# A New Dimming Control Scheme of LED Based Streetlighting Luminaires Using an Embedded LED Model Implemented on an IoT Platform to Achieve Constant Luminous Flux at Different Ambient Temperatures

János Hegedüs[1], Péter Horváth[1], Gusztáv Hantos[1], Tamás Szabó[2], András Szalai[2], András Poppe[1]
[1] Budapest University of Technology and Economics, Budapest, Hungary
[2]Hungaro Lux Light Ltd., Budapest, Hungary

***Abstract*—This paper describes a method with which a forward current control scheme that assures constant total emitted total luminous flux of streetlighting luminaires, by considering the operating temperature of the luminaire. To set up such a control scheme, the multi-domain modelling of the LED packages applied in the luminaire must be known along with the thermal model of the entire luminaire. With these two models combined, the relationship between the ambient temperature, the luminaire temperature and the LEDs' emitted total radiant flux/luminous flux can be established. Using this relationship a look up table based embedded model can be established that can be implemented in a smart luminaire that can decrease/increase the driving current of the LEDs with which temperature changes can be accounted for while maintaining the total emitted luminous flux of the luminaire at the required level. Such an embedded model has been developed for a given smart, LED based streetlighting luminaire family and has been implemented in a demonstrator system. Preliminary version of the suggested new control has been tested in the field and the recently built demonstrator system has also been precisely tested in a laboratory environment. Our most recent test results obtained for an ambient temperature range of -30 °C and 60 °C are also presented.**

***Index Terms*-- power saving, iso-flux control, smart dimming, temperature compensation, multi-domain LED model**

## I. INTRODUCTION

Temperature dependence of LED operation is often not fully considered during the design of solid state lighting products. If temperature dependence is not carefully considered, solid-state lighting products are typically overdesigned to be robust enough to fulfil the requirements under any possible environmental conditions. Temperature dependent nature of LEDs though, could even be a new benefit if properly considered. Overdesign means designing for the worst case that is the highest possible environmental temperature. Under high temperature LED efficiency/efficacy, thus luminaire efficacy/efficiency is lower than at lower temperatures. This means that e.g. a streetlighting luminaire in terms of its total emitted luminous flux must be designed for the highest foreseen environmental temperature (foreseen hottest summer night). If the LEDs in such a luminaire are driven with same constant forward current, in colder days (e.g. during the winter) the total emitted luminous flux of the luminaire will be significantly higher than required. This, with a control scheme resulting in constant emitted total luminous flux significant electrical power saving can be achieved since at lower temperatures, due to increasing efficiency/efficacy less electrical power, thus, lower forward current levels are sufficient.

This paper describes a method to specify the so called iso-flux control (or constant light output) of LEDs' operating point, in which effect of temperature changes on light output characteristics is compensated by adjustment of the forward current. Parameters for an automated temperature compensation can be identified with the help of multi-domain LED models [1]-[3]. This paper describes our LED multi-domain model based approach applied to the design of the light output control of an existing street-lighting luminaire [4], [5].

## II. DESIGNING LUMINAIRES FOR CONSTANT LIGHT OUTPUT

By monitoring the ambient temperature, a smart adaptive system can fix the light output values through a controlled current source or through pulse-width modulation (PWM) based dimming with variable duty-cycle while maintaining a constant forward current. Such a solution is also known as *constant light output* (CLO) design.

Practical realization of a CLO or *iso-flux* control would require a pre-specified look up table (LUT) of required forward current / duty cycle vs. ambient temperature. Obtaining such LUTs e.g. for PWM-based dimming is not easy; for the calculation the pulsed thermal resistance, the effective heating power and the actual temperature dependence of LEDs' luminous flux need to be known. Our alternate approach was the following.

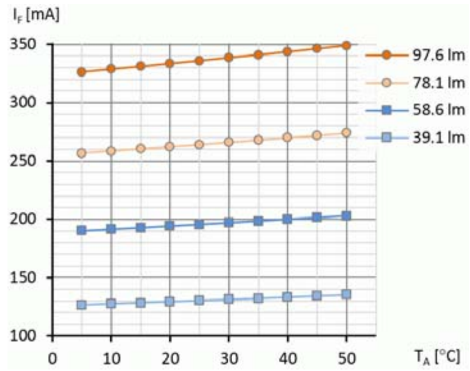


Figure 1. Luminaire Iso-flux characteristics of a test LED – keeping the $\Phi_V$ luminous flux constant at 40-60-80-100% of its reference value identified at $T_A$=50 °C ambient temperature and $I_F$=350 mA forward current

We had a less complicated, alternate approach based on an analog control scheme with variable forward current of LEDs, though, it requires detailed knowledge about the so called iso-flux characteristics (set of operating points providing constant radiant/luminous flux values under any environmental conditions) of the applied LEDs. Look up tables containing required forward current vs. ambient temperature pairs to be used for such a control can be obtained by properly set up simulations using a chip level multi-domain model of the LEDs to be controlled [6].

In case of simple 1-LED assemblies (or in cases when there are no considerable cross heating effects and the main heat-flow path is 1D like) merely the isothermal characteristics allow "hot lumen" calculations. Since the junction temperature is fixed, the power dissipation at any measurement point is independent from the thermal resistance of the actual mechanical structure; by substituting the thermal resistance of the required fixture it is possible to calculate the set of ambient temperatures corresponding to the specific points of the isothermal characteristics. (Such isothermal current-voltage-emitted total flux characteristics of LEDs can be measured in an automated way using the T3Ster/TeraLED combined thermal and radiometric/photometric test setup available from Mentor Graphics [7].)

Once the ambient temperature – forward current – radiant/luminous flux triplets are available, by simple regression and extrapolation methods the desired iso-flux *ambient temperature vs. forward current* function (such as shown in Fig. 1) can be derived. On luminaire level, however, multi-domain models of the single LED packages along with the complete thermal model of the luminaire have to be considered, in order to account for the mutual heating effect of the LEDs built into the luminaire.

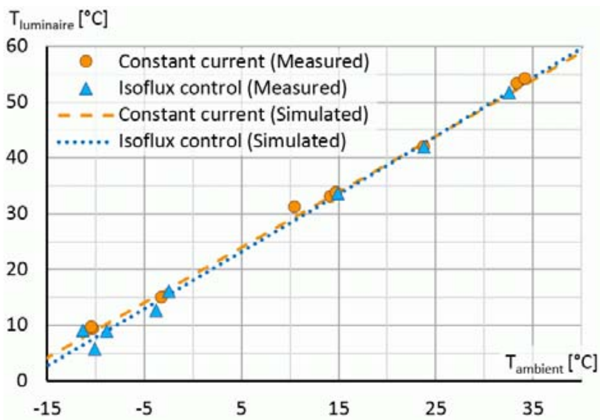


Figure 2. Luminaire temperature vs. ambient temperature for the Hungaro Lux PearlLight 48G luminaire

We modelled the LEDs used in the PearlLight family of LED based streetlighting luminaires of Hungaro Lux Light Ltd. [8] as well as the largest member of the luminaire family [4]. With luminaire level simulations the total "hot lumens" of the luminaire can be identified for any ambient temperature. The applied modeling techniques and the actual models were verified with thermal measurements [4] and also, with measurements of the light output at different ambient temperatures [9]. The thermal modeling of the luminaire allowed us to identify the relationship between the ambient temperature and the luminaire temperature, see Fig. 2. (This relationship is important for the physical implementation of a temperature dependent light output control scheme since it is simpler to measure the temperature of at the thermal test point of the luminaire in a reliable way than the ambient temperature.) In these experiments the forward current provided by the driver (which was removed from the luminaire itself) was set manually.

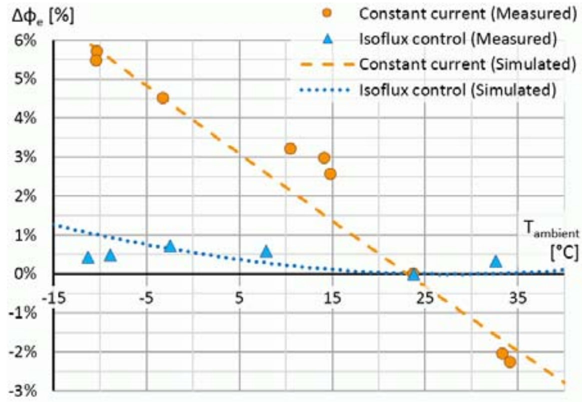


Figure 3. Relative change of luminous flux vs. ambient temperature for the Hungaro Lux PearlLight 48G luminaire

The forward current values resulting in the same total luminous flux at different ambient temperatures were identified with the help of these models. The luminous flux – ambient temperature relationship established this way was checked by actual field measurements [9]. We had two different forward current setting for the different ambient temperatures. In one set of simulations and measurements the nominal forward current of the original luminaire design was kept constant (constant current driving) while in a second set of simulations and measurements the forward current was adjusted according to the temperature in order to keep the emitted total flux of the luminaire constant (isoflux control). The results of these first experiments are shown in Fig. 3.

In both control schemes junction temperatures are the same – measured and simulated values perfectly match. When the luminous flux is kept constant (blue dots and curves in Fig.3), then, due to the increasing efficacy with decreasing temperature, the forward current can be reduced while the luminous flux is maintained at the specified value. This results in considerable power savings (blue markers and curves in Fig.4).

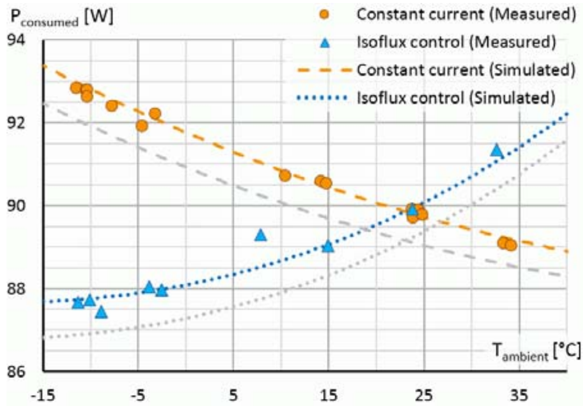


Figure 4. Consumed electrical power vs. ambient temperature for the Hungaro Lux PearlLight 48G luminaire

## III. Implementation in a demo system

In the framework of the EU H2020 project EuroCPS H2020 [10] Hungaro Lux Light Ltd. performed an industrial experiment, aiming the implementation of smart streetlighting luminaire with advanced self-diagnostics and communications capabilities, using an advanced IoT (internet of things) platform of a leading manufacturer [11]. As part of this project, the constant light output control (iso-flux control) the luminaire was also implemented. For the demonstration of the operation of the smart luminaire control the second smallest member of the HungaroLux PearlLight family, the PearlLight 24G model was used.

Using the modelling approach described in the previous section we established the luminaire temperature – forward current relationship needed to maintain the emitted total luminous flux of this luminaire model to its nominal value and we turned this into a look-up table (LUT) corresponding to the resolution of the digital reading of the smart lumianiare's built-in temperature sensor and the quantization steps of the forward current of the programmable LED driver used. The chosen IoT platform of smart streetlighting luminaire has sufficient processing capacity and is equipped with the right sensor and control interfaces to manage such LUT based control schemes.

With the right look-up table and the complete sensor and communications installed, the smart PearlLight 24G luminaire was placed in a light insulated climate chamber , see Fig. 5. An optic fiber (with the right cos-corrected measuring head) along with the wires of two thermocouples was fed through one of the measuring ports of the climate chamber. The optic fiber was connected to an Ocean Optics 2000+ spectroradiometer – this way we measured the relative change of the spectral radiance in the climate chamber as the ambient temperature was swept between -30 ºC and +60 ºC.

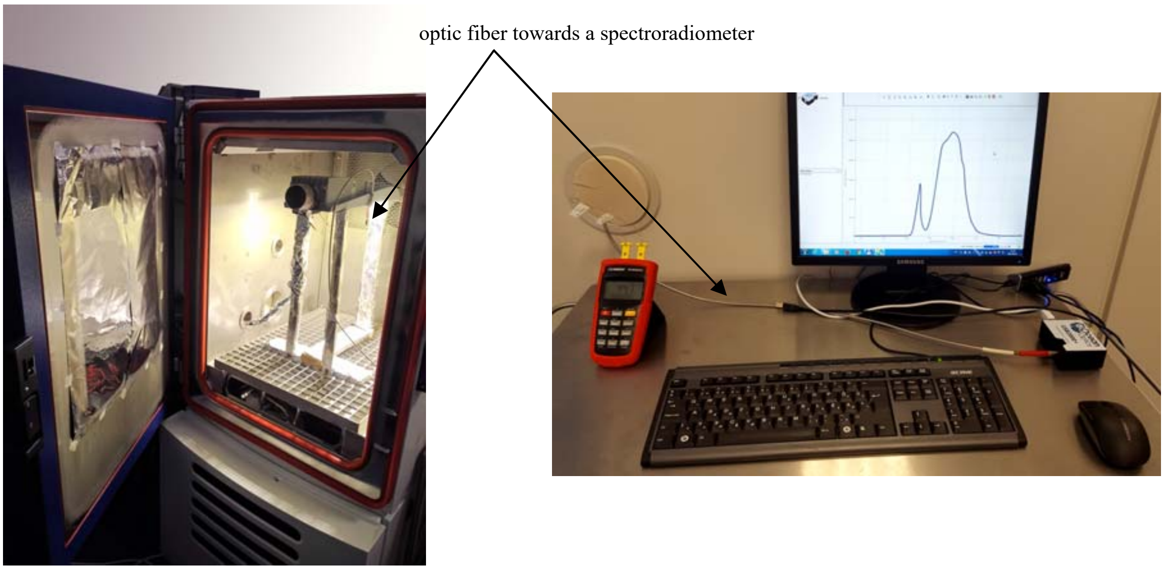


Figure 5. Testing the constant light output (iso-flux) control scheme of the demonstrator of the smart PearlLight 24G luminaire of HungaroLux: a) the luminaire in the light insulated climate chamber, b) measurement of the spectral radiance and the temperature in the chamber

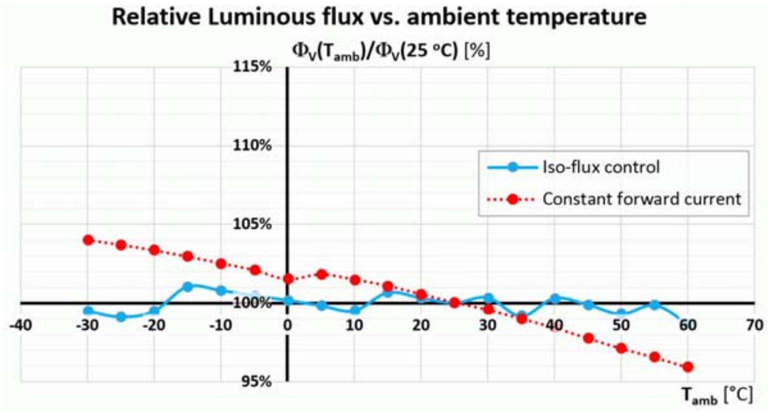


Figure 6. Measured relative change of the luminous flux of the smart luminaire

From the captured spectra the relative change of the luminious flux was calculated. We also measured the actual forward current provided by the LED driver of the luminaire. Like in the preliminary experiments [9], we applied both the constant current control scheme (no change in the forward current) and the constant light output or iso-flux control scheme. The measured relative changes of the total luminous flux of the luminare for both control schemes are shown in Fig. 6. For calculating the relative change, the total luminous flux value corresponding to 25 ºC ambient temperature was taken as reference. As seen in Fig. 7, the luminous flux of the demonstrator luminaire was kept constant with a relative error less than 1.9% over the investigated ambient temperature range. The diagram in Fig. 7 also shows the actual applied forward current and the ideal forward current. As seen in the diagram, the applied actual forward current changes in a step-wise manner (as it could be programmed in the driver) – this is thought to be the reason of the tiny changes in the relative error of the constant luminous flux.

## IV. CONCLUSIONS AND OUTLOOK

We proposed a new light output control scheme for streetlighting luminaires which is based on the improving LED efficiency/efficacy with decreasing temperature. We proposed a technique based on multi-domain modelling of LED packages and complete luminaires with which the ambient temperature – forward current relationship assuring constant luminous flux output can be established. Turning this relationship into a look-up table forms the basis of the implementation of the constant light output control of real luminaires. The applicability of the method was shown by a precise laboratory measurements of demonstrator of a new smart streetlighting luminaire. As suggested by Fig. 4, considerable energy saving is achievable with this new, iso-flux light output control scheme. Using archived meteorological data, detailed calculations of the energy saving potential for one of the examples presented here were carried out and published [9].

There are a few open issues. One question is how one should consider the production variance of LEDs' I-V-L characteristics in establishing the right models used for the light output control of the luminaire. This is among the problems currently studied within the Delphi4LED H2020 ECSEL project [12]. Another question is, how do the LEDs' iso-flux characteristics change with aging and how this could be compensated during the life-time of the luminaire. To answer this question requires further research. Some preliminary results in this regard are published in our recent research paper [9].

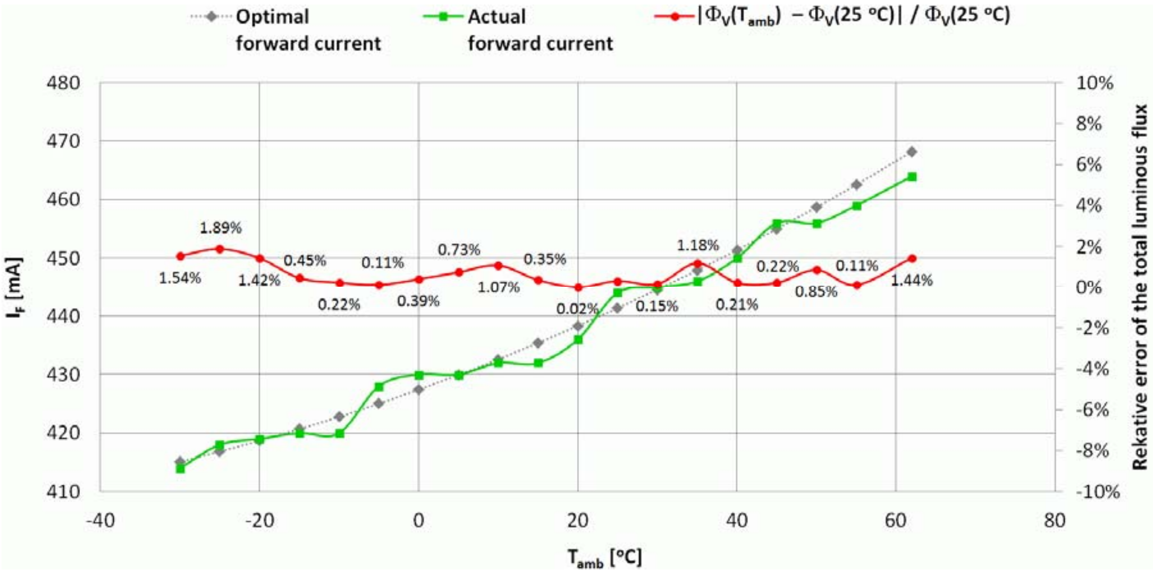


Figure 7. The relative error of the actual luminous flux with respect to the reference value and the applied actual forward current

ACKNOWLEDGEMENT

The work described here has received funding from the European Union's Horizon 2020 research and innovation programme through the industrial experiment of Hungaro Lux Light Ltd. performed in the framework of the EuroCPS H2020-ICT-2014-1-IA project (grant agreement 644090). This provided us the framework to implement and test our model in a real operating environment. The LED and luminaire modelling work received funding in the context of the H2020 ECSEL project Delphi4LED (grant agreement 692465). Co-financing of the Delphi4LED project by the Hungarian government through the NEMZ_16-1-2017-0002 grant of the National Research, Development and Innovation Fund is also acknowledged.

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