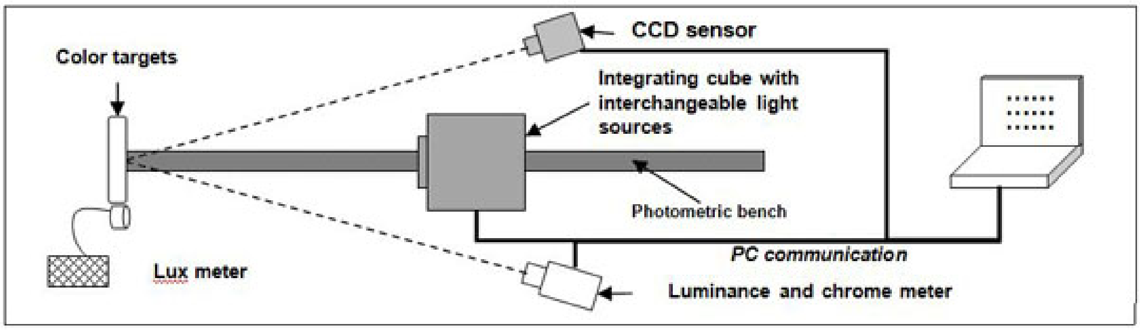


Fig. 8 – Proposed experimental set-up (No3)

The above described set-ups and calibration procedures will be standardized in order to be applied on any type/manufacturer of CCD photosensors and will be one of the main outcomes of this WP.

Figure 9 represents the way the proposed CCD sensor will operate after the completion of the calibration procedures. The real scene will be captured by the CCD sensor through an imaging lens and the V(λ) filter. Then, some imaging processing routines will apply all the necessary transformations and calculations in order to produce the final image of photometric quantities.

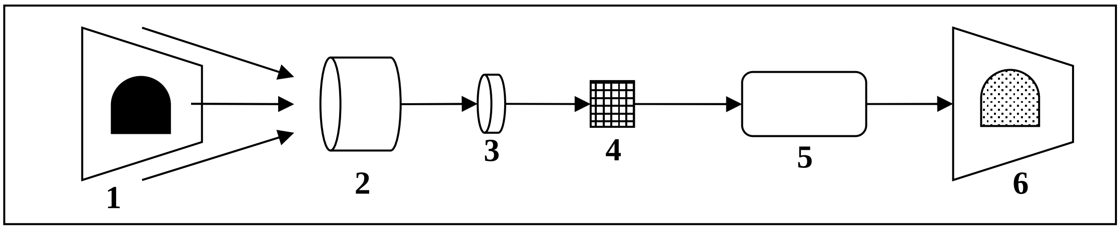


Fig. 9 – Overview of the operation of the proposed CCD sensor. 1) real scene, 2) imaging lens, 3) photopic filter V(λ), 4) CCD array, 5) image processing routines and 6)final image of photometric quantities

Deliverables

- Report on the procedures and the results for the calibration of CCD sensors.
- Report on the characteristics and profiles of the DALI type electronic ballasts
- Report on the design developments of the experimental apparatuses for the calibrations of the CCD sensors and the measurements of ballast characteristics
- Three (3) publications in scientific journals and conference proceedings.

WP4: Development of a new control algorithm for artificial lighting based on CCD sensor output.

The communication of the CCD photosensor with the lighting fixtures is important. Thus, a new algorithm will be produced using Digital Addressable Lighting Interface (DALI) protocol. This algorithm will recognize each lighting fixture individually. Therefore, different dimming levels in the same space will be achieved regarding the lighting needs. The appropriate components will be constructed so that the CCD sensor can communicate with the lighting system.

Current standards define the desired lighting levels in a room, which are expressed in illuminance values (lux). As mentioned above, the CCD sensor will be calibrated to measure luminance values (candela per square meter) with the highest possible accuracy in any conditions. As luminance values depend on the direction of the view, a set of algorithms will be developed in order to calculate the lighting level of any area of the room using the captured image. During the research, images will be examined and captured by both colour and monochrome CCD sensors. This will be based on the reflection characteristics of common materials, their colour characteristics as well as other image processing techniques.

A research milestone will also be the development of techniques to control each luminaire individually, in different dimming levels (if it is necessary) based on the results of a single image capture. This will be equal to a group of conventional sensors, each one aiming at a different section of the room and controlling a single luminaire. As the CCD sensor's field of view will cover areas of interest, the control system algorithm will segment the image in the pre-set parts, calculate the lighting level on each one and send the appropriate control signals (through DALI protocol) only to luminaires that must be dimmed.

WP5: Implementation of the proposed system.

This WP will constitute evolution of WP3 and WP5 and will start after their completion. This WP includes all the necessary procedures for the implementation and laboratory test of the proposed system. The main steps of the work package will be:

- Implementation of the development CCD sensor and its controller with a DALI compatible output.
- Implementation of the developed algorithm in the appropriate source code.
- Demo set-up and programming of the system and initial tests in the laboratory environment.

More analytically, the proposed CCD sensor will be implemented, based on the results of WP3. Depending on the same results, a set of different CCD sensors will be tested. Additionally, a controller will be designed and implemented in order to host and run the algorithm for image processing and luminaires control. The controller must be a standalone one (e.g. DSP), in order to be able to function independently from a computer or other supporting device. As a side task the control system will be able to be modified so that it can control DC lighting loads with the purpose to also control modern LED luminaires.

In parallel with the sensor implementation, the control software code will be implemented. The code will be written in the appropriate programming language (C++, Matlab or other). This code will include all the routines for the operation of the complete system which are the following: a) transformation equations for the calculation of photometric quantities, b) algorithms for the calculation of the lighting levels in the sub-regions of the room, c) decision procedures for modifications of luminaires dimming levels and d) final control signals for each luminaire in the room. In other words, this code will actually act as the operation system of the proposed intelligent lighting control system.

The outcome of this WP will be a complete system consisting of the CCD sensor, the controller and the operation system. The system will be ready for installation in an existing lighting system with DALI ballasts.

WP6: Test and fine-tuning of the proposed system in real conditions and side-by-side comparison with a conventional system.

This WP will be the actual benchmark for the developed system. The evaluation of the system and the feedback for further development, commissioning and fine-tuning will be the consequence of a "real life" test and of a comparison with a conventional one. There is planned a setup of two identical rooms (e.g. two common offices) and an implemention of the developed system in the first room and a conventional system in the second one. The test rooms will have the same dimensions, furniture setup and orientation. The conventional system will be one of the most efficient systems of the market. This test will be run for several moths in order to offer safe results. A measuring system will measure and log all the working parameters of the two systems, as well as the corresponding environmental data.

In predefined time intervals, the proposed system will be evaluated and will be fine-tuned if necessary. The test rooms will be real rooms with common users that will voluntarily participate in the tests. The final evaluation of the test results will be done after the end of the test period and is expected to confirm the research concepts.

WP7: Dissemination of research results.

The last WP will be the promotion of the research progress and results. From the first days of the research project, a website will be designed and launched as the information centre of the project. The role of the website will be double. Firstly, it will host all the announcements about the progress of the research and the deliverables of the project that will be open to public. Secondly, it will be a communication and collaboration centre for the research teams located in four different regions of Greece and in two countries abroad (taking into account the invited researchers from UK and Serbia).

Also, this will be the final stage for the preparation of publications and the participation in conferences. Furthermore, a guide, such as a booklet for commissioning of any kind of CCD photosensors, will be prepared, gathering the final results of the proposed research.

According to all the above, the main expected results of this particular WP are:

- Creation of a webpage presenting the research results.
- A guide for commissioning CCD photosensors as a booklet.
- Briefing and updating institutes and constitutions for the benefits derived from the research.
- A total number of fifteen publications (5 publications in international scientific journals and 10 publications in international conference proceedings).

5. Outcomes

According to the above-described workpackages the main expected results of the research are:

- Reports describing:
    - The current technology for harvesting daylight with CCD photosensors, the problems created by lighting control systems using conventional photosensors and the advantages of using a new photosensor with CCD camera (WP2).
    - Procedure, analysis and experimental results of the calibration of the CCD photosensor and the technical characteristics of the corresponding DALI ballasts (WP3).
    - Control algorithm of the CCD photosensor (WP4).
- Construction of:
    - The new CCD photosensor system.
    - Development of its corresponding control algorithm code (WP5).
- Testing of the CCD photosensor, its control algorithm and the whole system in real time conditions (WP6).
- Creation of a webpage presenting the research results (WP7).
- Briefing and updating institutes and constitutions for the benefits derived from the research (WP7).
- A total number of 15 publications.

6. Further research

The research results are expected to be a reference for the next research projects and a motivation for lighting designers for the implementation of the new technology. A successful completion of the research will lead to a complete new system. During the development of each subsystem (CCD sensor, control system, image processing algorithms etc) some additional research benefits are expected.

The technical knowledge from CCD calibration procedures and the experimental set-ups will be used on similar research activities concerning CCD sensors on other applications. A calibrated CCD sensor can be used as a general standalone imaging luminance meter beyond measurement of room lighting.

Another parallel finding that could arise during the research is the knowledge for the optimal position of the CCD sensor on a room. The sensor will be tested on a variety of positions in the room and with more than one field of view.

The implementation of the control algorithm based on the DALI protocol will lead to the development of an image-based lighting control platform. Such a platform does not exist and will be the base for the the development of control systems with imaging sensors in the future.

7. Conclusions - Summary

The aim of this project is the development of an automated lighting control system exploiting daylight with the use of a new CCD photosensor. Significant energy saving is expected within the installed lighting system in various types of buildings.

The expected results of the project are:

- Development of a new photosensor based on a calibrated CCD sensor.
- Setup of the experimental procedure for the calibration of the CCD photosensor.
- Development of the algorithm for the determination of the room luminance and the calculation of the illuminance map
- Development of the algorithm for the control of the lighting output of the individual luminaires
- Development of the control system for controlling the luminous flux of the individual luminaires of the artificial lighting system
- Comparison of the new system with a conventional one in real conditions.

The innovative CCD photosensor with the corresponding control system and the commissioning procedure can be implemented in areas with high levels of daylight (offices, schools and non-residential buildings that are used mainly during daytime). Thanks to the innovative system, the obstacles of the poor performance of the conventional systems will be overthrown. Thus, additional energy saving will be achieved, ensuring the proper function of the system (avoiding low lighting levels and glare) with an immediate profit for the consumers, the energy production, the transmission system and the environment (less pollutants). The significant energy saving will lead to a short pay-back period of the investment, giving a great promotion tool for its use.