A Case Study of Tunable White LED Lighting with Networked Lighting Controls

Pacific Northwest NATIONAL LABORATORY

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CONTENTS

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Figure 1: Photos of the Cognitive Empowerment Program facility in Atlanta showing an electronic help bar (left) and movement activity spaces (right) near the facility entrance. *Photos: PNNL.*

INTRODUCTION

Emory University and the Georgia Institute of Technology (Georgia Tech) partnered to create the Charlie and Harriet Schaffer Cognitive Empowerment Program (CEP) facility in northeast Atlanta. Together with the funders, they are building a program to help individuals experiencing mild cognitive impairment (MCI) to maintain their physical and cognitive health and independence for as long as possible. In addition to applying effective strategies and therapies, the two research groups are investigating the responses of the MCI members to treatments that involve acoustical conditions, exercise and movement, and lighting changes that may support retention or relearning of skills. Care partners and family members receive support and instruction to improve home and work life, promoting joy, purpose, and wellness in the family groups.

The facility takes up one floor of a medical building in the Executive Office Park in northeast Atlanta consisting of 20,000 ft^2 of office, group rooms (classrooms), treatment, exercise, kitchen, dining, and conference space. *Figure 1* shows two spaces near the entry. The facility also includes innovation spaces for designing equipment or developing methods that can assist those with MCI. The renovated space was designed by a team of architects and engineers in 2018 and 2019, and was installed by a building contractor in late 2019. The lighting design was executed by Smart Lighting Solutions, a large lighting agency in Atlanta. The

FIELD EVALUATIONS

Pacific Northwest National Laboratory conducts field evaluations of advanced solid-state lighting systems to collect empirical data and document building owner and end-user experience with lighting systems. The evaluations produce independent, third-party data and recommendations for use in decision-making by lighting manufacturers, designers, facility managers and other professionals. Real-world installations often reveal product limitations and application issues that are not apparent from laboratory testing. The evaluations include the gathering of feedback from the everyday people who live, work and play under the lighting systems in a variety of space types. For more information and additional resources, please visit ***energy.gov/eere/ssl/solid-state-lighting***.

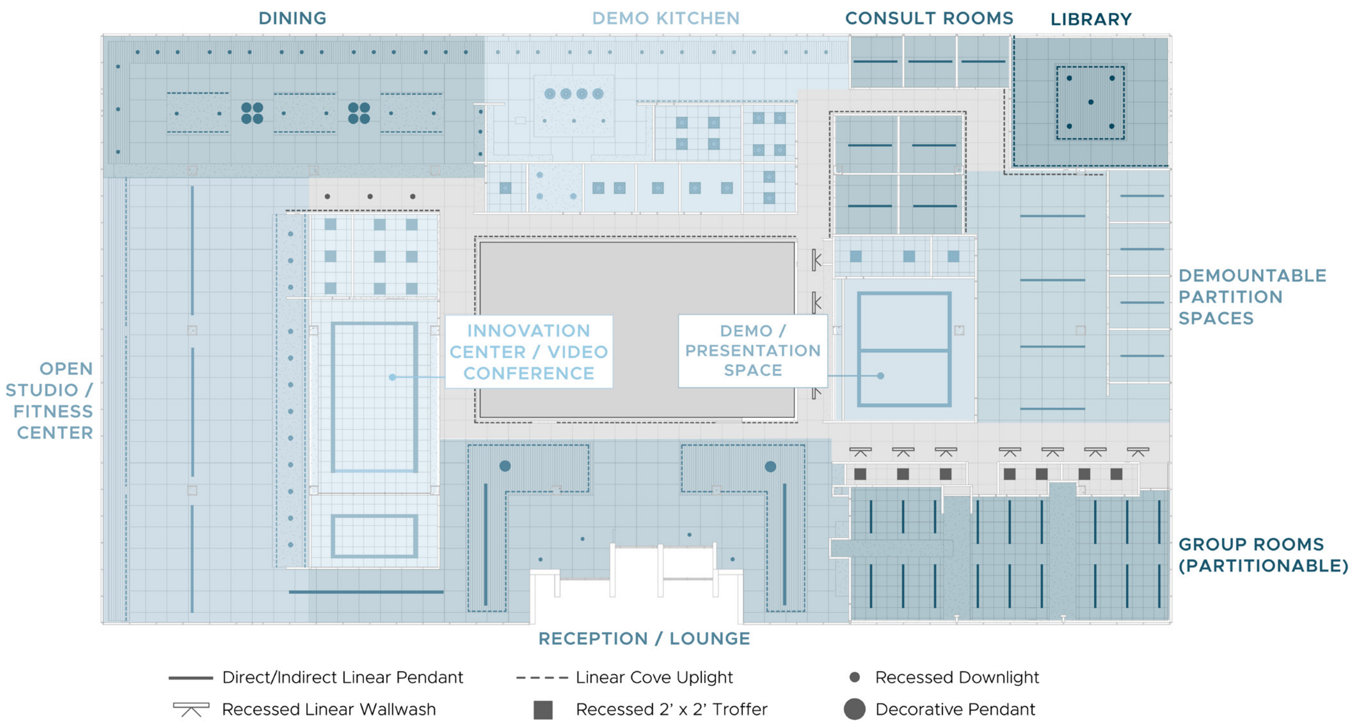


Figure 2: Lighting plan of Emory Cognitive Empowerment Program Facility, showing spaces and luminaire locations.

agency also designed the control system with input from Georgia Tech's SimTigrate Design Lab, funded by the James M. Cox Foundation, which hoped to use the control system to monitor usage and settings of the system over the course of days and months for research purposes. Pacific Northwest National Laboratory (PNNL) joined the effort during the design stage to consider the special visual and health needs of the older individual, contribute to the lighting design and specification, and observe the progress of the project as the lighting and controls went through final installation and commissioning.

The goals for the lighting and controls were to provide a visually comfortable, bright and cheerful environment for the MCI members, supportive of visual tasks, therapeutic movement, interviewing, teaching, evaluation, treatments, and even classes in food preparation *(Figure 2)*. Lighting flexibility was important because many spaces are used for a variety of activities and there were potential plans to offer programing in the evening hours. In addition, knowing that bright days and dark nights support physical, cognitive, and psychological health, the lighting was designed to be tunable for different colors and intensities of white light to support alertness during the day without being too stimulating in the evening to support sleep quality at night. Controls were essential to providing the flexibility and programmability of individual spaces and the whole floor together, with the added code-compliant bonus of energy efficiency functions to dim or switch off lighting when not needed, and measurement and reporting of lighting system operation and usage for research.

The lighting system uses tunable-white light-emitting diodes (LEDs), employing luminaires with both warm- and cool-color emitters that can be dimmed separately to produce any white correlated color temperature (CCT) between 2700 and 6500 K. All luminaires were dimmable to achieve subdued or lively surroundings for different treatments, times of day, and moods. A central networked digital control system was employed to allow tuning of multiple spaces together (for example, bright, cool morning light could be programmed for extra stimulation, or

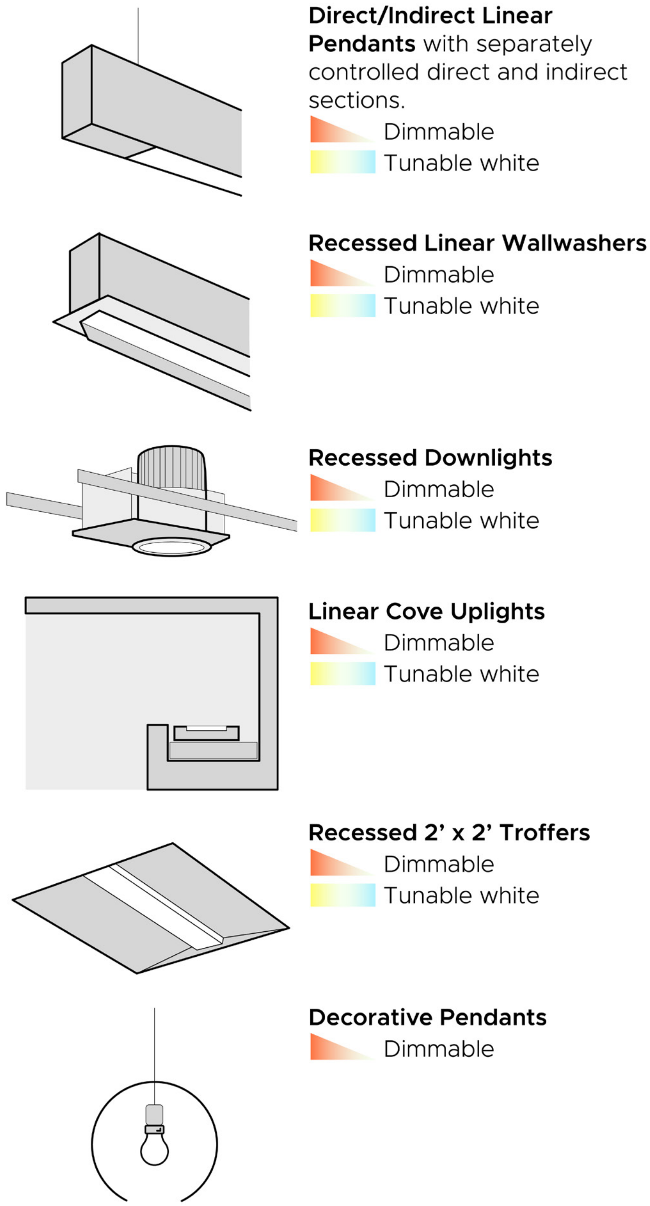


Figure 3: Principal luminaire types employed in the Emory Cognitive Empowerment Center. See Figure 2 for luminaire locations.

lighting in all spaces at the end of the day could be reduced in both light output and CCT to promote relaxation and not interfere with the melatonin cycle of occupants). Almost all spaces were equipped with individual room control of dimming and color temperature with touch screens to allow users to tune the lighting as desired, but each room's controls could also be specially programmed through the server in case the research staff were investigating the effects of lighting settings on activities such as learning. The server incorporates a timeclock and can send signals to switch off all lighting after occupancy hours or enable occupancy sensors to control the lighting.

The bulk of the construction was completed in January 2020. It was clear from an initial walk-through that, although the lighting system produced the expected high light level with low-glare qualities, there were issues and inconsistencies to be resolved. These were noted in an initial visit and were expected to be resolved when the technical representatives from the agency visited with the electrical contractor in the following few weeks. What followed was 2.5 years of unexpected lighting performance in terms of light output, color, scheduling, and occupancy. The CEP facility was closed in March 2020 because of COVID concerns, but the contractors were able to continue working intermittently while the floor was inaccessible to medical clients and most staff.

The lighting system luminaires came from either manufacturer lines owned by the Acuity Brands Lighting (ABL), the lighting and building management controls portfolio represented by the agency, or other manufacturers from the agency's line card of manufacturers. All luminaires were specified to be compatible with the selected control system (also from the manufacturer), and this meant ordering and integrating drivers to make all luminaires completely compatible with the controls and one another. The luminaires included direct/indirect linear pendants with separately controllable up and downward sections, recessed linear wallwashers, recessed downlights, linear cove uplights, recessed 2'x2' troffers, and decorative pendants that were dimmable but not tunable-white. The main luminaires used in the project are illustrated in *Figure 3*.

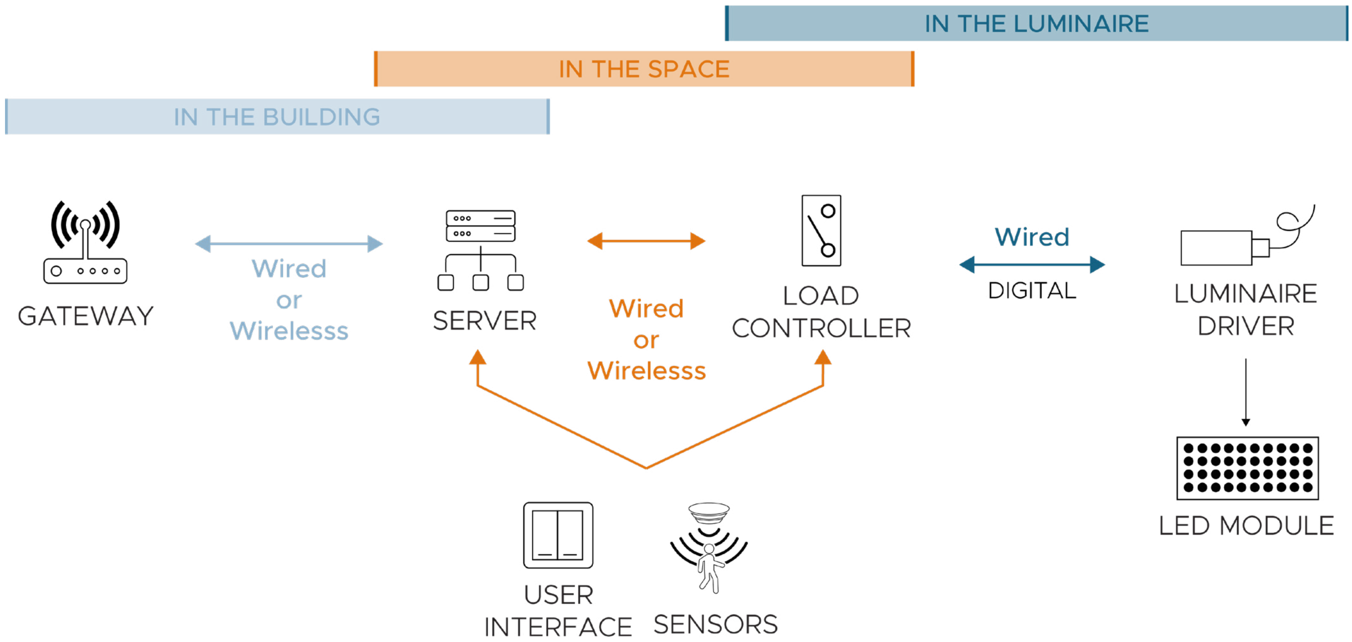


Figure 4: Schematic system architecture depicting the location of each controls component and the communication methods used for data exchange. *Source: PNNL.*

CONTROLS DESCRIPTION

With the exception of building core stairwells and restrooms, all CEP facility luminaires are controlled using a wired digital networked system, nLight by Acuity Brands. Its basic architecture is illustrated in *Figure 4*.

The server is an Eclypse system panel networked to receive building automation signals if desired, but in this case it operates as a stand-alone lighting controller for increased security. The Eclypse server allows the facilities and technical staff to discover devices, adjust settings, and set schedules, for which it has an integral time-clock. The Eclypse system can send signals to individual luminaires, or it can send control signals to user interfaces in individual rooms. There are three types of user interfaces on the project, as described in *Table 1*.

Almost all luminaires in the CEP were tunable-white, meaning the intensity and spectrum (CCT is used as a proxy) could be modified. Each luminaire, whether linear direct/indirect, cove lighting, recessed downlights, or recessed 2'x2' troffers, has two sets of LED emitters, one 6500 K and the other 2700 K CCT. The driver in each luminaire or in multiple luminaires in continuous rows receives a separate color and output signal via a Cat5e cable from the room's user interface through a load controller, or directly from the Eclypse server. Intelligence built into the driver translates that signal into signals for each of the two LED colors that will be mixed to achieve the selected CCT and output. The luminaires are separately hard-wired with 120V building power through load controllers that manage both power and control signaling. Luminaires that were not within the manufacturer's suite of lighting products but were represented by the agency (e.g., cove lighting from Axis Lighting) were ordered with nLight-compatible dimming drivers so that they would be programmable through the nLight system and would respond in the same way as the manufacturer's products in terms of light output and color.

Wiring was 24VDC Class 2 with Cat-5e cables, daisy-chained from server, sensor device, or user interface to room load controller, then to the luminaire driver. For security, the wired digital approach was selected over wireless communication, in consultation with Emory's building management IT team.

Table 1: User Interfaces Used on the CEP Facility		
User Interface Name	**Photo**	**Description**
Fresco		The multi-gang Fresco architectural touchscreen user interface is used in larger spaces. It features a display screen for controlling multiple zones of luminaires. One such space is the group room, which can be subdivided into four smaller spaces for classes/group discussions or other combinations as needed. The Fresco, in combination with partition detectors mounted in the ceiling of the group rooms, handles the logic of the group room partitioning. The user interface screen can display preset lighting scenes for selection, and another screen "page" can be used to control CCT separately from light output. A third screen page can be used for customization by staff or researchers, requiring further training. Figure 5 shows a staff member interacting with the touchscreen. *Source: SimTigrate Design Lab.*
nLight Unitouch		A single-gang user interface is used in conference rooms and larger collaboration spaces. It displays three preset scenes plus off/on control on its first screen page, and a second page allows customization of the room luminaire output and CCT.
nLight nPODMA		This single-gang user interface is similar to a traditional light switch, but with on/off and raise/lower buttons for CCT and light level. These are located in private offices, conversation rooms, and other spaces with simpler lighting functions. There is one user interface for each group of separately controlled luminaires, so there may be one user interface for linear luminaires alongside one for recessed downlights, for example. Some of these user interfaces integrate vacancy sensors to shut off lights when the room is no longer occupied.

The control system included occupancy sensors, daylight sensors, user interfaces, and input/output communication devices, all programmable using the ABL-proprietary "Ledcode" digital communication protocol. This allowed programming of the devices and drivers either in the factory or on site with in situ equipment. (Manufacturer-proprietary protocols are not interchangeable with other controls systems or protocols without gateways or other devices to translate from one protocol to another.) Wall-switch occupancy sensors, employing both passive infrared and microphonic technologies, were specified for restrooms, utility closets, and similar areas for automatic response to occupancy and vacancy.

Figure 5: A staff member adjusts the lighting conditions at the touchscreen user interface. Users can adjust the intensity and CCT settings.

COMMISSIONING, PROGRAMMING, AND CONFIGURATION OF THE LIGHTING CONTROL SYSTEM

Figure 6: Photo of the ceiling of the exercise studio where one section of the linear indirect luminaire exhibits a much lower CCT than either the cove lighting or the rest of the pendant. *Photo: SimTigrate Design Lab.*

The initial installation of the lighting and controls was completed in January 2020. At that point, it was expected that the system would be commissioned by the agency to perform as described in the sequence of operations formulated by SimTigrate together with the agency. A lighting punchlist was prepared, which noted the controls functions that were not yet implemented and those that were not performing at all. What followed was 2-1/2 years of field issues, replacements, and reprogramming to get the control system working as intended, achieving consistent performance, with intuitive user interfaces, and durable solutions to the problems so that they didn't recur. Of course, this was complicated by the pandemic, although when the building was closed to client visits and staff use from March 18, 2020, to June 7, 2021, it was easier for the agent and the manufacturer to make changes without affecting facility programs and staff. The following is a partial list of issues that arose over the 30-month period:

Color Tuning

- After initial programming, cove lighting responded incorrectly to the CCT signals, as shown in *Figure 6*. Consequently, three technicians from Canadian vendor Axis Lighting visited Atlanta for troubleshooting. A solution involving LED board and driver changes was prescribed, although this proved to be a stubborn issue, recurring multiple times.
- Luminaires in the entryway did not correctly follow the global control scheme, resulting in incorrect CCTs during the afternoon and evening when the CCT was changed by the global schedule.
- Sometimes downlights, covelights, and linear pendants all responded differently to the same color control signal. Light output was often higher or lower than the setting selected and reported by the room's user interfaces.
- Default CCTs for luminaires would occasionally shift warmer or cooler with no explanation.
- Reconfiguration tools used by the agent frequently fixed the misbehaving drivers, but the same problems would occur again days later, although it was not always the same luminaires exhibiting the inappropriate color or output behavior. *Figures 7 and 9* show examples of incorrect or unexpected outputs.
- CCT mismatch was sometimes attributed to faulty LED boards. Replacement parts were ordered and installed. Other color mismatches were attributed to incorrect programming.
- The server's global programming became garbled 18 months into the process. CCTs, light levels, and other functions were confused, and many previously "fixed" luminaire groups reverted to inconsistent behavior.
- These and other inexplicable lighting system behaviors prompted replacements of drivers, input/output communication devices, load controllers, and Cat-5e connections, often more than once.

Figure 7: An 8-ft-long direct/indirect luminaire in a conversation room, with one half of the downlight responding incorrectly. *Photo: SimTigrate Design Lab.*

Figure 8: The group room with no partitions closed. The CCT of the pendant linear luminaires in the partitionable area on the right is higher than those of the smaller, subdividable classroom areas on the left, even though all are programmed to match in CCT and output. *Photo: SimTigrate Design Lab.*

Timeclock Controls and Programmed Scenes

- The time clock function frequently appeared out of sync. Lights were reported on at night multiple times over the first year. The system time clock was ultimately found to be 9 hours off. Correcting it fixed some, but not all, of the issues of lights being on at night.
- CEP staff members were frustrated that their preferred office lighting settings were overridden daily by the server's global channel event control. In response, the agent reprogrammed the staff offices and conversation space lighting, removing them from the global scheduling function.
- The group room that is partitionable into four separate smaller rooms needed extra attention to get the partition detection working properly (as in partitionable ballrooms, there is a pair of sensors on either side of the partition wall that detects when the wall is in place); getting the local multi-scene user interfaces to respond appropriately to the number of rooms linked together was challenging, and color consistency continued as a problem until the final days of troubleshooting. This is shown in *Figure 8*.

Occupancy Sensing

- Occupancy sensors did not reliably switch off lighting when the building was unoccupied. Some were fixed or reprogrammed multiple times. Some dual technology sensors incorporated both passive infrared (PIR) and microphonic detection technologies, but the microphones did not seem to be picking up sound signals consistently.
- Insensitive microphone detection combined with some low-movement activities in the space resulted in lights turning off during programmed activities.

Firmware and Software Updates

- User interface devices with touchscreens needed three separate firmware updates. Each device update required a 25-minute wired connection to a laptop computer carried by the agent.
- After one set of firmware and software updates, all luminaires appeared to perform perfectly. When subsequent CCT mismatches occured, the problem was attributed to a grounding issue.
- Problems were attributed to an issue with building power quality. The plan to correct this was to update the driver firmware (again), then follow up with system software updates for load controllers. However, the issues continued after these updates.

Figure 9: Tunable lighting in the consultation rooms can be adjusted to suit individual preferences and needs, although the very cool light setting here was not intentional. *Photo: SimTigrate Design Lab.*

Commissioning Takeaways

In summary, there were multiple visits by the contractor, the agent's technical staff, the luminaire manufacturers' technical staff, and the control system manufacturer's technical experts. There were many LED board, driver, load controller, and user interface replacements. The manufacturer ordered product hardware and firmware design changes to correct the issues, and there were several iterations of reprogramming through firmware and software upgrades. The inconsistent performance persisted until September of 2022.

There is no finger-pointing to be done. The controls design was done in conjunction with the agency, an experienced and technically savvy team. The desired function of the control system was expressed by SimTigrate to the agency through a sequence of operations, and the agency designed the system components to respond to those requirements. The agency and the manufacturer reviewed the design intent and reassured SimTigrate that the desired performance was achievable.

Once the lighting control system was installed on the jobsite, the agency's responsiveness to construction issues was exemplary, and they worked with the electrical contractor to resolve wiring issues. When the agent encountered undiagnosable control problems, they called in the experts from the manufacturer. There were video calls among the client (Emory), SimTigrate, PNNL, the agency, and the manufacturer to describe the inexplicable behavior of the controls and resolve the unpredictable performance. There were reassurances that the next update/reprogramming/equipment replacement would fix the problems. Hundreds of hours of honest effort were expended in troubleshooting, re-engineering hardware and software, and replacing product components in the field. As of September 2022, the lighting control system appears to be stable at last, but there has not been an accounting of the problems and solutions to understand the fundamental issues and inspire confidence that the next installation will be better.

One might conclude that the control system used at the CEP was simply fraught with design errors, and that it is an unfortunate anomaly. However, PNNL's experience with multiple tunable lighting projects, in many different applications and buildings, using many different brands of networked control systems, shows that this type of systemic poor performance is all too common.

SUGGESTIONS FOR SPECIFYING ARCHITECTURAL CONTROL SYSTEM WITH FEWER COMPLEXITIES

How can control systems be designed and specified for improved performance going forward? Several parties have commented that the control system was too complex, making it difficult to pinpoint the cause of problems and to implement solutions. Until systems have truly achieved "plug-and-play" functionality, *Table 2* addresses interim recommendations for system simplification:

Table 2: Recommendations for Simplifying Lighting Control Systems

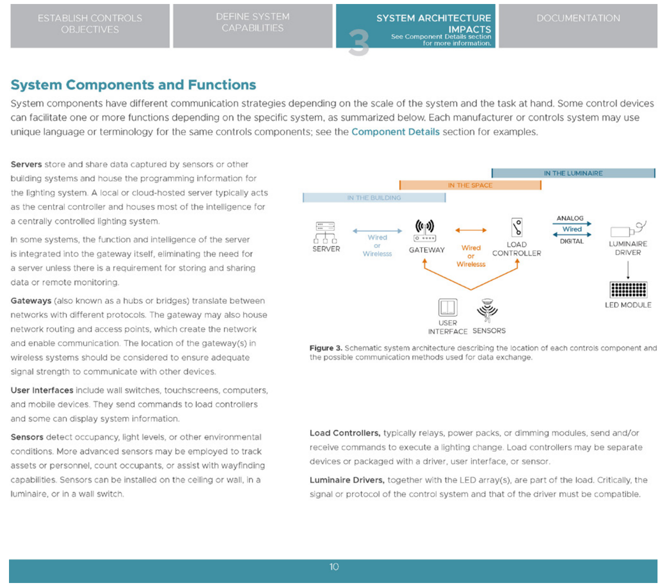
Keep Tunable White Systems Simple	Keep systems small and local. For example, confine the tunable lighting and controls to single rooms, not to a large number of rooms that must be coordinated through controls to match each other over the course of a day.
Align Tunable White Color Range	Tunable white does not have a consistent range from one manufacturer's system to another. One may be 3000 to 5000 K and another 2700 to 6500 K. If two different manufacturers' products are controlled as a system in a single space, it is best to specify luminaires with matched ranges.
Test Acceptability of Color Range Extremes with Occupants	Design professionals may want to test the tunable light colors with their clients. At CEP, most of the users, both clinical staff and MCI clients, reported that the 6500 K setting was too "cold." A setting of 5000 K may provide the needed "blue" spectral content for daytime stimulation without the negative reactions from tuning the lighting to 6500 K.
Avoid Customizing Control System	Requesting an additional feature not already offered in a control system's suite of capabilities may introduce performance that unexpectedly affects other functions.
Pay Careful Attention to Control Station Interfaces	Test wall controls and their displayed pages for usability before specifying. Changing scenes or even selecting OFF or ON may not be intuitive, especially to unfamiliar users. Also, a single screen or subsequent scene pages may be so crowded that the text becomes too small to read comfortably, especially for older users.
Team Relationships are Key to Troubleshooting and Good Outcomes	Work closely with the local manufacturer's agent for support. This company is a valuable link to getting service or replacement parts for the system, and is a necessary connection to the manufacturer(s) if insurmountable problems arise. All parties on the jobsite, including electrical contractors, are needed to report, diagnose, correct, and reprogram misbehaving systems. Ask for training on the controls system. A maintenance contract with the controls manufacturer or local agent is worth considering, especially if frequent changes are likely.
Occupancy Sensor Operations can be Distracting	Occupancy sensors are great for saving energy when a space is vacant, but some occupants can become confused, distracted, or irritated by lights switching on and off unexpectedly. Because of this, the CEP's server was ultimately programmed to override control signals from the occupancy sensors during daytime hours.
Timeclock Functions and Server Settings can Go Awry	When lights are on or off at unusual hours, check for multiple time-clock settings, server time settings, and programming of timed signals. Keep time clock functions as simple as possible, for example, by avoiding having each room on a slightly different time schedule.
Which Power Quality Problems are Relevant?	Sometimes manufacturers blame building power quality for performance issues. Control systems need to be resilient to power outages and brief events, since that is a normal occurrence in most U.S. locations. If the system is not resilient to common power distribution anomalies, marketing literature needs to clarify which power quality issues will disqualify the building from using that system.
Use Generic Terms for Controls Components	Different manufacturers may use different terms for each of the system components. Using more generic vocabulary makes it is easier to communicate the system architecture and components, as well as compare and bid alternate systems. See the Selecting Lighting Control Systems link below.

DOCUMENTS THAT CAN HELP

The U.S. Department of Energy's Next Generation Lighting Systems (NGLS) program has studied these networked control system issues and developed helpful documents that

- define a common vocabulary for controls to make it is easier to communicate with design professionals, lighting and controls agencies, contractors, and manufacturers;
- explain the different ways that networked controls work (wired vs. wireless as a simple example), system components, and the variety of capabilities to look for; and
- provide guidance by writing a controls intent narrative, sequence of operations, and design documents.

Figure 10 shows an example page from the NGLS brochure *Selecting Lighting Control Systems*.



ESTABLISH CONTROLS OBJECTIVES | DEFINE SYSTEM CAPABILITIES | 3 SYSTEM ARCHITECTURE IMPACTS See Component Details section for more information. | DOCUMENTATION

System Components and Functions

System components have different communication strategies depending on the scale of the system and the task at hand. Some control devices can facilitate one or more functions depending on the specific system, as summarized below. Each manufacturer or controls system may use unique language or terminology for the same controls components; see the Component Details section for examples.

Servers store and share data captured by sensors or other building systems and house the programming information for the lighting system. A local or cloud-hosted server typically acts as the central controller and houses most of the intelligence for a centrally controlled lighting system.

In some systems, the function and intelligence of the server is integrated into the gateway itself, eliminating the need for a server unless there is a requirement for storing and sharing data or remote monitoring.

Gateways (also known as a hubs or bridges) translate between networks with different protocols. The gateway may also house network routing and access points, which create the network and enable communication. The location of the gateway(s) in wireless systems should be considered to ensure adequate signal strength to communicate with other devices.

User Interfaces include wall switches, touchscreens, computers, and mobile devices. They send commands to load controllers and some can display system information.

Sensors detect occupancy, light levels, or other environmental conditions. More advanced sensors may be employed to track assets or personnel, count occupants, or assist with wayfinding capabilities. Sensors can be installed on the ceiling or wall, in a luminaire, or in a wall switch.

Figure 3. Schematic system architecture describing the location of each controls component and the possible communication methods used for data exchange.

Load Controllers, typically relays, power packs, or dimming modules, send and/or receive commands to execute a lighting change. Load controllers may be separate devices or packaged with a driver, user interface, or sensor.

Luminaire Drivers, together with the LED array(s), are part of the load. Critically, the signal or protocol of the control system and that of the driver must be compatible.

10

Figure 10: Descriptions of control system components and functions from the *Selecting Lighting Control Systems* brochure.

CONCLUSION

Building lighting controls offer great potential for reducing energy use while delivering color and intensity of light that may support health and learning. A whole-floor networked control system has many advantages, but with so many features and possible settings, the system can become too complex for easy installation, commissioning, troubleshooting, and use. The CEP project embodies all of these complexities, plus the special need to produce customized settings for research test conditions, the ability to log control system button presses, and the need accumulate data on lighting usage in multiple areas over days and months.

Once installed, the component parts, firmware, system controller, and software were not able to communicate and respond to commands consistently. Even when LED boards, drivers, and load controllers were replaced, some sections of cove lighting and linear pendants would tune to unexpected, inconsistent colors and light output, drawing attention. Timeclock functions, occupancy sensors, and photosensors all exhibited unexpected and unwanted behavior, and the problems were frustratingly difficult to diagnose and correct. In spite of good-faith efforts by the agent and manufacturer, the timeline of the corrections was untenable.

The NGLS has prepared a series of documents to help the lighting and controls industry understand the different kinds of control system architectures and components, communicate the control system's intent and function more clearly, specify systems, and diagnose solutions when difficulties occur.

ACKNOWLEDGEMENTS

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RESOURCES

- Selecting Lighting Control Systems
  (Guide, November 2022)
- Presence Detection in Connected Lighting Systems
  (Report, February 2022)
- Characterizing Connected Lighting Systems
  (Report, January 2022)
- The Influence of Communication on the Complexity of Connected Lighting Systems
  (Report, July 2021)
- An Observational Understanding of Connected Lighting Systems
  (Report, May 2021)
- The Impact of Wall Control Performance on Connected Lighting Systems
  (Report, March 2021)

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