Introduction

As the lighting industry continues to make the transition to LED technology, there is an increasing need for more intelligent controllers and drivers. The rising price of electricity presents a major operating cost to consumers and businesses; however, efficient operation of LEDs can result in substantial savings. Many applications need to produce consistent light quality while supporting advanced control functionality such as dimming, balancing and accurate color mixing. Remote connectivity is also becoming a regular requirement in applications where high-maintenance expenses can be reduced through self-diagnostics that allow technicians to make a service call only when there is an actual reason to visit a site.

Bringing intelligence into many LED lighting applications may require moving from fixed function LED drivers to microcontroller-based or programmable architectures. For applications that need advanced functionality, using a microcontroller enables many intelligent features such as native dimming control, specialized color mixing, adaptive lighting control and even remote connectivity. Specialized power electronics microcontrollers can even further benefit lighting applications with the capability to efficiently and cost-effectively control the luminaire power supply in addition to the lighting control and communications. Like many modern electronics trends, moving to digital control opens up flexibility and can bring new levels of intelligence and differentiation to lighting products.

Enable intelligent LED platforms with microcontroller-based architectures

The lighting industry is moving to LED technology across all major segments for the advantages they provide over incandescent, CFLs and even high-pressure sodium lights:

Benefits of LEDs

- Higher Efficiency: high lumens/watt provides substantial energy savings over traditional lighting sources.
- Lower Maintenance: LEDs have a lifetime on the order of 50,000 hours, and therefore require less frequent replacement or maintenance.
- Directional: Less light output is required to light an area when the light source can be directed. There is also less light run-off or light “pollution.”
- Resilience to Vibration: This is important for applications like street lighting where external forces can impact a light’s operating life.
- Safer Technology: LEDs do not contain mercury and are environmentally safer than other lighting technologies.
- Intelligent Control: LED light systems can support a wide range of advanced features to improve efficiency and provide more optimized lighting. Features range from automatic dimming to matching available ambient light and adaptive time-of-day operation to maximize energy cost savings.
- Fast Operation: LEDs offer quick on-off switching and have a low startup time.

LED Lighting Applications

- Residential: Applications include light bulb replacement, accent lighting and small outdoor lighting. In general, only a few LEDs need to be lit, in usually one or two strings. Given the low-cost pressures of this market, advanced controls are generally not common.
- Commercial: Applications include fluorescent ballasts, light bulb replacement and accent lighting. Only a few LEDs need to be lit, usually one or two strings. While concerned about cost, this market is very energy conscious. Higher-end applications will require remote connectivity and some controller intelligence.
- Entertainment: Applications include high-end display and mood lighting. Full intensity control and consistent color quality are essential, as is remote connectivity and support for industry-standard protocols like DALI or DMX-512.
- Outdoor and Infrastructure: Applications include street lighting, lighting for factories and large office buildings, among many others. Equipment typically has a high number of LEDs and must support many strings. High brightness LEDs are common, as well. These applications require remote connectivity and a high level of controller intelligence.

The simplest LED-based lighting systems use an LED driver. These typically, fixed-function devices provide a straightforward and low-cost method for controlling LEDs. In general, they offer good power efficiency and do not require software programming. At worst, developers have to make several calculations when selecting a driver or determining which configuration values to use for board-level components.
While straightforward to use, many LED drivers lack flexibility for more advanced systems. To support various types of LEDs (e.g., higher wattage or different color) or different LED string configurations, a different solution may be required. In fact, any change in the system (e.g., the number of LEDs in a string or the number of the strings) may result in a need to change the driver. Thus, most of the lighting products an OEM offers will likely require a unique analog driver. For a large portfolio of products, this can increase the number of items an OEM or supplier must stock in inventory, possibly leading to lower economies of scale and higher equipment cost.

On the other hand, an intelligent controller enables developers to potentially create more flexible lighting systems. In a microcontroller-based system, the code can be configured to support varying types of LEDs, unique power stage requirements, different string lengths and varying number of strings without significantly changing the hardware. The system could even be designed to auto-detect what LEDs it needs to drive. The programmable nature of a microcontroller-based system even can enable advanced lighting scene control and automated light levels.

The flexibility of digital control enables OEMs to design a single controller that can drive a large portfolio of end-products. Because controller IP is reused, design investment can also be substantially reduced. A flexible controller reduces the number of devices that need to be stocked in inventory while lowering overall system cost through greater economies of scale.

Integration through digital control

The basic architecture of a smart LED-based lighting system includes three primary stages: power conversion, LED control, and communications (see Figure 1). The power conversion stage delivers the correct voltage and current to the LEDs. It begins with AC/DC rectification followed by a power factor correction (PFC) stage and then one or more parallel DC/DC conversion stages. To provide efficient power conversion requires precise and flexible control of these conversion stages.

![Figure 1: A smart LED-based lighting system includes three primary stages – power conversion, LED control, and communications – each of which requires an intelligent controller to maintain efficiency and functionality. By taking a flexible digital approach to power, several or all of these controllers can be combined on a single MCU to reduce system complexity and cost.](image)

Each of the primary stages requires an intelligent controller to maintain efficiency and functionality. With a fixed-function, analog approach, separate PFC, DC/DC, LED and communications controllers may be required.

However, with specialized power electronics microcontrollers, the component cost of a power supply for a luminaire can also be reduced through high levels of integration. With enough performance, power-optimized peripherals and communications ports, a single microcontroller can potentially control all three major components of a lighting system: the power stages, LED lighting control and communications. With this level of integration, a lighting system could potentially eliminate many excess components while enabling a central programmable platform to harmoniously control all three stages of an intelligent lighting system.
Digital control of power also has the potential to enable greater conversion efficiency for dynamic systems. While LEDs offer a major efficiency boost over traditional lighting sources — with a corresponding reduction in operating and energy costs — not all LED-based systems are created equal. Digital power control can enable higher efficiency in the power stages of an LED lighting system when dimming, varying color outputs, or adjusting the light output in any way. Likewise, under fixed lighting conditions, a microcontroller also has the potential to increase operating efficiency through enablement of more advanced power stage design. Such efficiency gains are highly attractive to end-customers and can stand as a key differentiating point between two LED systems that are otherwise equal.

Consider a city looking to replace 2,000 street lights and comparing between two models with a 10 percent difference in efficiency (see Figure 2). Note that the input power into the system for the higher efficiency system is 178 W while the lower efficiency system requires 200 W to generate the same 160 W light output. This translates to roughly an additional 10 percent savings in energy cost per year or $33,726 for this example based on the power efficiency of the power supply alone. Note that these savings are over and above the savings from being an LED-based system.

For many applications, including commercial display and entertainment lighting, the quality of the light produced is important. Quality, in this case, refers to the ability to output consistent intensity and color. However, three primary factors impacting LED performance are manufacturing variations, temperature and aging.

LED output can vary significantly from lot to lot. Consistency of quality in a single device can be maintained by using LEDs from the same lot. However, devices within the same product line that use LEDs from different lots may provide different light quality because of these variations in manufacturing. When two such devices are installed next to each other, they may produce a noticeable – and unacceptable – difference in the quality of the light they produce. With an intelligent controller, the system can be calibrated to compensate for any variations. As this is done in software, the calibration process can be streamlined during manufacturing when consistency between products is required.
As the ambient temperature changes, the output of the LED will change, as well. To compensate for this, the system needs to be able to sense the environmental temperature with a sensor. The microcontroller will need to be able to read the sensor and adjust the LED drive accordingly to dynamically correct the color and intensity. As the temperature needs to be checked only periodically, this function has a low overhead. In addition, it enables the system to monitor its own safe operation; if the temperature of the LED exceeds a specific threshold, the lighting controller can reduce the intensity or shut the string down while remotely notifying an operator of the issue. Extreme heat can prematurely age an LED and degrade its light output. Ensuring that an LED does not exceed a certain temperature will prolong its usable life.

Quality is also affected as LEDs age, causing color profile variations. For example, a red LED ages faster than a blue LED, and the color produced by a particular power output or pulse-width modulation (PWM) frequency will shift over time. An intelligent controller can account for aging and correct the color profile to maintain consistent lighting across the entire life of an LED system.

The same technology that manages quality can also improve safety and efficiency. For example, lighting can be adjusted to match available ambient light; on a stormy day, street lights can be turned on early at a partial setting. Similarly, if there is a lot of ambient light, the lighting can be adjusted down to consume less power.

With the availability of various sensors and remote connectivity, safety and efficiency can be even further extended. For example, sensors at traffic lights or specific street lights could monitor late-night traffic conditions. If traffic becomes extraordinarily active, the network can turn on more lights than would normally be active.

An intelligent LED controller does more than just provide higher light quality and added functionality such as dimming or color blending. By accounting for how lights are to be used, individual lights can be turned off or dimmed when their full intensity is not required. For example, in a warehouse, workers may utilize different spaces sporadically. Using occupancy sensors, it becomes possible to light only those sections that are currently in use. If only 50 percent of the floor is in use at any time, then the rest of the lights can be turned off for a 50 percent energy savings.

Again, consider the street light example from Figure 2. During late night hours, many street lights can be run at less than their full illumination due to reduced traffic loads. If motion sensors are in use with a communications network, lights can be dynamically turned on and off to meet actual traffic needs. If the lights can be shut down 25 percent of the time (see Figure 3), this results in a corresponding 25 percent energy savings ($68,218). In this example, when power supply efficiency savings are combined with savings from intelligence operation, the total savings per year for the system are a substantial $101,844 or ~33 percent.

Remote connectivity is a key capability for intelligent lighting systems. Intelligent devices can automatically manage some aspects of their operation to improve efficiency and quality. However, unless the equipment can communicate with a centralized controller, such intelligence has to be pre-programmed and can only maximize the efficiency of that single piece of equipment.

By networking the various components in a lighting system, the operation of equipment can be coordinated across an entire installation. This enables a whole new class of functionality, including remote dimming, remote shutoff and emergency control. For example, operators can adjust lighting intensity of an entire installation of lights from a centralized location rather than have to individually adjust each light.

To achieve the most functionality, each component must be able to not only receive information, as well as pass information back up to operators. In this way, lights can perform simple self-diagnostics to identify issues, such as whether an LED has burned out or is performing below a minimum quality threshold and alert operators to initiate any necessary maintenance. Rather than send out technicians on
a regular maintenance schedule to ensure equipment is operating as expected, equipment can be checked remotely. Technicians are only sent out if there is actually an issue to take care of. This, coupled with the extended operating life of LEDs, can result in significant maintenance cost savings, as well as increased operational safety since failures can be identified immediately.

Remote control enables other advanced features that substantially impact operating efficiency and cost. Remote control allows both dynamic control of lights, as well as networking of multiple lighting installations to a single point of control at a location that may be a great distance from the actual installations. For example, street lights may need to be adjusted for daylight savings time. Rather than send a technician out to each control box, the schedule of all lights in a system can be remotely corrected. This also enables operators to easily accommodate unexpected changes in schedules, such as the need to light the roads after a late-ending sports event or keep the lights in a factory on during the rush season. Remote control can also be used to improve safety by enabling direct control of lights during emergency conditions.

One of the more beneficial features of intelligent lighting for commercial and industrial installations is the ability to accurately track power consumption. Cities, for example, traditionally pay a fixed rate to operate street lights. With an intelligent lighting controller, the actual power consumed can be measured and sent to a centralized location, resulting in substantial operating savings by ensuring that cities are not paying for more power than they actual use.

Data logging of actual usage enables operators to refine planning of operating costs, maintenance resources, and future investment. It also allows for more advanced predictive diagnostics to be put into place. For example, if energy consumption increases or the number of replacement bulbs required changes dramatically, this can alert operators to a potential issue that can be addressed quickly before it results in escalating operating and maintenance costs.

Connectivity is also essential for many lighting systems, especially entertainment applications. There are many established communications standards in this market space – including DALI, DMX-512, and KNX – and equipment that can support these protocols can be more competitive.

Figure 3: By accounting for how lights are to be used, individual lights can be turned off or dimmed when their full intensity is not required. For example, using occupancy sensors, it becomes possible to turn on only those lights that are currently required. Building on the example in Figure 2, if street lights can be shut down 25 percent of the time, this results in a corresponding 25 percent energy savings ($68,218). When power supply efficiency savings are combined with savings from intelligence operation for this application, the total operational savings per year for the system are a substantial $101,844 or approximately 33 percent.
An important technology for lighting applications is power line communications (PLC). Rather than having to run a separate cable to serve as the communications link, PLC enables engineers to network equipment over the same lines used to power equipment. For applications not requiring the full feature set of PLC, developers can implement PLC-Lite. PLC-Lite is a flexible alternative to PLC that, through its simplicity, reduced protocol overhead and lower data rate, can be implemented at a substantially lower cost per link than more complex varieties of PLC such as G3 or PRIME.

Because it isn’t a fixed standard, developers can exploit the flexibility of PLC-Lite to optimize an implementation to specific channel characteristics to improve link robustness in environments where interference on the line requires exceptional handling. PLC-Lite is well-suited for applications where a low-cost but a robust communications channel is needed such as simple light bulbs or wall switches within a home network.

Developers can also connect devices wirelessly using radio frequency (RF) technology. With a modular architecture, devices can use whichever connectivity technology best meets the need of the customer. Whether the link is PLC- or Wi-Fi-based, data is passed to the microcontroller over a standard I²C or SPI port.

TI’s C2000™ Piccolo microcontroller platform offers a high-performance architecture ideal for a wide range of lighting applications (see Figure 4). The Piccolo microcontroller architecture was designed for digital power control and is flexible in its support of a variety of power topologies. Its industry leading PWM generation, with capabilities such as high-resolution duty-cycle control and high-resolution deadband, enables more efficient and higher performing control of power stages. Likewise, the advanced PWMs extend benefits to lighting control with the capability to generate very precise color outputs and dimming levels. In addition, with up to 16 PWM outputs, Piccolo MCUs can individually control up to 16 separate LED strings.

![Figure 4: TI's Piccolo platform of microcontrollers offers a high-performance, highly integrated architecture designed for digital power control that is flexible in its support of a variety of power topologies.](image-url)
Complementing the PWMs are 12-bit high-resolution analog-to-digital converters (ADCs) with fast sampling and conversion speeds up to 4.6 Mega samples/second. Together, the PWM and ADC modules allow engineers to create a tight feedback loop to respond quickly to changing system and environmental operating conditions.

Built-in fault protection mechanisms ensure systems are able to handle over-current and over-voltage conditions. PWM fault trip zones enable the system to bypass the CPU and quickly override PWM signals with a preprogrammed state in the unexpected system conditions before system can be damaged. Availability of integrated I2C, SPI, UART, USB and CAN peripherals with production-ready firmware drivers also enable Piccolo to meet the connectivity needs of every application.

To keep system cost down, developers need a microcontroller that provides enough processing capacity to implement the power stage, LED control, sensor input and remote connectivity with a single microcontroller. This level of integration enables substantial cost reductions in lighting designs. With Piccolo, TI offers a platform of microcontrollers that can support all of these functions from entry-level devices to complex, multi-string systems with PLC. The 32-bit TMS320C28x™ core offers digital signal processing (DSP) performance in a microcontroller device that can handle power stage calculations, LED string control and any lighting protocols such as DMX512. With optimized math operations, an interrupt-driven architecture for real-time control, and programmable flexibility to respond to changing events, Piccolo microcontrollers are ideal for lighting applications.

Piccolo F2803x devices also integrate TI’s Control Law Accelerator (CLA). This is a separate processing core that enables dual-core operation without the added cost or overhead of a second microcontroller. Able to run independently of the C28x DSP core, the CLA is designed to provide efficient parallel processing. By partitioning functions of a lighting system between the C28x core and CLA core, Piccolo microcontrollers can implement a complete intelligent LED controller in a single chip. For instance, the CLA could be used to run PLC algorithms while the C28x core focuses on digital power conversion and LED string control. For applications where more advanced or higher bandwidth PLC is required, an integrated Viterbi Complex Math Unit (VCU) is available on Piccolo F2806x microcontrollers, which is specifically tuned for PLC algorithms and can accelerate PLC processing by up to seven times compared to devices without a VCU.

Piccolo provides a broad range of devices to support entry-level to highly intelligent lighting systems. For example, low-cost systems can utilize the Piccolo F2802x microcontrollers to provide enough performance to reduce system component count and take advantage of real-time digital power technology, while also implementing adaptive lighting technologies with communications such as DALI, DMX512 or KNX. For systems requiring entry-level PLC remote connectivity, the Piccolo F2803x microcontrollers support PLC-Lite, as well as offering more LED channels and performance than the F2802x. For high-performance systems, the Piccolo F2806x microcontrollers support advanced PLC and USB while offering even more LED channels and processing capabilities.

Note that, in general, a single-chip design that integrates all of a system’s controllers is less expensive than one that requires multiple microcontrollers. In some lighting systems, however, the presence of high and low voltages often requires the use of an isolation boundary, with PFC and DC/DC conversion on different sides of this boundary (see Figure 5). As it is difficult to cross the isolation boundary, this can make a single MCU architecture difficult to design. In such cases, it may be easier to utilize two MCUs that communicate using an I2C or SPI interface across the isolation boundary. If the design is non-isolated, then it is relatively more straightforward to implement PFC and DC/DC conversion functionality on the same microcontroller.
Figure 5: In some lighting systems, the presence of high and low voltages often requires the use of an isolation boundary. Given the difficulty of crossing this boundary, it may be easier to utilize two MCUs that communicate using an I²C or SPI interface. If the design is non-isolated, then it is relatively more straightforward to implement PFC and DC/DC conversion functionality on the same MCU.

Companies like TI offer a wide range of development tools to assist engineers in evaluating and designing LED-based lighting applications, ranging from low voltage, auxiliary powered systems to high voltage, full-AC mains powered systems with remote connectivity. For example, the TMS320C2000 AC LED Lighting and Communications Developer's Kit (TMDSIACLEDCOMKIT) provides a complete platform for accelerating the design of AC mains-powered, intelligent lighting products (see Figure 6) with high operating efficiency (approximately 90 percent) and full support for remote connectivity and lighting communication protocols such as DALI, DMX512, KNX and PLC.

TI offers a wide range of development tools to assist engineers in evaluating and designing LED-based lighting applications, ranging from low voltage, auxiliary powered systems to high voltage, full-AC mains powered systems with remote connectivity. The TMS320C2000 AC LED Lighting and Communications Developer's Kit (TMDSIACLEDCOMKIT) provides a complete platform for accelerating the design of AC mains-powered, intelligent lighting products (see Figure 6). Based on the F2802x and F2803x Piccolo microcontrollers, the board supports up to 250 W output across six LED strings. Its full-featured power supply enables higher operating efficiency (approximately 90 percent), reduces manufacturing cost, and is highly adaptable to match varying design and implementation requirements. It includes hardware and software support for remote connectivity and lighting communication protocols such as DALI, DMX512 and PLC.

Figure 6: Tools like the TMS320C2000 AC LED Lighting and Communications Developer's Kit provide a complete platform for accelerating the design of AC mains-powered, intelligent lighting products with high operating efficiency (~90 percent) and full support for remote connectivity and lighting communication protocols such as DALI, DMX512, KNX and PLC.
The DC/DC LED Lighting Developer’s Kit (TMDSDCDCLEDKIT) provides the SEPIC DC/DC power conversion stage with 12-20 V input and 24 V output. It supports eight independent 10 W LED string driver stages with current sensing and independent brightness control for each string. Low CPU utilization provides headroom for other system tasks.

Also available is the Multi-DC/DC Color LED Kit (TMDSRGBLEDKIT). With a digital DC/DC SEPIC power conversion stage and boost closed-loop regulated control, this kit drives up to eight LED strings of variable length and type, each with their own independent power stage. With a maximum 36 V DC input, 50 V maximum DC output, and up to 400 mA/string current, this kit enables digital brightness and color control of each string using average current-mode control. The kit also comes with a simple GUI interface for out-of-the-box evaluation of LED color mixing.

To support the implementation of PLC in lighting applications, TI also offers the Piccolo MCU Power Line Communications (PLC) Add-on Kit (TMDSPLCMDA-P23X). The kit includes a plug-in PLC daughter card that can be used to evaluate and experiment with PLC functionality on the TMDSCIACLEDKIKIT. TI has an entire group dedicated to developing PLC across a wide range of industries. Developers also have access to TI’s industry-leading plcSUITE software providing production-ready software libraries to accelerate PLC design.

TI’s development kits are based on the modular controlCARD form factor. This enables developers to evaluate different C2000 microcontrollers to optimize performance, peripheral set and price to their application. In addition, TI’s controlSUITE software suite provides an extensive range of additional software developers need when designing intelligent lighting systems, including full closed loop control of an AC/DC power supply, multi-string LED control and advanced communications. The software suite includes easy-to-use, open-source demonstration GUIs, software examples and complete documentation.

Both controlSUITE and plcSUITE provide an optimized suite of software for developers to easily differentiate their products for different end-customer applications, allowing one design to serve across multiple markets. For example, depending upon the design, the same power stage design can be used to efficiently drive 70 W fixtures all the way up to 250 W light fixtures. This reduces inventory count, eliminates components and reduces manufacturing costs.

Today’s LED-based lighting systems need to provide much more than just bright light. With the high performance and integration of the Piccolo microcontroller architecture, developers can improve power stage efficiency to substantially reducing energy operating costs. They can also introduce advanced functionality such as dimming and color blending that enable consistent and robust lighting over the life of an LED. Finally, with the ability to easily integrate power line communications, developers can bring the benefits of remote connectivity to lighting applications to improve ease of operation, enable predictive self-diagnostics, and significantly reduce maintenance expenses.

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