EVALUATION OF IMAGE SENSORS FOR LIGHTING CONTROL APPLICATIONS

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ABSTRACT

Image sensors (CCD and CMOS) are considered as a promising technology for lighting control applications. Aim of this paper is the ranking of different commercial models of CCD and CMOS sensors in order to use them in the more efficient way and to maximize the energy saving in lighting control systems. The contribution of the image sensors in lighting control applications to reduce the energy consumption is also investigated. A method based on multicriteria analysis is used for the evaluation and the selection of the most appropriate sensor for the specific application. According to the method (Promethee II), a consistent set of criteria comprised of the selected features is specified for each alternative sensor selection (commercial model). A specific weight for each criterion is determined. A transfer function is applied (to each criterion) and the preference and indifference thresholds are found. The next steps are the calculation of the preference index and the calculations of outgoing and incoming flows for each alternative. The final step is the ranking of the alternatives by a total preorder through the calculation of the net flows.

Keywords: Image sensors, Lighting control, Daylighting, Energy saving, Promethee II

1. LIGHTING CONTROL AND IMAGE SENSORS

1.1. Lighting control with image sensors

A promising application of image sensors is the determination of the daylight level inside a room (figure 1). The sensor is placed anywhere on the ceiling and aims to the control zone. It captures images of the room with a wide field of view (the widest possible).

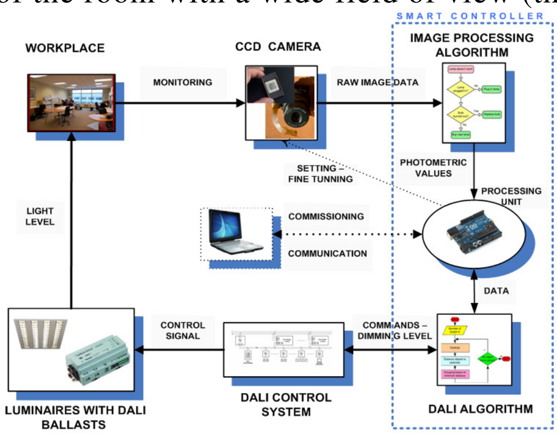


Figure 1 – Block diagram of a lighting control system with image sensor

The captured images are converted to real luminance images using image-processing routines. The corresponding light levels (illuminance) on the surfaces of the room are calculated by the luminance maps using light emitting models. The light levels on one or more parts of the room are calculated and compared to the desired levels (set-points). The installed luminaires are 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.

1.2. Image sensors technical specifications

Charge-Coupled Device (CCD) and Complementary Metal Oxide Semiconductor (CMOS) are two image sensor technologies that used to capture images and to digitalize them. Both of them convert light into electric charge and via a specific process into electric signal.

Figure 2 – Image sensor and image camera

Each one of the imagers has unique advantages and disadvantages that make them appropriate or not for specific applications. The advantages of the CCDs are lower noise, smaller pixel size, lower dark current, 100% fill factor, higher sensitivity and electronic shutter without artifacts. On the other hand the advantages of the CMOS are lower power consumption, single power supply, higher integration capability, lower cost, single master clock and random access. There are some technical specifications of the image sensors that are associated with specific commercial models of the sensors and not with the overall technology of them such as resolution, frame rate, effective dynamics, saturation, exposure time, gain, power consumption, dark current, noise etc.

Six commercial models of image sensors have been selected, namely three CCD and three CMOS. Their technical specifications are presented in Table 1. Number of active pixels is the number of the sensor pixel that is sensitive to light. The fill factor is the percentage of each pixel that is sensitive to light. Quantum efficiency is the measure of the efficiency with which incident photons are detected. Well capacity is the capacity of the well in which the electrons are collected. It is the resistance of the sensor in blooming. Blooming is an effect that occurs when, during the integration period, a potential well becomes full of electrons; this is usually caused by the presence of a bright object in the scene being imaged. When a potential well overflows, the electrons flow into surrounding potential wells, thus creating an area of saturated pixels.

Table 1 – Image sensors technical specifications

	Active pixels	Fill factor	Quantum eff.	Well capacity	Dynamic range	Dark current	Readout noise	Power cons.
	Mp	%	%	e^-	db	e/s	e^-	W
CCD 1	1.4	100	62	16000	68.5	0.05	6	20
CCD 2	4.2	100	55	40000	76.5	0.5	7	21
CCD 3	1.4	100	62	18000	69.5	0.05	7.5	12
CMOS 4	1.3	40	26	63000	59	70	70	0.35
CMOS 5	2.2	42	62	13500	60	125	13	0.6
CMOS 6	1.3	40	53	13700	64	21	30	0.2

Dynamic range refers to the ratio of the pixel's saturation level to its signal threshold. Dark current (noise) can be defined as the unwanted charge that accumulates in the sensor pixels due to natural thermal processes that occur while the device operates at temperatures above absolute zero. The readout noise is the noise of the on-chip amplifier which converts the charge into a change in analogue voltage. Finally, power consumption is the necessary power that the sensor requires in order to function.

2. MULTICRITERIA ANALYSIS

The PROMETHEE methods were designed to treat multicriteria problems and their associated evaluation table. The additional information requested to run PROMETHEE is particularly clear and understandable by both the analysts and the decision-makers. It consists of information between the criteria and information within each criterion.

Weights represent relative importance within the criteria. These weights are non-negative numbers, independent from the measurement units of the criteria. The higher the weight, the more important the criterion. There is no objection to consider normed weights, so that $\sum_{j=1}^{k} w_j = 1$. Assessing weights to the criteria is not straightforward. It involves the priorities and perceptions of the decision-maker. The selection of the weights is his space of freedom.

The preference structure of PROMETHEE is based on pair wise comparisons. In this case the deviation between the evaluations of two alternatives on a particular criterion is considered. For small deviations, the decision-maker will allocate a small preference to the best alternative and even possibly no preference if he considers that this deviation is negligible. The larger the deviation, the larger the preference. There is no objection to consider that these preferences are real numbers varying between 0 and 1. This means that for each criterion the decision-maker has in mind a function:

$P_j(\alpha,b)=F_j[dj(\alpha,b)]\ \forall a,b \in A$ where,

$d_j(\alpha,b)=g_j(\alpha)-g_j(b)$ and for which $0 \leq P_j(\alpha,b) \leq 1$.

In case of a criterion to be maximised, this function is giving the preference of α over b for observed deviations between their evaluations on criterion $g_j()$.The preferences equals 0 when the deviations are negative. The following property holds: $P_j(\alpha,b)>0 \rightarrow P_j(b,\alpha)=0$.

For criteria to be minimised, the preference function should be reversed or alternatively given by: $P_j(\alpha,b)=F_j\ [-d_j(\alpha,b)]$

The pair $\{g_j(.), P_j(\alpha,b)\}$ is called the generalised criterion associated to criterion $g_j(.)$. Such a generalised criterion has to be defined for each criterion. In order to facilitate the identification, six types of particular preference functions have been proposed (see Table 2). In each case 0, 1 or 2 parameters have to be defined, their significance is clear, q is a threshold or indifference, p is a threshold of strict preference and s is an intermediate value between p and q.

The indifference threshold is the largest deviation which is considered as negligible by the decision maker, while the preference threshold is the smallest deviation which is considered as sufficient to generate a full preference. The identification of a generalised criterion is then limited to the selection of the appropriate parameters.

PROMETHEE II consists of the (P^{II},I^{II}) complete ranking. It is often the case that the decision-maker requests a complete ranking. The net outranking flow can then be considered: $\varphi(\alpha)=\varphi^{+}(\alpha)-\varphi^{-}(\alpha)$

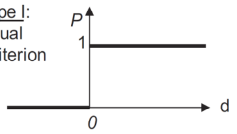
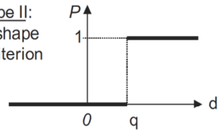
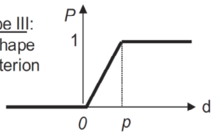
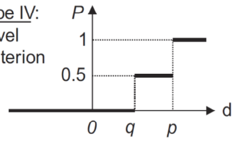
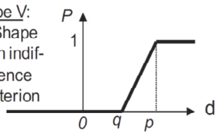
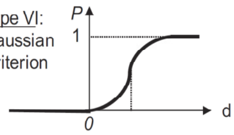
It is the balance between the positive and the negative outranking flows. The higher the net flow, the better the alternative, so that:

$$\alpha\ P^{II} b \text{ iff } \varphi(\alpha)>\varphi(b),\ \alpha\ I^{II} b \text{ iff } \varphi(\alpha)=\varphi(b)$$

When PROMETHEE II is considered, all the alternatives are comparable. No incomparabilities remain, but the resulting information can be more disputable because more information gets lost by considering the difference of φ(α).

The following properties hold: $-1 \leq \varphi(\alpha) \leq 1$, $\sum_{\chi \in A} \varphi(\alpha) = 0$

Table 2: Types of preference functions

Type I: Usual Criterion 	$P(d)=\begin{cases}0, d\le 0\\1, d>0\end{cases}$	Type II: U-shape Criterion 	$P(d)=\begin{cases}0, d\le q\\1, d>q\end{cases}$
Type III: V-shape Criterion 	$P(d)=\begin{cases}0, d\le 0\\ \frac{d}{p}, 0\le d\le p\\1, d>p\end{cases}$	Type IV: Level Criterion 	$P(d)=\begin{cases}0, & d\le q\\0.5, q\le d\le p\\1, & d>p\end{cases}$
Type V: V-Shape with indif-ference Criterion 	$P(d)=\begin{cases}0, d\le 0\\ \frac{d-q}{p-q}, 0\le d\le p\\1, \quad d>p\end{cases}$	Type VI: Gaussian Criterion 	$P(d)=\begin{cases}0, d\le 0\\1-e^{\frac{-d^2}{2s^2}}, d>0\end{cases}$

When φ(α)>0, α is more outranking all the alternatives on all the criteria, when φ(α)<0 α is more outranked. One advantage of the net flow is that it is built on clear and simple preference information (weights and preferences functions) and that it relies on comparative statements rather than absolute statements.

3. EVALUATION OF SENSORS USING PROMETHEE II

For each one of the technical specifications in Table 1, a weight is set depending on the contribution of this feature to a lighting control system. In figure 3 the weights of each one of the specifications are presented. The sum of the weights is 100%. Well capacity is related with the blooming effect, the larger the well capacity the weaker the blooming effect. The higher value of the dynamic range indicates the resistance of the sensor in the saturation. Thus, the weight of these two properties is 20% according to its significant contribution to the sensor function. Dark current and readout noise weight is 15% because these two properties are associated with the noise of the sensor. Noise is the part of the signal that is unwanted. Active pixels are the number of the sensor analysis. The bigger is this number, the sensor can measure the light in more points of a room, but the regions of interest for lighting control need high resolution only in places with large area. The quantum efficiency is a quite significant property because is related with the number of active pixels. If the sensor has high resolution (great number of active pixels), it does not bother if quantum efficiency is low. That is the reason why these two properties have the same percentage of weight (10%). The fill factor and the power consumption have little contribution to the overall performance of the image sensor in lighting control applications (5%).

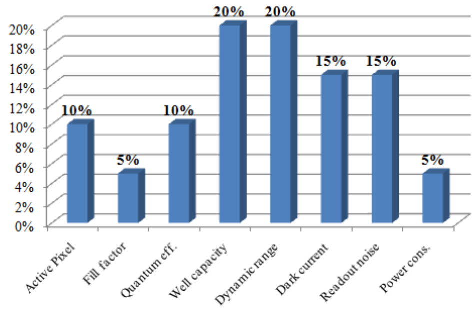


Figure 3 – Technical specifications weights for Promethee II method

Table 3: Promethee II ranking with φ(α), φ+(α) and φ-(α) scores

Sensor	φ(α)	φ^{+}(α)	φ^{-}(α)
CCD 2	0,4869	0,5421	0,0552
CCD 3	0,2081	0,3176	0,1094
CCD 1	0,1649	0,2997	0,1347
CMOS 6	-0,2480	0,1422	0,3903
CMOS 5	-0,2825	0,1318	0,4143
CMOS 4	-0,3294	0,2192	0,5487

For the implementation of the method the function type V (table 2) has been selected. According to the multicriteria method Promethee II type V preference function is best suited for quantitative criteria. The indifference threshold (q) for a given criterion represents the largest deviation that is considered as negligible in the comparison of two sensors. The preference threshold (p) for a given criterion corresponds to the smallest definition that is considered as definitely important when actions are compared.

The implementation of the method gave the ranking of the six different sensors. The scores of the method are shown in table 3. The complete ranking with the technical properties are shown in figure 4. For each sensor (CCD or CMOS) the stacked slices show the components of the sensor net flow.

For each sensor the bar is drawn with as many slices as the number of criteria. Each slice corresponds to the contribution of the criterion to the φ net flow score of the action taking into account the weight of the criterion. This way the sum of the positive slices minus the sum of the negative ones is equal to the φ net flow score of the sensor.

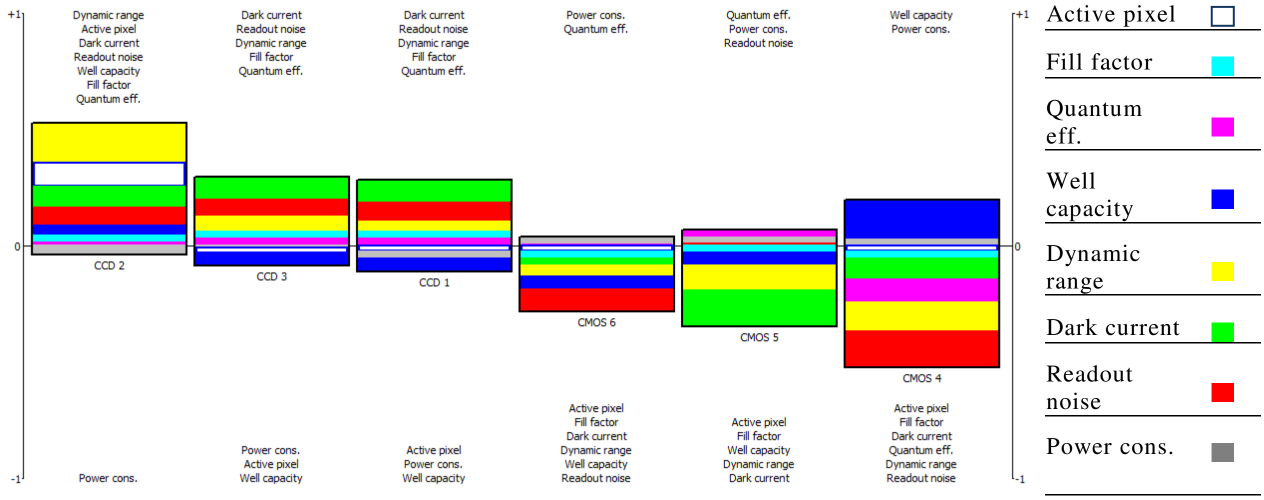


Figure 4 – Promethee II complete ranking

4. CONCLUSIONS

The examined CCD sensors have negative contributions to their φ score in comparison with the CMOS due to the power consumption. Regarding sensor CCD 2 the power consumption consists of the only one negative contribution to its φ score compared to the other sensors. That is the reason of the ranking of the specific sensor in the top of the list. The other two CCD sensors, 3 and 1, have negative contributions because of the increased power consumption in comparison with the CMOS, lower resolution (active pixels) and well capacity in comparison with the CCD 2. The three CCDs have better image quality (higher efficiency with low noise levels). On the other hand, CMOS image sensors have intrinsic advantages with low weight for the method (low power consumption, high quantum efficiency) and other such as low cost, high speed imaging, integration capability and radiation hardness etc. that are not included in the ranking method. For example the cost was not used as criterion because in lighting control the system uses only one image sensor whose the cost is negligible compared to the cost of overall installation (control system and luminaires). The implementation of the Promethee II method shows that the specific CCD sensors are selected between the upper three selections of the method ranking. The results are in accordance with the bibliography relatively with the comparisons of image sensors and prove that their use in lighting control systems can yield significant improvement in rates of saving energy in buildings. Nevertheless CMOS appears to be a good solution in lighting control with wireless sensors network due to their low power consumption.

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REFERENCES

REINHARD, E., WARD, G., PATTANAIK, S., DEBEVEC, P., HEIDRICH, W., MYSZKOWSKI, K. High Dynamic Range Imaging: acquisition, display, and image-based lighting. Elsevier, 2010

HOLST, G. CCD arrays, cameras and displays, 1998, SPIE

OHTA, J. Smart CMOS image sensors and applications, 2008, CRC Press, Taylor & Francis Group

NAKAMURA, J. Image sensors and signal processing for digital still cameras, 2006, CRC Press, Taylor & Francis Group

SARKAR, A. MISTRICK, R. A novel lighting control system integrating high dynamic range imaging and DALI. *Leukos* 2006, vol.2, No.4, 307–322

NEWSHAM, G., ARSENAULT, C. A camera as a sensor for lighting and shading control. *Lighting Research and Technology* 2009, vol.41, No.3, 143–163

HOWLETT, O., HESCHONG, L., MCHUGH, J. Scoping Study for Daylight Metrics from Luminance Maps. *Leukos* 2007, vol.3, No.3, 201–215

EL GAMAL, A., ELTOUKHY, H. CMOS image sensors. *IEEE circuits & devices magazine*, May/June, 2005, 6–20

HAIN, R., KÄHLER, C., TROPEA, C. Comparison of CCD, CMOS and intensified cameras. *Springer Exp Fluids*, 2007, 42, 403–411

CARLSON, B. Comparison of Modern CCD and CMOS Image Sensor Technologies and Systems for Low Resolution Imaging. *Sensors Proceedings of IEEE* 2002, vol.1, 171 – 176

BIGASA, M., CABRUJAA, E., FORESTB, J., SALVI, J. Review of CMOS image sensors. *Microelectronics Journal* 2006, 37, 433–451

ZHANG, L., JIN, Y., LIN, L., LI, J., YUNGANG, D. The Comparison of CCD and CMOS Image Sensors. *2008 International Conference on Optical Instruments and Technology: Advanced Sensor Technologies and Applications Proceedings of SPIE*, 2009, Vol. 7157

GLENNIE, W., THUKRAL, I., REA, M. Lighting control: Feasibility demonstration of a new type of system. *Lighting Res. Technol.* 1992, 24(4) 235-242

TAYLOR, S. CCD and CMOS imaging array Technologies: Technology Review. *Technical Report EPC-1998-106*, 1998

TRÄGER, F. Springer Handbook of Lasers and Optics. Berlin 2012, Springer

KONTAXIS, P., BOUROUSSIS, C., DOULOS, L., TOPALIS, F. Applications of CCD sensors in photometry and in daylight responsive systems. *Balkan Light 2012*, 331-338

FIGUEIRA, J., GRECO S., EHRGOTT, M. State-of-Art of Multiple Criteria Decision Analysis, 2005, Kluwer Academic Publishers