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FINAL PROJECT REPORT

High-Efficiency Dynamic Lighting Systems

Gavin Newsom, Governor

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

High-Efficiency Dynamic Lighting Systems is the final report for the High-Efficiency Dynamic Lighting Systems project (EPC-18-007) conducted by Glint Photonics, Inc. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

Through this program, Glint Photonics has developed high-efficiency automated directional lighting fixtures. The fixtures produce beams of light whose direction, intensity, and color temperature can be adjusted remotely via an app or automatic control system. The project also included a demonstration of a fully automated task-lighting system, in which sensors detected the location of room occupants and automatically directed task lighting to their location.

Such automated systems can dramatically alter the deployment of lighting in the built environment, making lighting dynamic and responsive to changing use patterns and conditions, rather than fixed static distribution. The potential impacts include not only higher quality lighting and greater visual comfort, but also significant energy savings by reducing wasted light that results from uniform lighting in most spaces to account for maximum use cases at all times. Indeed, potential annual energy savings of up to 8 terawatt-hours are possible within California investor-owned utility service areas.

The fixtures developed in this program employ Glint's proprietary LightShift optics, which enable beam-steering adjustment via small in-plane motion of a lightweight optical component while the fixture itself remains stationary. This unique design is particularly valuable for remotely adjustable fixtures, as it greatly reduces mechanical complexity and load magnitude, enabling low-cost and high-reliability designs. The stationary nature of the fixture also results in simplified and highly attractive installation and eliminates the distracting motion otherwise associated with remotely adjustable fixtures. The prototypes developed in the program met all technical performance targets and were tested successfully in a pilot installation at the offices of a prominent California lighting designer.

Keywords: Solid State Lighting, Automated Lighting, Dynamic Lighting

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Introduction

Light emitting diodes (LEDs) have rapidly displaced legacy technologies in a wide range of lighting applications, yet the approach to designing and using lighting fixtures in buildings has remained largely unaffected by technological advances in recent decades. Lighting remains generally static, with ambient fixtures often providing uniform lighting over large areas, regardless of how the area is occupied or used at any given time. This traditional approach to lighting is not only unresponsive to changing uses, but it also wastes a great deal of energy by constantly lighting areas regardless of need.

This project was undertaken to pursue a different vision of lighting: fixtures that can dynamically target light wherever it is needed. The fixtures offer a beam that can be aimed and otherwise adjusted remotely, either through a user control or as part of a smart lighting system that automatically reconfigures lighting patterns depending on activities taking place within the space. Specific lighting patterns can be pre-programmed and called up when needed for different room uses. Intelligent controls can provision ensembles of steerable lights to provide any desired lighting distribution within a room. Sensor-driven systems can intelligently allocate extra lighting where tasks are being performed, allowing reduction of the ambient light levels. Such systems can not only transform the experience of the built environment, but can also greatly reduce the operational energy consumed in lighting. Indeed, experts at the U.S. Department of Energy have called out the need for smart dynamically targeted luminaires and estimated such luminaires can improve efficiency of light use by two to three times.[1] This improvement makes use efficiency the single largest energy-savings opportunity in lighting today.

Automated lighting is at present limited to occupancy sensing and dimming, but this leaves most of the energy-saving opportunity on the table as it does not provide high-resolution control over the spatial light pattern. State of the art in steerable luminaires is gimbaled spotlights with adjustable projector optics, produced by a handful of lighting companies. These are fundamentally bulky, expensive, and unreliable because they must pivot to change their pointing angle. Further, when aimed in different directions, these gimbaled spotlights have a disorderly appearance, and their beams are often occluded by the lighting enclosure or by adjacent lights. For these reasons, their use has largely been limited to a few niche applications such as event spaces with high ceilings, and the energy savings benefits of the approach have gone unrealized. New designs are needed that address these drawbacks and provide a highly capable, reliable, easy-to-use, and visually appealing fixture that can catalyze the development of advanced smart automated lighting systems.

Project Purpose

The goal of this project was to develop a market-ready remotely adjustable luminaire that provides substantial improvements over current technical solutions to expand the

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[1] J. Y. T. Tsao, M. H. Crawford, M. E. Coltrin, A. J. Fischer, D. D. Koleske, G. S. Subramania, G. T. Wang, J. J. Wierer and R. F. Karlicek, " Toward Smart and Ultra-efficient Solid-State Lighting," *Advanced Optical Materials*, vol. 2, 2014.

implementation of this energy-saving technology. Glint Photonic's fixture design is fundamentally different from other remotely adjustable fixtures, with anticipated advantages in reliability, cost, speed, glare, and visual appearance.

Glint's proprietary LightShift optical technology achieves beam steering by moving a lightweight internal optical part while the fixture itself remains stationary, rather than pivoting the entire luminaire as is the case for all conventional fixtures. The required motion for beam steering is short-distance (a few millimeters), low-force, and in plane; as a result, the fixtures can use low-cost commodity motors and can achieve fast steering and adjustment. Reliability is improved because the moving parts are fully enclosed to protect against fouling, and electrical and thermal components are largely stationary, reducing flexing or rotating of electrical connections. The LightShift optics are fundamentally low glare, and the stationary design results in consistent beam cutoffs that prevent high-angle light. LightShift also enables a unique sleek, compact, and stationary form factor, which makes installation easier and provides the design advantage of a compact and orderly array rather than the disorderly appearance that is typical of variously pointed spotlights.

This project sought to address three distinct categories of applications for remotely adjustable lighting fixtures. The first is user-aimed applications, in which the user actively aims the fixtures each time they are adjusted (for example, in a gallery or retail shop that changes display periodically). The second is scene-based applications, in which various lighting configurations ("scenes") are saved and can be called up afterward as needed (for example, in a multi-purpose room or conference space). The final is dynamic applications, in which lighting is continuously adjusted, either according to fixed programs or in response to sensor inputs (for example, to actively adjust for moving daylight and shadows, or to track room occupants and automatically provide task lighting for their activities). In the order listed, these applications require increasing performance level from the motion mechanics, control system, and user interface. Most current remotely adjustable lighting products only address user-aimed applications, while a few are also applicable for scene-based use. Dynamic applications provide the most transformative opportunity for new functionality and energy savings but are still nascent within architectural lighting to date.

Project Approach

This project was carried out entirely by the team at Glint Photonics. Glint is a start-up LED lighting manufacturer developing novel fixtures based on clean-slate innovation in optics and design. The company's workforce includes mechanical, electrical, optical, and systems engineers, and the team has deep experience in both optical design and automated motion control.

A technical advisory committee helped advise the effort. Committee members included Adel Suleiman, California Energy Commission lighting expert; Tal Margalith, executive director of the Solid-State Lighting and Energy Electronics Center at UC Santa Barbara; and George Loisos, founder of Loisos + Ubbelohde Lighting Design. The members provided valuable input on design, market, and energy usage considerations both during the advisory committee meeting and through separate conversations.

In addition to the technical advisory committee, Glint pursued many one-on-one conversations with potential customers, lighting designers, architects, and industry experts, to refine the product concept and key specifications.

The project proceeded through several phases: (1) an information-gathering phase that informed the technical specification requirements for the system, (2) many rounds of design iteration and prototyping to achieve high-performance product design, (3) thorough testing and evaluation of the final design for reliability and performance, and (4) demonstrations, including both a demonstration installation of products for scene-based control and an in-house demonstration of automatic sensor-driven dynamic lighting.

The remotely adjustable fixtures developed in this program shared the design and capabilities of Glint's award-winning Hero spotlight, the company's first commercial product, but add the ability to remotely aim and control the fixture. To do so, Glint engineers tackled a wide range of system design issues, including specifying motors; developing the mechanical design; integrating encoders to monitor the position of the optics for repeatable aiming; developing the control electronics and firmware that interface with the encoder and drive the motors; developing the communications electronics and firmware for passing information from the luminaire to the user control system; and customizing the user interface for easy control and programming.

Project Results

The project achieved all of its technical goals. The final pilot prototypes featured a nearly production-ready design and met all the target specifications established for their performance. They provided beams steerable to at least a 40-degree tilt in any direction, aiming repeatability to less than 1 degree, and straightforward control via the Casambi app or any DMX control system.

The prototypes are suitable for application in any of the three areas identified: user-aimed, scene-based control, and dynamic control. Ten units of the final pilot design were built and tested. All worked successfully and met the various performance metrics. Initial reliability testing was performed on one unit, which was operated at elevated temperature and to 10,000 cycles of the actuation system without significant performance degradation. These are promising initial results, although further reliability testing is warranted before product finalization.

An automatic task light capability was developed as a demonstration of dynamic sensor-controlled lighting. A thermal infrared camera was used to locate a person in the field of view, and an automated control system adjusted the beam to illuminate the area around the person as he or she moved within the angular range of the fixture, providing task light wherever the person was located, a simple demonstration of a valuable new type of functionality.

Finally, a demonstration installation of the pilot fixtures was arranged in the offices of Loisos + Ubbelohde, one of the nation's leading lighting design firms. The installation provided real-world validation of the fixture performance as well as a compelling knowledge transfer opportunity, as the fixtures were centrally displayed and viewable by all visitors to the office.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

The project results have been shared with the lighting community through presentations at conferences, meetings, and tradeshows. The audience for these presentations included the lighting designers and architects that ultimately specify lighting fixtures; other companies active in the lighting industry; academic researchers in lighting and lighting technologies; and government labs and funders of lighting research. Presentations were unfortunately limited during the course of the program because of pandemic-related shutdowns, but Glint will continue this outreach following the conclusion of the program.

The goals of the presentations were to showcase the new technical capabilities of the fixtures, as well as their functional benefits and energy-savings potential. The presentations have contributed to the growing community interest in dynamic lighting, helping to kick-start the broad research on optimized sensing platforms, control systems, and response algorithms that will be required to fully realize the promise of dynamic lighting systems.

The overarching goal of this project was to develop a fixture design that could lead to a commercial product manufactured and sold by Glint, advancing the energy savings potential of dynamic lighting while simultaneously supporting the business goals of the company. Glint anticipates launching a commercial product based on the output of this project within a year of the project's conclusion.

The global luminaire market is estimated at approximately $70 billion annually, of which $18 billion is explicitly in directional lighting (track and downlights), and as much as 30 percent of the remainder is also accessible to the technology developed in this program. The California portion of the directional lighting market alone is estimated at about $160 million annually, of which about 37 percent is residential, 23 percent is retail, and 16 percent is office/industrial.[2]

Benefits to California

This project has supported the EPIC goals of lower costs, increased safety, and greater reliability by advancing more precise and adaptable illumination in occupied spaces in California and working to increase the adoption of efficient, long-lasting LED-based luminaires.

Anticipated energy savings originate from improved targeting of light (reducing the amount of light that needs to be generated to light a particular setting), reduced embodied energy from the smaller form factor and more efficient use of materials, and reduced occlusion. Taken together, these factors can reduce the total five-year energy footprint of a track-mounted directional lighting fixture from 569 kilowatt-hours to 193 kilowatt-hours, a savings of 66 percent.

Present annual energy expenditures in investor-owned utility territories for residential and commercial lighting total 40.9 terrawatt-hours. Approximately one quarter of this market is addressable by versions of the remotely adjustable luminaire, meaning 10.2 terrawatt-hours of

[2] Strategies Unlimited, Global Luminaires – Market Analysis and Forecast 2017.

energy is consumed by lighting fixtures that could be replaced with such dynamic luminaires.[3] The potential annual energy savings range from 1 to 8 terrawatt-hours, for varying levels of dynamic lighting sophistication. This amount of potential energy savings corresponds to as much as 331,000 metric tons of avoided carbon dioxide emissions, worth between $160 million and $2.3 billion per year.

Remotely adjustable luminaires also offer many qualitative benefits to California ratepayers and citizens. They eliminate the effort, cost, and physical danger associated with manual re-direction of steerable lights from ladders. Further, a single adjustable luminaire can replace multiple conventional luminaires when used in scene-based applications, saving cost in equipment and installation. Most fundamentally, the use of remotely adjustable luminaires makes it easier to provide optimal lighting distributions in any lit environment, which will enhance safety, productivity, and occupant experience.

[3] DOE EERE Report "LED Market Adoption: Status and Trends" – Nov 2015

CHAPTER 1: Introduction

Motivation

Light emitting diodes (LEDs) have rapidly displaced legacy technologies in a wide range of lighting applications, dramatically reducing the energy required to generate light. However, lighting remains a significant portion of overall energy use. There is further opportunity for energy savings in lighting by improving not only the efficiency with which light is generated, but also the efficiency with which it is used. The goal of this project was to develop new LED-based lighting products that can address this energy-saving opportunity by providing the ability to dynamically target light wherever it is needed. The fixtures offer a beam that can be aimed and otherwise adjusted remotely, either through a user control or as part of a smart lighting system that automatically reconfigures lighting patterns depending on activities taking place within the space.

This novel capability represents a second revolution in LED lighting: an enormous amount of light is currently wasted because it is poorly targeted. This waste cannot be addressed solely by occupancy controls and dimming, as this provides a low spatial resolution response to lighting requirements and typically requires installing many more luminaires than necessary. Indeed, the U. S. Department of Energy (U.S. DOE) solid state lighting research and development plan calls out the need for smart dynamically targeted luminaires and estimates those luminaires can improve the efficiency of light use by two to three times. This makes use efficiency the single largest energy-savings opportunity in lighting today.

In addition to reduced operating energy, such lighting products can provide new functionality, enable substantial customer cost savings by reducing the number of installed luminaires needed, and provide improved lighting quality and safety in the lit environment. Lighting can become a dynamic and responsive part of the built environment. Specific lighting patterns can be pre-programmed and called up when needed for different room uses. Intelligent controls can provision ensembles of steerable lights to provide any desired lighting distribution within a room. Sensor-driven systems can intelligently allocate extra lighting where tasks are being performed, allowing the ambient light levels to be reduced.

State of the art in steerable luminaires are gimbaled spotlights with adjustable projector optics, produced by a handful of lighting companies. These are fundamentally bulky, expensive, and unreliable because they must pivot to change their pointing angle. The design has exposed joints subject to fouling, large moving mass that requires high-power motors, and electrical components that must flex and rotate. Further, when aimed in different directions, these gimbaled spotlights have a disorderly appearance, and their beams are often occluded by the lighting enclosure or by adjacent lights. New designs are needed that address these drawbacks and provide a highly capable, reliable, easy-to-use, and visually appealing fixture that can catalyze the development of advanced smart automated lighting systems.

Application Areas

Remotely adjustable lighting fixtures can address a range of applications. To define product requirements, the personnel of Glint Photonics, a start-up LED lighting manufacturer developing novel fixtures based on clean-slate innovation in optics and design, explored these various applications through discussions with lighting designers, potential customers, and potential end users in a variety of settings. Among those interviewed were lighting professionals at 8 Inc, Loisos + Ubbeholde, Clanton & Associates, and Larry French. Glint also exhibited at the Lightfair International tradeshow in May 2019, and used a robot-driven luminaire demonstration as a launch point for discussions of the value of lighting automation with many visitors to the booth.

A partial list of applications discussed follows, along with notes on example use scenarios. It is divided into three categories. The first is user-aimed applications, in which a user is actively adjusting the luminaires each time the aiming is changed. Most existing remotely adjustable architectural lights are targeting these applications. Examples include:

- Retail. Remotely adjustable fixtures are particularly attractive in those retail environments where large merchandise is displayed and changed regularly — for example furniture stores and auto dealerships. In these settings it is difficult to manually adjust the fixtures because the merchandise blocks ladder placement.
- Spaces with high ceilings. The atriums of hotels and large office buildings can feature spaces with very high ceilings that make directional adjustment of fixtures prohibitively difficult, expensive, and dangerous. Remotely adjustable fixtures make sense in these spaces even if they are rarely adjusted. Indeed, in some cases they have been specified simply to enable one-time initial aiming adjustment.

A second category of uses is scene-based applications. In this case, multiple different configurations are defined in advance and can then be called up by users via a controller. This enables significantly more functionality. Examples include:

- Office conference rooms. Conference rooms often have multiple and redundant sets of lights controlled by a bank of switches — one set for general discussion, another for teleconference, and a third for presentations. Cost and energy savings can be obtained by replacing these multiple sets of lights with a single set of lights that can be adjusted to produce different pre-programmed scenes.
- Multi-purpose rooms (for example, in school and university settings). Such rooms are used for meetings, classes, presentations, and performances. Reconfigurable lighting greatly simplifies setup and provides the ability to improve the occupant experience.
- Event spaces (for example, reception areas, hotel ballrooms, and similar venues). Remotely adjustable lights are used to reconfigure lighting quickly and easily for various uses, such as to accommodate varying placement and size of tables, and similar adjustments.
- Museums. Remotely adjustable fixtures are particularly useful in galleries that host regularly changing exhibitions and in galleries that are used as event spaces.

The final category is dynamic applications, which make use of high duty-cycle dynamic movement and adjustment. At present, the application of such capabilities is limited primarily to theatrical lighting. However, a goal of the work undertaken in this program is to begin enabling more widespread adoption to achieve improved lighting functionality and significant energy savings in a variety of applications. Some involve dynamic adjustment according to a pre-programmed pattern, and others involve the integration of sensors and control intelligence that allow the light distribution to respond to changes in the environment. A few possible scenarios, developed through discussions both within Glint and with outside experts, include:

- Dynamic lighting for displays, with moving light patterns to draw viewer interest
- Slowly varying lighting patterns for home and office environments, to provide a naturalistic sense of changing light
- Daylight simulation with lighting that adjusts both color spectrum and direction over the course of the day to align with natural circadian rhythms
- Daylight compensation: intelligent lighting systems that automatically compensate for the changing distribution of natural sunlight in a room, ensuring that all surfaces are lit to the necessary levels.
- “Follow-spot” lighting that automatically follows a speaker during a presentation
- Automated task lighting that identifies where work is being performed and provides the appropriate task lighting (allowing ambient lighting levels to be reduced to save energy)
- Smart lighting systems that combine many of the features listed above. For example, a smart dynamic lighting system in a hotel lobby could be designed to (1) adjust lighting over the course of the day in response to changing daylight and traffic patterns, (2) identify where guests are sitting on sofas or at tables, providing light for reading or conversation, (3) provide automatic safety lighting as appropriate, for example when detecting guests walking up a stairwell at night or appearing to stumble as they walk, and (4) provide dynamic lighting displays for dramatic effect in the evening or other times or situations.

These three areas of application have very different requirements in terms of mechanics, user controls, and system integration. One obvious difference is duty cycle: in user-aimed applications re-aiming might occur several times per year; in scene-based applications, several times per day; and in dynamic applications, several times per minute. This difference in duty cycle (or lifetime cycles) spans several orders of magnitude, with resulting differences in required durability of the mechanical system. Response time is another key element of the mechanical design, with faster slew time required for high-speed dynamic applications.

Controls are another key difference. For user-aimed applications, all that is needed is a directional controller to aim an individual fixture. For scene-based applications, the requirements are more complex. Each fixture must have an internal encoder that allows it to accurately track its aiming direction to faithfully replicate pre-programmed aiming positions. The control system must present a user interface that allows easy programming and recalling of scenes. Finally, dynamic control requires a complex user interface allowing programming of timed animations and integration of sensor data for feedback control.

These differences also affect system integration. User-aimed applications may be achieved with simple stand-alone fixtures, but scene-based applications require a control system that networks fixtures together so that scenes involving multiple lights can be defined. The system should not be proprietary only to the Glint fixtures but encompass an entire ecosystem of luminaires for scene-setting in realistic installations involving multiple fixture types.

Interoperability is even more important in dynamic applications. Since these applications are nascent and involve integration with various sensor types, an open and highly flexible control system is desired to enable easy programming and experimentation.

Table 1 summarizes these three types of application scenarios.

Table 1: Application Scenarios for Remotely Adjustable Fixtures

Scenario	Re-aiming Frequency	Application Examples	Functionality Benefits
User-aimed	<1x per day	• Event spaces (hotel ballroom, school multi-purpose rooms) • Retail (periodic re-arrangement of floor layout) • Galleries	• Better lighting distribution (re-optimize regularly) • Save labor cost on re-aiming • Eliminate safety risk from ladders and cherry-pickers
Scene change	<10x per day	• Office • Conference room • Home • Multi-purpose rooms	• Multiple scenes can be called up on command • Cost savings from fewer installed fixtures • Automatic commissioning • Better lighting distributions
Dynamic tracking	Continuous	• Sensor-driven intelligent task-lighting • Smart outdoor lighting that tracks individuals for security • Automated conference room lighting that illuminates speakers	• Best lighting for activities, all the time • Save money and save energy • Programmable for many sensor-driven applications

Project Goals and Objectives

The goals of the technology developed under this project were to:

- Improve light use efficiency by allowing dynamic light configuration
- Reduce the cost and complexity of automated steerable lighting systems
- Improve user experience and safety in lit spaces
- Enable greater market penetration of solid-state lighting
- Help meet California's lighting energy use goals

The specific objectives of the project to address these goals were identified as follows:

- Optimize core luminaire performance to meet the market requirements
- Develop the luminaire motorization system to meet long-term durability targets

- Develop intuitive systems for luminaire control that provide required feature sets
- Develop a luminaire product for scene-based applications that meets all product requirements
- Demonstrate a sensor-linked luminaire for dynamic applications that tracks room occupants and directs a task light that follows their location

These objectives were chosen to provide stepping-stones toward general-purpose automated lighting systems. The luminaire product for scene-based applications can meet current and near-term use cases for remotely adjustable luminaires and provide initial market opportunities for the product.

Automated dynamic lighting systems are not yet well defined. The prototype luminaire for dynamic applications was therefore intended to serve as a test bed, enabling experimentation with sensor-connected smart lighting approaches. The automated task light demonstration was chosen to provide an example of such a system.

Technology Approach

The foundation of Glint's dynamic lighting technology is the company's patented LightShift optics. These novel optics are designed to take advantage of the unique properties of LEDs as small high-brightness directional light sources. LightShift optics allow luminaires to be mounted stationary, while still projecting beams that can be aimed over a wide steering range. This breakthrough design is behind the company's manually adjusted Hero lighting fixture, which has won many industry awards for its technology and design. It is the first approach to enable robust, reliable, low-cost automation of beam pointing. Further, the luminaires are energy efficient, low-profile, easy to install, and very low glare, and they offer new flexibility in form factor and design.

Glint's LightShift optics platform addresses all the limitations of current technology and is naturally suited to low-cost, high-reliability motorization. The sleek fixture design is stationary, and steering is achieved by moving a lightweight internal optical part rather than pivoting the entire luminaire. The required motion is short-distance, low-force, and in plane, and the moving parts are fully enclosed to protect against fouling. Further, all electrical and thermal components are stationary, so there is no flexing or rotating of electrical connections.

In this project, Glint developed remotely adjustable luminaires based on the Hero spotlight platform. The joystick-driven mechanical linkage within the manual Hero was replaced with a motorized motion system. Control electronics and software were developed through multiple iterations. A final pilot fixture design was developed for scene-based applications, extensively tested, and validated through a demonstration installation in the offices of Loisos + Ubbelohde, a prominent lighting design firm located in Alameda, California. Dynamic control methods were also developed, and a demonstration of an automated lighting system was achieved using overhead sensors to detect the presence of individuals within a room and automatically direct a task light to their location.

CHAPTER 2: Project Approach

Product Requirements

The goals of this program were (1) to develop a highly capable remotely adjustable product that could address both user-aimed and scene-based applications and (2) to develop a prototype product for dynamic applications, along with a control system that allows experimentation and evaluation of dynamic use-case scenarios.

Based on these applications, the Glint team developed a draft of requirements for the project, organized into a market requirements document (MRD), product requirements document (PRD), and technical specifications document (TSD). Separate MRD, PRD, and TSD specifications were developed for the user-aimed/scene-based applications and for dynamic applications. These documents were reviewed and revised during the program and served as the basis for the prototype development effort that formed the main body of work undertaken.

One key decision made at the outset of the project was to align the form factor of the remotely adjustable products with Glint's manually adjustable Hero spotlight product (concurrently under development). The manually adjustable product uses a joystick located in the front face of the fixture to allow the user to adjust the beam aiming through a mechanical linkage inside the fixture. Beam aiming can be adjusted up to a 40-degree tilt angle at any pan angle, a range that covers most use cases for adjustable fixtures.

Aligning with the manual Hero form factor had several advantages. First, from a product perspective, it allowed the remotely adjustable product to fit directly into an existing product family, as an upgrade option from the manually adjustable version. Second, from a development perspective it allowed the design to leverage the large existing investment in the manual Hero product, copying its mature industrial design and allowing reuse of many parts that are common between the two versions. This allowed the work performed under this bridge program to focus on developing the novel elements of the motorized product—its mechanics, motorization, and controls—rather than having to invest substantial efforts in developing a new cosmetic housing, optics mounting hardware, and other components.

There was also one downside of adopting the manual Hero platform: optical performance was limited to that achieved by the manual product. This meant that the beam could be steered to aim but could not be broadened and narrowed. In early program planning Glint had considered designs that offered this beam-broadening capability, but offering that capability would have required an entirely new fixture design and form factor and would not allow the synergies just described. Further, the greatest benefit in remotely adjustable fixtures comes from control over beam aiming, not beam width. Control over beam width was therefore omitted from the work under this program and left as an area of future work.

The target flux level for the product was set at a minimum of 700 lumens for residential and gallery type applications, with 1,200+ lumens preferable for retail type settings. High-quality color rendering was a requirement, so the target color rendering index (CRI) was set at 90 or more. Variable correlated color temperatures (CCT) were a useful feature in some applications

— for example, to adjust the color temperature over the course of the day in accordance with natural circadian rhythms — while other applications called for a fixed color temperature. This program explored both types of product designs. Finally, overall luminaire efficacy was maximized to ensure energy efficiency. High-end, narrow-beam spotlights with high CRI typically provide efficacy of 40 – 70 lumens per watt (Lm/W). The target for this program was set at 60 Lm/W to be competitive with conventional fixtures in efficacy while still providing all the other advantages of remote adjustability.

Table 2 presents summary product requirements abstracted from the MRD, PRD, and TSD documents.

Table 2: Target Technical Specifications for the Program

Technical Specifications	User-aimed / Scene-based	Dynamic
Light Engine		
Efficacy (Lm/W)	>60	>60
Color uniformity (Δu'v')	≤0.004	≤0.004
Correlated color temperature (K)	2700 - 4000 fixed or variable	2700 - 4000 fixed or variable
Color rendering index (Ra)	>90	>90
Lumens per beam (Lm)	>700 or >1200	>700 or >1200
Fixed beam width (°)	13, 22, 32	13, 22, 32
Adjustability		
Steering range tilt (°)	40	40
Steering range pan (°)	infinite	infinite
Steering accuracy (°)	<2	<2
Slew rate (°/sec)	>20	>50
Control interfaces	Wireless, app-based	App-based, DMX/RDM
Control capabilities	Aim, scenes	Aim, scenes, dynamic
Reliability		
Rated duty cycle (actuations/day)	10	1000
Rated lifetime (actuations)	>50,000	>5,000,000

Product Design

Industrial Design

As previously noted, the remotely adjustable fixtures developed in this program are based closely on Glint's manually adjusted Hero light fixture, currently being manufactured. This was a direct result of decisions taken in the target definition and was chosen to ensure high production readiness at the end of this program. The remotely adjustable fixture shares almost all key components with the manually adjusted version, including all housing components, optics, LED circuit board, and many of the mechanical components. All these shared components are currently in production, with identified suppliers and existing validated production tooling.

The Hero design features a linear array of 10 LEDs, each paired with a focusing optic. Optics are available to produce beam widths of 11, 13, 22, and 32 degrees. These novel LightShift optics allow the beam to be steered to tilt angles of at least 40 degrees in any pan direction.

Hero is initially being brought to market as a track-mounted fixture. Its sleek form measures 311 millimeters (mm) x 74mm x 45mm (not including stem and track adapter) and is available in black, white, or silver finish. Hero's tilted top allows field-adjustable mounting either pointing straight down (for center-of-room applications) or tilted up 35 degrees (for edge-of-room applications). In either configuration, the fixture provides unparalleled beam uniformity, extremely low glare, and the completely novel functionality of LightShift beam-steering optics.

The pleasing minimalist design of the Hero fixture is the result of collaboration with the renowned California-based industrial design firm Whipsaw. Hero has won a large number of industry awards for its design and technology, including a Red Dot award (2021), iF Design Award (2021), IDEA Award (2020), Silver IDA Design Award (2020), Good Design Award (2020), Lightfair Design Excellence Award (2020), Light + Building Design Plus Award (2020), LEDs Magazine Sapphire Award (2020), Best Products Award from Architectural Record (2020), Spark Platinum Award (2020), German Innovation Award Gold (2020), and LIT Lighting Design Award (2019).

LightShift Optics

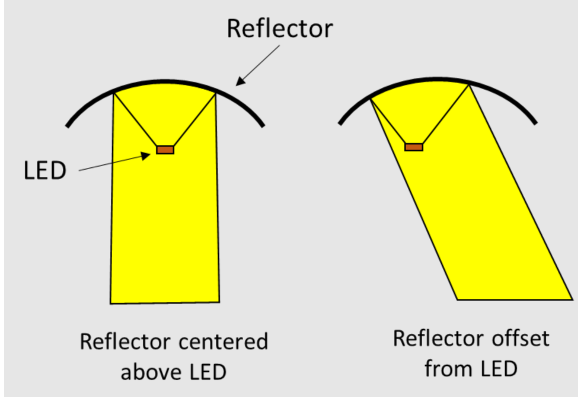
The optical design for the Hero uses a linear array of reflective lenses associated with a matching array of LEDs. The diodes face into the fixture body and fire back into the reflectors. This design provides a highly compact collimating optic and low glare because the emitters are facing away from viewers. Adjusting the placement of the LED relative to the optic adjusts the angle of the light beam leaving the luminaire, as shown in Figure 1. Only small (mm-scale) in-plane motions of the lightweight optics are required to steer the beam.[4]

This functionality makes LightShift uniquely suited to automation. Conventional luminaires need the entire light engine to pivot to aim the beam, which results in high-torque and high-load requirements on the motors and mechanics. These systems also necessarily involve external pivoting joints and flexing wires. As a result, these systems can suffer from poor reliability and/or high costs. LightShift should provide a superior platform for designing remotely adjustable fixtures, enabling the use of commodity motors in a high-reliability but low-cost final product.

Prototype fixtures were built with both fixed CCT and variable CCT designs. The latter used arrays of low CCT LEDs and high CCT LEDs in an alternating pattern, with control over the relative drive current for the two types of LEDs.

[4] J. Lloyd, P. Kozodoy, C. Gladden and A. Kim, "Stationary Adjustable Luminaires Via Optical Beam Steering," in *Optical Devices and Materials for Solar Energy and Solid-state Lighting 2019*, Burlingame CA, 2019.

Figure 1: Beam Steering with LightShift Optics



Thermal Design

Heat produced by the LEDs must be conducted to the external surfaces of the luminaire (or its mounting hardware) for convective cooling into the environment. Hero's thermal design includes optimization of the circuit board design, housing design, and the thermal interface between the two.

The housing is made of extruded aluminum, which provides an excellent thermal path. Optimization of its design for convective heat shedding has been carried out experimentally by varying the shape and surface area of the housing and testing its thermal performance under a range of ambient and drive conditions.

Mechanization

Mechanization formed a major area of technical work in this program. Several mechanical approaches were evaluated for motorizing the internal motion. These included cam-driven systems, crankshaft-driven systems, and various types of linear sliders. In addition, various motor types were sourced and evaluated, and a variety of encoder technologies were tested.

Key constraints on the design included (1) target positioning precision and slew speed, (2) torque requirements for motor drive, (3) design for high-reliability operation over many cycles, (4) the need to operate smoothly at various mounting orientations (that is, directions of gravitational force on the system), (5) maintaining smooth motion and resisting jamming of the moving parts, (6) tightly constraining any rotation of the optics array, as this can result in degraded beam properties, and (7) cost.

Potential designs were evaluated through paper study as well as experimentation, both in dedicated testbeds and through the various prototype generations fabricated in the project.

The ultimate design implemented because of these optimization procedures is summarized here. The mechanical design borrowed most elements from the manual Hero product, which had undergone its own optimization for cost and control of unwanted rotation in the optics array. Motorization was achieved using small stepper motors with integrated gearboxes. These commodity motors are low-cost and very compact and available in a range of torque/speed bands thanks to various gearbox configurations. The brushless nature of the stepper design aids with long-term reliability. Encoding was provided via a Hall effect sensor mounted on the LED circuit board and a neodymium magnet mounted on the optics array. This non-contact encoder mechanism provides a long-lifetime, temperature-insensitive, high-precision absolute measurement of x and y position. The parts used were designed for automotive application and are very inexpensive.

Communications

A second major area of technical work during the program was development of the communications for the control system. A wireless control system accessible from a mobile app was desired for easy access in user-aimed and scene-based applications. Additional requirements included an intuitive and straightforward user interface, the ability to set and control scenes with multiple fixtures in a group, and interoperability with other (non-Glint) fixtures and components. Dynamic applications required more complex programming, so an interface allowing control from a personal computer (PC) was preferable, whether connected by wireless or wired communication.

It was decided early in the project to pursue a wireless control system operated over Bluetooth Low Energy (BLE) Mesh, which is emerging as a standard protocol for wireless lighting control and allows app-based control from mobile platforms. This wireless protocol allows each BLE fixture to form a network node exchanging information with its neighbors, greatly expanding the signal reach, and eliminating the need for centralized control nodes.

There are three key portions of the wireless control system: (1) the communications hardware that goes in the luminaire, consisting of the Bluetooth communications module and control microprocessor, (2) firmware, the software resident on the luminaire that controls communications, and (iii) user interface, a control app that runs on mobile platforms such as iOS or Android phones and tablets.

Several options were evaluated for implementing the control system. One option was for Glint to develop its own communications hardware, firmware, and user interface. However, this would not be easily interoperable with fixtures and components from other manufacturers. A second option was to use a BLE lighting control technology platform from one of the companies developing these products for lighting manufacturers. These companies include Xicato, Casambi, Silvair, Bubblynet, BlueRange, and others. Each of these companies offers a different combination of hardware, firmware, and user interface components.

After analyzing each of the options, Glint chose the Casambi platform for wireless communications. Casambi provides a dedicated Bluetooth control module running its proprietary firmware, as well as a control app that operates on both iOS and Android platforms. Casambi is an appealing choice for several reasons. Its control system has achieved widespread adoption (especially in Europe) and is seen as a market leader. As a result, there is a substantial ecosystem of Casambi-controlled fixtures and components with which the Glint product can integrate. The Casambi system provides one of the most complete turnkey solutions available, allowing the Glint team to focus project work on developing the control elements that are unique to the motorized Hero platform. And, unlike many of the other BLE control platforms, Casambi already provides a mechanism for sending pan and tilt aiming requests from the user to the fixture.

For dynamic applications, Glint implemented a digital multiplexing (DMX) control option within the fixtures. DMX is a well-established standard for entertainment lighting and has been used in theatrical applications for many years. DMX is an open standard, allowing easy implementation on a variety of hardware. There are many DMX control components and software packages that are readily available, so DMX was a compelling choice for an open platform to enable easy experimentation in sensor-controlled dynamic lighting. DMX is a wired standard, requiring a direct wired communications channel to the luminaire. This can be achieved through the embedded data bus option in many track systems including those offered commercially by Glint.

Control Hardware and Firmware

The final major area of technical work was the development of control hardware and firmware within the luminaire. Glint developed a control circuit board with a microprocessor that receives commands from the Casambi Bluetooth module and the onboard DMX communications circuit. The microprocessor also receives the position signal from the Hall effect encoder, and it controls two on-board stepper driver circuits to move the motors. Glint developed firmware that runs on the microprocessor to parse the incoming commands and control the motors as appropriate. The architecture and implementation of the control hardware and software were developed through several generations and extensive internal testing and debugging.

Generations of Prototypes

Demonstrator

The demonstrator was a proof-of-concept prototype created by crudely adding motorization to a manual Hero fixture. It served as an early demonstration of technical capability. However, it lacked many key elements, including an encoder system for absolute positioning. It could be driven using a handheld wired joystick controller or a basic implementation of the Casambi interface, in a user-aimed mode only.

Scene-based Prototype

The scene-based prototype (or "beachhead design") included the Hall effect sensor for absolute position encoding, as well as a Casambi module for wireless communications. An early version of Glint control hardware and firmware was implemented. This prototype was used to iterate the mechanical design as well as the control hardware and firmware. Tests of aiming range, accuracy, and speed were carried out. Demonstrations of scene-based control through the Casambi app were achieved, with scenes including two individually aimed prototype luminaires.

Dynamic Prototype

The dynamic prototype added the DMX communication channel with associated circuitry and firmware updates. DMX control of the dynamic prototype was demonstrated via Open DMX software on a PC.

A demonstration of a sensor-driven automatic task light was also achieved. This entailed mounting two sensors (a thermal camera and a depth sensor) next to the luminaire and connecting them to the control PC. Software determined the location of a warm "blob" on the thermal camera to identify where a person was performing a task within the field of view of the camera. Glint's control software then determined the appropriate pan and tilt setting for the luminaire to illuminate the task and sent the appropriate steering commands via DMX. The automatic task light demonstration provided a beam that followed an individual as he or she moved about a room and dimmed if no one was present. This is a simple example of the type of dynamic lighting that could generate novel functionality and significant energy savings by providing targeted task light only where it is needed.

Pilot Prototypes

The final pilot prototypes represent a production-compatible design. They were built using many of the parts from the production Hero and share its external design. Consolidated control circuitry fit easily within the production form factor. These prototypes offered both Casambi and DMX control. In addition, they provided adjustable CCT from 2,700 Kelvin (K) to 4,000K, a feature that is not yet implemented on the manual Hero product.

The pilot prototypes were tested extensively for steering range, beam quality, and temperature stability. Prototypes were cycle tested to greater than 10,000 operational cycles without degradation. Calibration procedures were developed to ensure consistent aiming between different units.

Pilot prototypes were installed in a demonstration installation at the offices of Loisos + Ubbelohde, a premier lighting design firm located in Alameda, California. The demonstration installation consisted of nine luminaires (three each at three different beam angles).

CHAPTER 3: Project Results

Demonstrator Prototype

The goal of the demonstrator prototype, shown in Figure 2, was to demonstrate the fundamental capability of the product and to serve as a platform for exploring various control schemes.

Figure 2: Demonstrator Prototype

Design and Fabrication

The demonstrator prototype was built using an early version of the manually adjusted Hero luminaire parts. The prototype successfully demonstrated adjustable beam pointing with control through the Casambi Bluetooth mesh interface using a mobile app. This exceeded the initial target, which was only to implement a wired control system.

Results

The measured performance of the demonstrator luminaire is tabulated in Table 3 and compared to the strawman specifications listed in the original project proposal for the demonstrator prototype.

Performance meets or exceeds most targets, including providing faster slew rates and a more mature control system than originally targeted. Steering range was limited artificially by the design of the crankshaft mechanisms and does not represent the full plus-or-minus 40 degree range of which the platform is capable. Because encoders were not included, it was not possible to drive to a target pointing angle to test positioning accuracy. Durability and reliability were not rigorously assessed, but the prototype was put through more than 1,000 cycles during the testing with no gross reliability issues observed.

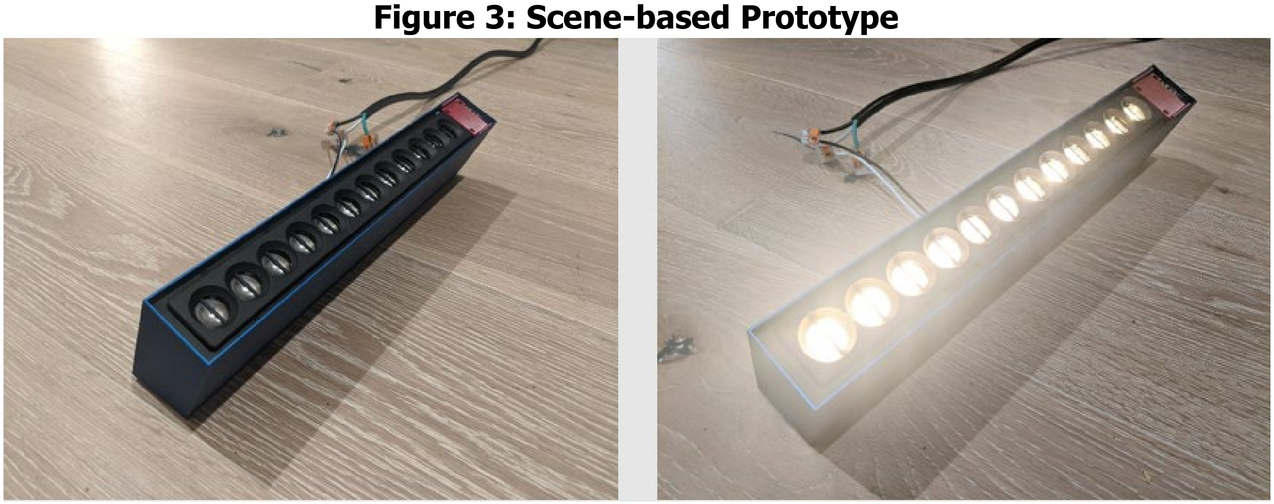
Table 3: Measured Performance of Demonstrator Prototype

Light Engine	Target	Demonstrated
Efficacy (lm/W)	>60	61
Color uniformity (Δu'v')	≤0.004	≤0.004
CCT (K, fixed)	2700 – 4000	4000
CRI (Ra)	>90	> 92
Lumens per beam (lm)	>700 or >1200	1340
Fixed beam width (°)	13, 22, 32	22
Adjustability		
Steering range tilt (°)	± 35°	± 32° (long axis) ± 21° (short axis)
Steering range pan (°)	infinite	infinite
Steering accuracy (°)	<2	Not measured (theoretically 0.068°)
Slew rate (°/sec)	>10	> 70 (long axis) > 50 (short axis)
Control interfaces	Direct wired	Wireless, app-based
Control capabilities	Aim	Aim
Reliability		
Duty cycle (actuations/day)	0.1	N/A
Lifetime (actuations)	>1000	>1000 cycles performed

Scene-based Prototype

The goal for the scene-based prototype, shown in Figure 3, was to produce a luminaire with sufficient duty-cycle and control capabilities to provide programmed scene changes a few times per day.

Figure 3: Scene-based Prototype

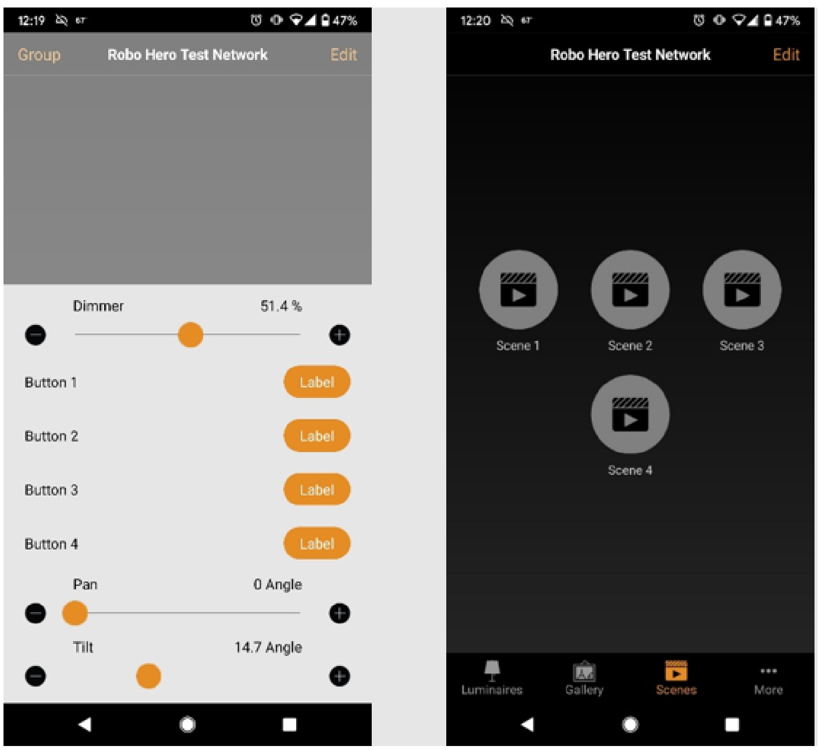


Design and Fabrication

The mechanical design for the scene-based prototype was updated from that used in the demonstrator prototype and based closely on the then-emerging production design for the manually adjusted Hero. The new mechanical design proved more robust than the crankshaft approach used in the initial demonstrator and provided for greater positioning precision. The scene-based prototype also included the Hall effect sensor to provide position feedback to the control system. The fixed sensor measured the position of a magnet mounted on the moving optic holder, providing feedback on both *x* and *y* position of the optics array. In this prototype the sensor was mounted on its own circuit board, abutting the LED board.

The Casambi user interface, Figure 4, was updated to include three sliders: one for dimming level (0 percent to 100 percent) and two for beam aiming (0 degrees to 360-degree pan and 0 degrees to 32-degree tilt). In addition to using the slider control, fine adjustments to each of these values can be achieved using the "+" and "-" buttons. The Casambi app also allows a configuration to be saved as a "scene," and different scenes can then be called up at will. It further provides for "animations" that fade one scene into another and for animations to be scripted to run at particular times.

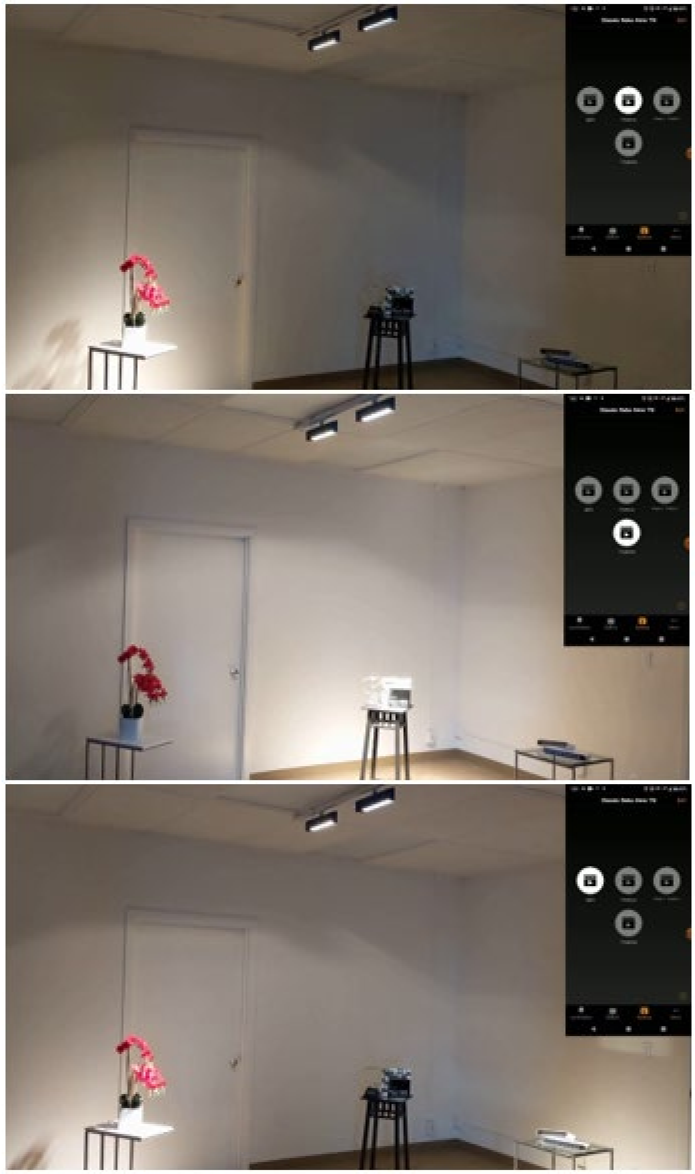
Figure 4: Screenshots of Casambi Control Interface for Scene-based Prototype



Left: Individual luminaire control showing sliders for dimming, pan, and tilt. The four buttons were reserved for future use. Right: Group control showing saved scenes.

Figure 5 shows stills from a video shot at Glint demonstrating the scene capability of the system. Two fixtures are mounted to the track on the ceiling, and the Casambi interface is visible inset in the camera image. Various lighting scenes are demonstrated, and the fixtures may be seen stationary on the ceiling in the video stills.

Figure 5: Three Different Scenes Lit by Scene-based Prototypes



Results

Table 4 shows summary data on the performance of the scene-based prototype vs. targets. The main conclusions from the testing are:

- Performance meets or exceeds almost all targets.
- Tilt steering range of 32 degrees falls short of target due to mechanical issues with the prototype build.
- Slew rate varies with angle orientation but is above the target minimum in almost all orientations. This rate can be further optimized with adjustments to the motor drive rate and/or gearing.
- Audible humming noise was produced by the DC-DC driver during dimming.
- Reliability of the prototype luminaire was not thoroughly assessed, but a preliminary test was performed in which the luminaire was cycled through a pointing direction loop

once every 15 seconds for 1,000 cycles. No mechanical failures or loss of precision was observed.

- Mechanical issues caused occasional motor stalling. Such stalling would interrupt smooth motion of the beam and would also cause increased noise levels. The stalling was determined to originate from binding of the mechanical system at certain steering positions.

Table 4: Target Specifications and Achieved Performance of Scene-based Prototype

Technical Specifications	Target	Demonstrated
Light Engine		
Efficacy (Lm/W)	>60	62
Color uniformity (Δu'v')	≤0.004	≤0.004
Correlated color temperature (K)	2700 – 4000 fixed or variable	4000
Color rendering index (Ra)	>90	92+
Lumens per beam (Lm)	>700 or >1200	1370
Fixed beam width (°)	13, 22, 32	22
Adjustability		
Steering range tilt (°)	40	32
Steering range pan (°)	infinite	infinite
Steering accuracy (°)	<2	0.5
Slew rate (°/sec)	>20	70
Control interfaces	Wireless, app-based	Wireless, app-based
Control capabilities	Aim, Scenes	Aim, Scenes
Reliability		
Rated duty cycle (actuations/day)	10	N/A
Rated lifetime (actuations)	30,000	Tested 1000 cycles

Dynamic Prototype

The goal for the dynamic prototype, shown in Figure 6, was to integrate sensors with the luminaire and demonstrate the ability to intelligently alter the light distribution in a room in real-time.

Figure 6: Dynamic Prototype with Attached Sensors

Design and Fabrication

The luminaire mechanics of the dynamic prototype were unchanged from the scene-based prototype; however, the control electronics and firmware were upgraded. In addition to Casambi control, a wired DMX control channel was added to enable control of the luminaire via computer for programmability. Sensors were mounted on the luminaire to enable measurements of occupant activity in the room.

Demonstration

A demonstration of an automatic task light was set up in a back room of the Glint offices using the prototype luminaire with the thermal camera sensor mounted to it. A computer program analyzed the thermal camera data to determine the presence and location of room occupants and then directed the luminaire to light the location of the occupant using the DMX control. Media from this demonstration was shown in the project technical advisory committee meeting held in November 2020, and still frames of this video demo can be seen in Figure 7.

The luminaire is visible on the ceiling-mounted track at the top of the frame, and the thermal infrared (IR) camera data is shown in the inset. The automated system successfully tracked an individual as he walked about the room, keeping the beam centered on his location to automatically light the tasks he was carrying out. The system dimmed and centered the beam if no occupants were detected.

The prototype dynamic luminaire system successfully achieved the targets for its demonstration. More important than the demonstration is that the prototype is a showcase of the capabilities of automated lighting and how this technology can enable unique applications and lead to gains in use efficiency. By building automated systems that understand the events occurring in a lit space, it is possible to direct beams where, when, and how they are needed.

Figure 7: Still Frames from Video of Automatic Task-tracking Demonstration

Pilot Design

The pilot design maintains the core design and performance targets of the dynamic prototype but implements it in a more polished package. Figure 8 shows a photo of two completed units of the pilot design.

Figure 8: Pilot Fixtures

Design and Fabrication

The pilot design is intended to represent the appearance and performance of an eventual production motorized fixture for scene-based applications. Improvements from the dynamic prototype included:

- Use of the award-winning form factor and cosmetic design of the manually adjusted Hero product
- Re-use of many of the production components from manually adjusted Hero
- Improvements to the mechanics to realize full 40 -degree-plus tilt steering range
- Addition of CCT adjustability from 2,700K to 4,000K by using alternating 2,700K and 4,000K LEDs on the circuit board, with two drivers independently driving the two different circuits
- Integration of Hall effect sensor onto LED circuit board for greater precision in pointing angle
- Multiple improvements to the control circuit board and firmware
- New DC driver components to minimize audible hum

More than 10 total units were fabricated and tested to thoroughly vet the design. Figure 9 shows the units during testing at Glint. The alternating CCT LEDs used in the light engine are apparent.

Figure 9: Pilot Prototypes During Testing at Glint

Results

Table 5 shows summary data on the performance of the pilot fixtures vs. the overall program goals. The main conclusions from the testing are:

- All performance metrics were met.
- CCT tuning was implemented.
- Audible noise from motors was greatly reduced vs. earlier generations.
- Excellent reliability was demonstrated to more than 10,000 cycles with some indications of initial wear.
- No mechanical issues were encountered when steering beam was pointing within the allowed product steering range.

Table 5: Performance Summary for Pilot Fixtures vs Program Goals

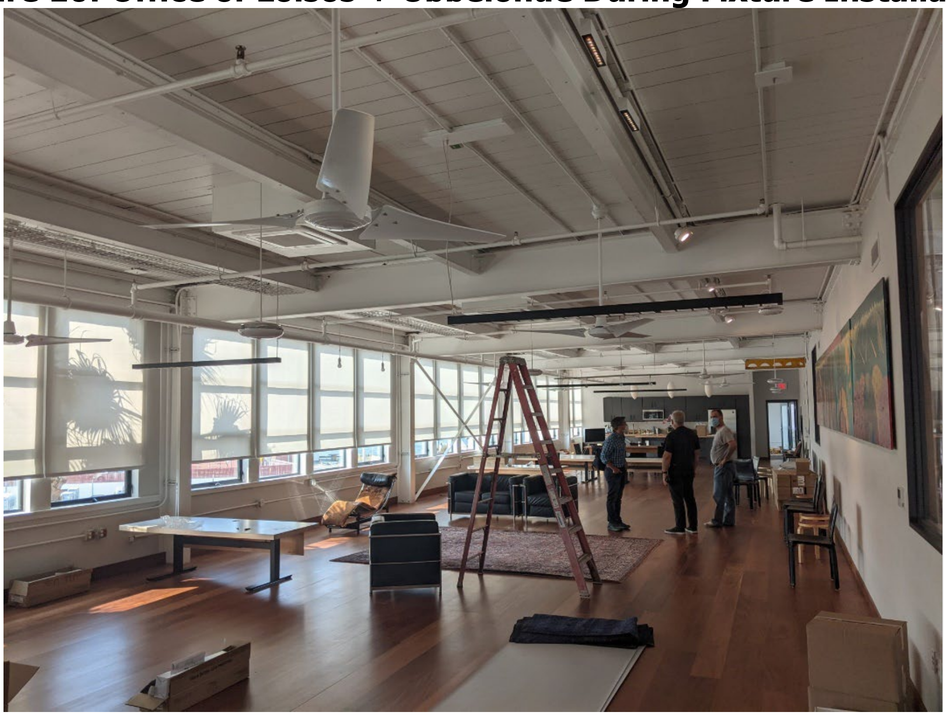
Technical Specifications	User-aimed / Scene-based	Dynamic	Achieved
Light Engine			
Efficacy (Lm/W)	>60	>60	>60
Color uniformity (Δu'v')	≤0.004	≤0.004	≤0.004
Correlated color temperature (K)	2700 – 4000 fixed or variable	2700 – 4000 fixed or variable	2700 - 4000 variable
Color rendering index (Ra)	>90	>90	92-95
Lumens per beam (Lm)	>700 or >1200	>700 or >1200	>700
Fixed beam width (°)	13, 22, 32	13, 22, 32	13, 22, 32
Adjustability			
Steering range tilt (°)	40	40	40+
Steering range pan (°)	infinite	infinite	infinite
Steering accuracy (°)	<2	<2	0.5
Slew rate (°/sec)	>20	>50	70
Control interfaces	Wireless, app-based	App-based, DMX/RDM	App-based, DMX/RDM
Control capabilities	Aim, Scenes	Aim, Scenes, Dynamic	Aim, Scenes, Dynamic
Reliability			
Rated duty cycle (actuations/day)	10	1000	N/A
Rated lifetime (actuations)	30,000	1,000,000	10,000 cycles tested

Demonstration Installation

The goal of the demonstration installation was to install several the final pilot luminaires in an occupied space where they could be used and evaluated by third-party individuals. The demonstration installation was set in the new offices of Loisos + Ubbelohde, one of California's premier lighting design firms located at 1500 Ferry Point, Suite 201, in Alameda, California. George Loisos was a member of the technical advisory committee for this project. The Loisos + Ubbelohde offices were chosen as the demonstration site for several reasons. First, the site provided an opportunity to receive detailed feedback on luminaire and control system performance from leading lighting experts. Second, it provided an excellent opportunity for market transfer activities, as many clients visit the offices and would be able to experience and learn about the technology. Third, the space lends itself to exercising the scene-based control for which these fixtures are intended. It is a large open office space with reception and gathering areas, located in a converted naval building that faces the San Francisco Bay. Artwork is displayed in the reception area and changed periodically, and the room is used for evening events at times.

Nine pilot motorized Hero fixtures were built, tested, and delivered to the demonstration installation site. In accordance with the request from Loisos + Ubbelohde, these fixtures were three each of the narrow beam, medium (spot) beam, and wide beam designs. At the time of delivery, the office was still being prepared for occupancy following its renovation and was experiencing a gradual resumption of in-person work as the coronavirus pandemic situation eased. Figure 10 shows the fixtures being installed in the offices. The demonstration installation is ongoing and will continue past the conclusion of this program. Glint will remain in regular contact with the staff at Loisos + Ubbelohde regarding the fixtures, providing any technical support needed and receiving detailed feedback on the fixture performance and operation.

Figure 10: Office of Loisos + Ubbelohde During Fixture Installation



CHAPTER 4: Technology/Knowledge/Market Transfer Activities

The lighting industry can be conservative in adopting new technologies, so technology and knowledge transfer activities are critical for promoting a new approach such as the one developed in this work. Further, there are many influencers throughout the lighting sales chain that must be considered. Specification-grade lighting products such as those manufactured by Glint are generally not sold through retail channels. Instead, the manufacturers are represented by local sales agents who promote the company's products to lighting designers and architects within their territory, who, in turn, specifies the product, which is ultimately purchased by a construction contractor and supplied through an electrical distributor.

To inform the broad commercial market and other potentially interested parties of this innovative technology, the project results were shared with the lighting community through presentations at conferences, meetings, and tradeshows whose audiences included (1) the lighting designers and architects who specify lighting fixtures, (2) other companies active in the lighting industry, including competing lighting fixture manufacturers as well as companies providing controls systems and components (3) academic researchers in lighting and lighting technologies, and (4) government labs and funders of lighting research. These presentations were unfortunately limited during the program because of pandemic-related shutdowns, but Glint will continue this outreach following the conclusion of the program.

Glint has also presented the technology to its own network of sales agents as a preview of products and technologies to come to prepare them to be effective promoters for the technology once it is ready for market entry. Widespread knowledge transfer is expected once the product is prepared for commercialization and becomes the subject of marketing efforts.

Public Presentations

- Andrew Kim, *Light Extraction,* U.S. Department of Energy Solid State Lighting Research and Development Workshop, San Diego, January 29, 2020
- Peter Kozodoy, panel presentation on *Building Design with Innovation in Mind: Efficiency as a Secondary Benefit*, California Energy Commission (CEC) Electric Program Investment Charge Virtual Forum "Reimagining Buildings for a Carbon-Neutral Future," virtual forum, September 3, 2020
- Peter Kozodoy, *Transforming Directional Lighting*, CEC Technology Showcase, Sacramento, October 25, 2019
- Glint Lighting, *Light!* design expo, San Francisco, July 11, 2019.
- Peter Kozodoy, *Pioneering Dynamic Connected Lighting*, "M37" Project Pitching Session, ARPA-E Summit, Denver, July 9, 2019
- Glint Lighting, *Lightfair* trade show, Philadelphia, May 21 – 23, 2019

Government Presentations

- Peter Kozodoy, *Rethinking Optical Tradeoffs in Directional Lighting*, U.S. DOE SSL R&D Workshop, virtual forum, September 7, 2021
- Peter Kozodoy, *Transforming Directional Lighting*, CEC Review, Sacramento, December 9, 2019

Outreach

- *Lighting designers*. Glint consults regularly with a range of leading lighting designers in California and beyond. In these discussions Glint has presented the company's technical progress and learning and exchanged ideas on product capabilities and impact.
- *Commercial sales channels*. Glint has established a network of commercial sales agents for sales of manually adjusted fixtures as well as future sales of remotely adjustable fixtures. Glint has engaged with these sales agents in discussions of product roadmaps and capabilities.
- *Potential collaborators*. Glint has met with potential collaborators in a range of fields including lighting controls, lighting installations, and adjacent areas such as theater lighting.
- *Demonstration installation.* The demonstration installation at the offices of Loisos + Ubbelohde provided an opportunity to present the technology to lighting experts, architects, and clients for lighting design services.

Follow-on Activities

- *Commercialization.* Future work will include introduction of the motorized fixture as a commercial product. This effort will include widespread publicizing of product performance and capabilities as part of marketing campaigns.
- *UV applications.* Glint is currently pursuing application of the remotely adjustable fixture technology with ultraviolet light sources as a targeted disinfection system. This work has received initial funding from the U.S. Air Force.
- *Controls systems*. Glint's work on remotely adjustable lighting products in this program inspired ideas for improved control systems for aiming and adjusting lighting. Glint is actively pursuing additional research on these concepts going forward.

CHAPTER 5: Conclusions/Recommendations

Project Outcomes

This project achieved its targets, successfully developing prototype motorized fixtures that meet the defined specifications. The pilot design represents a state-of-the-art adjustable fixture suitable for use in a wide range of scene-based applications and with all the benefits that the Hero platform offers in sculpted beam profiles, low glare, visual harmony from consistent orientation, and easy installation into small niches and narrow plenums. No other motorized fixture on the market provides these benefits. The successful demonstration in the offices of Loisos + Ubbelohde underscored the value of these product capabilities and the maturity of the product and provided valuable feedback on its advantages and performance.

In addition to developing the fixture design to a high state of production readiness for scene-based applications, the team also achieved the project goals regarding dynamic applications. The realization of DMX control channels means that the fixtures can be easily connected to PCs and controlled programmatically. Researchers can include various sensor inputs and easily experiment with control algorithms to determine optimal lighting responses. The automated task-light demonstration achieved at Glint in this program provides a demonstration of what can be achieved with such systems and is a testament to the energy-saving potential of advanced, smart, dynamic lighting systems.

Energy-Saving Benefits

As described in Chapter 6, these motorized fixtures can offer substantial energy savings from improved targeting of light (reducing the amount of light that needs to be generated to light a particular setting). In addition, there are manufacturing and materials benefits from reduced embodied energy and more efficient use of materials than in conventional gimbaled fixtures. Taken together, these factors can reduce the total five-year energy footprint of a track-mounted directional lighting fixture from 569 kilowatt-hours to 193 kilowatt-hours, a savings of 66 percent.

We estimate annual energy savings from 1 to 8 terrawatt-hours within California IOU territories, for varying levels of dynamic lighting sophistication. This amount of potential energy savings corresponds to as much as 331,000 metric tons of avoided carbon dioxide emissions, worth between $160 million and $2.3 billion per year.

The high end of this energy-savings range will be reached through the use of sophisticated lighting control systems that dynamically adjust lighting, targeting it automatically where needed depending on the changing utilization of individual rooms. This represents a transformation in lighting implementation, replacing static lighting design with smart and responsive lighting systems. The present work helps lay the foundation for such a transformation, providing the adjustable lighting hardware upon which the system can be built. However, further development in the associated sensing and control systems will be needed to realize the full benefits such a system can provide.

Production Readiness

The remotely adjustable fixtures developed in this program are based closely on Glint's manually adjusted Hero light fixture currently in production. This is a direct result of decisions taken in the target definition and was chosen to ensure high production readiness at the end of this program. The remotely adjustable fixture shares many key components with the manually adjusted version, including all housing components, optics, and most of the mechanical components. All these shared components are currently in production with identified suppliers and existing validated production tooling. The manually adjusted product has already achieved safety certification by Intertek, a nationally recognized testing laboratory, and Glint's production assembly line has passed its factory assessments.

Some elements are unique to the remotely adjustable version. These include the motors, motor-mounting hardware, position encoder, and control and power electronics. The motors are off-the-shelf components from an identified supplier. The mounting hardware is a custom design that can be produced using the same production suppliers developed by Glint for other mechanical components within the luminaire. The encoder and control/power electronics are a combination of off-the-shelf components and custom circuit boards. The circuit board designs have been validated through the experimental work performed in this program and can be produced by any of many production suppliers, including suppliers that Glint works with for other production needs.

Several steps remain to finalize a production design:

- *Improve design for manufacturability/ease of assembly*. Assembly of the 10 pilot fixtures revealed some design flaws that complicate the assembly process. Design improvements to some parts will improve manufacturability and ease of assembly.
- *Optimize reliability of mechanical design*. Testing has been completed successfully to 10,000 cycles, meeting initial performance targets. However, this testing was only performed on a single unit, and it was not subject to external stresses beyond its own self-heating. Further testing is needed to fully validate the mechanical design.
- *Finalize production firmware*. The firmware has been tested extensively but further optimization and error-testing would be needed prior to production release. Over-the-air updates will be enabled in the production version of the firmware, allowing remote updates to fix any performance issues.
- *Produce mechanical parts*. Tool and validate those mechanical parts that differ from the manually adjustable fixtures.
- *Finalize board designs*. Finalize production control board designs with debugging test features removed.
- *Update driver circuitry*. The current prototypes use separate AC/DC and DC/DC stages to power both the LED light engine and the motion system. The design is functional and meets all target specifications, but it is complex and cannot achieve the deep dimming (less than 1 percent) required in some applications. Glint will monitor the emerging availability of commercial driver circuits with sufficient auxiliary power to drive the motors and will also consider developing a custom solution.

- *Certify to industry standards*. Certification includes standard safety testing to UL standards as well as Federal Communications Commission testing because of Bluetooth wireless emitter.

Glint plans to carry out these steps in the months to come and bring the motorized fixture to market by late 2022 through the company's existing commercial sales network.

Market Conclusions

Throughout the program, Glint team members engaged in discussions with lighting designers, architects, lighting sales agents, and potential end customers regarding automated and remotely adjustable lighting. These conversations led to four major conclusions.

First, there is widespread interest in remotely adjustable lighting. The topic comes up organically in nearly every conversation. Lighting professionals are interested in the latest technology, in bringing new functionality to lighting installations, and in the opportunity for creative design that is presented by such configurable lighting platforms.

Second, lighting professionals immediately recognized the advantages of Glint's LightShift optical platform as applied to remotely adjustable lighting. Lighting designers recognized that the ability of fixtures to remain stationary while their beams are actively directed would make remotely adjustable lighting more aesthetically pleasing and broadly applicable in a variety of settings. The other benefits of the remotely adjustable Hero platform for product reliability, easy and compact installation, and low glare were also widely acknowledged.

Third, lighting designers are excited about the dynamic effects that can be achieved with remotely adjustable fixtures. This is a new direction for creative lighting design. For example, one idea that came up in discussion was slowly varying light pattens to create an organic feel in an open space. Another example was lighting in a retail environment that would react to customers walking near a display with moving light patterns to draw interest. Such applications may represent the initial market entry points for dynamic lighting systems, with more broad-use, energy-efficient applications coming later as the technology matures.

Finally, and despite the first three conclusions, there is a general reluctance to specify remotely adjustable fixtures for scene-based use outside of existing applications in which manual adjustment is extremely difficult and needed regularly (such as in event spaces with high ceilings). Only a few lighting designers expressed interest in applying these fixtures in settings in which remotely adjustable lighting has not typically been used, such as office conference rooms. There were several factors cited, including complexity of operation, concerns about reliability, and concerns about cost. These are perception barriers that will need to be overcome to enable widespread adoption.

The Glint team has concluded that a key to widespread market acceptance will be impactful demonstrations that show the benefits of automated lighting in a range of non-traditional applications such as office conference rooms or retail displays. Also important will be continued work to make control systems simple and intuitive, to improve and document the long-term reliability of the fixtures, and to reduce costs close to parity with non-remotely adjustable fixtures.

Even more work is needed to enable truly automated intelligent lighting. Such systems will require sophisticated sensor-linked control systems to identify and automatically respond to occupant activities in a room. Significant research is required to ensure that the response algorithms generate pleasing and effective lighting outcomes. This is essentially a new research field, sitting at the intersection of building technologies, lighting design, and human factors response. Development of optimized approaches in this field will take time but can pay enormous dividends in energy savings and improved occupant experience and safety. The work undertaken in this project represents some initial steps in this direction and an exciting jumping off point.

Recommendations

The first recommendation from this work is to undertake a variety of demonstration efforts to evaluate and document the performance and tangible benefits of the remotely adjustable lighting products in real-world applications. These can include offices, schools, stores, public spaces, and more. Demonstration efforts will help pinpoint any performance issues and needed upgrades or changes and will allow for thorough documentation of the benefits achieved and the longevity and optical performance of the fixtures. All of these will help to improve the product and to grow the market acceptance, so that the benefits of improved lighting quality and reduced energy use can be more widely enjoyed. Forward-looking lighting designers are ready to take on such projects, and they can be accelerated significantly if support can be obtained from public sources such as the CEC and the U.S. DOE.

The second recommendation is to pursue further fundamental research on smart automated lighting. The fixtures developed in this project provide a hardware basis for achieving automated lighting demonstrations, but how such systems should best operate remains largely undefined. Key questions include (1) how best to determine occupant locations and activities within a room, (2) how the lighting distribution should be adjusted in response to room usage information to provide the most pleasing and effective lighting outcomes, and the greatest energy savings, and (3) how a desired lighting distribution should be optimally implemented in a given space with its particular set of lighting fixtures and capabilities. Developing, testing, and refining general purpose algorithms that address these questions will advance the capability of automated lighting systems and bring the technology closer to realizing the promise of ubiquitous smart and responsive lighting.

Work in this area will require time and public support. Glint recommends that the CEC, U.S. DOE, and other public agencies develop focused funding opportunities for interdisciplinary teams undertaking research in optimization of automated lighting systems. If successfully implemented, this work has the potential to deliver significant benefits in energy efficiency and improved lighting quality.

CHAPTER 6: Benefits to Ratepayers

This project has supported the EPIC goals of lower costs, increased safety, and greater reliability by advancing more precise and adaptable illumination in occupied spaces in California and working to increase the adoption rate for efficient, long-lasting, LED-based luminaires. The project has developed a valuable new lighting technology. As commercial sales of this technology have not yet begun, the analysis presented here estimates the potential energy and cost savings, assuming eventual widespread adoption.

Every lit space has an illumination objective function that lighting designers, facilities managers, and occupants strive to match. The illumination objective function is specific to each lit space, and it is naturally a function of both time and space, as the occupation and use of spaces change on multiple timescales. Any mismatch between the actual illumination pattern and the objective function has undesirable costs to occupants and ratepayers. Insufficient illumination reduces the productivity and effectiveness of lit spaces and generally poses a safety hazard to occupants. Excessive illumination is wasted energy with all the associated economic and environmental costs of generation and distribution.

Glint's dynamically adjustable lighting technology allows a better match between light output and lighting requirements, with a resulting increase in end-use energy efficiency, productivity, and safety in lit spaces. Furthermore, the new functionality can promote more rapid market adoption of energy-efficient, LED-based lighting, with further energy savings.

Quantitative Estimates of Potential Benefits to California IOU Ratepayers

Energy savings originate from several different characteristics of the motorized Glint luminaires:

1. Reduced self-occlusion. Gimbaled spotlights deployed in proximity (for example in a track system) can occlude each other, wasting light and creating glare. Pivoting lights that are recessed into an enclosure in the ceiling will often spill light inside the enclosure when steered. The LightShift design eliminates these loss mechanisms, providing an estimated 5 percent energy savings on average.

2. Reduced embodied energy. Glint's analysis indicates that the embodied energy of a typical LED spotlight luminaire is equal to its energy draw over about 2.5 years of operation. This embodied energy is primarily from fabrication of the LEDs and the aluminum heatsink/enclosure. LightShift luminaires use less aluminum than conventional spotlights because the luminaire orientation is fixed so the heatsink design can be optimized. Further, the ability to dynamically steer light where it is needed means the need for installation of fewer luminaires since each is more flexible and capable. This results in substantial savings in embodied energy.

3. Improved targeting. Remotely steerable lights can be more easily adjusted to provide optimal lighting for a given scene and therefore will more effectively use light than manually adjusted lights, providing an opportunity to reduce lighting intensity and save energy. This is true even for lights that are only rarely re-directed. The savings can be even more substantial in a scenario where the lights are dynamically steered to illuminate task work and therefore provide an opportunity to reduce ambient light levels. The U.S. DOE Solid State Lighting roadmap estimates improvements of up to three times of lighting use efficiency can be achieved in this way.[1]

A 20 percent reduction in illuminance of excessively lighted areas, a lumen contrast ratio that would be nearly imperceptible to most people, results in a 10 percent to 15 percent reduction in total lumens and concordant energy consumption. Thus, reasonable estimates for energy savings spans from 10 percent in a very conservative and simple installation, to 70 percent for advanced controllable networks of luminaires.

Additional savings are possible via the potential for more rapid adoption of LED-based directional lighting. The U.S. DOE reports that in 2016, 12.6 percent of existing lighting installations in the United States used LED-based light engines, which represent an annual energy savings of 140 GWh.[5] Fewer than 0.1 percent of these LED-based lighting installations contained connected controls. The U.S. DOE estimated that if these installations featured connected controls, the potential energy savings would be an additional 80 percent, representing 110 GWh of energy savings. The increased value and functionality of the configurable luminaire proposed here would increase the adoption rate of connected luminaires and realize that energy savings. Calculating the extent and value of this potential energy savings suggests potential energy savings corresponding to 331,000 metric tons of avoided carbon dioxide emissions, worth between $160 million and $2.3 billion per year.

Further, reduced electrical loads for lighting in interior spaces improves building energy efficiency by reducing heating, ventilation, and air conditioning (HVAC) loads, which can yield additional energy savings for Californians. This effect was estimated to add approximately 13 percent additional energy savings for office buildings in California, thus avoiding an additional 130 GWh to 1.1 TWh of electricity consumption through synergistic HVAC savings.

Finally, the networked controllable nature of the Glint luminaire, allowing for real time control of the distribution of illumination in space, is ideally suited to improving demand response in lighting. In California, Title 24 calls for demand response capabilities in lighting under certain scenarios. The current level of demand response is generally crude zonal dimming capability, with a 15 percent reduction required. The additional control afforded by the Glint luminaire will allow precise illumination tailoring and larger demand response capacity with less impact, both in satisfaction and safety to the occupants. This effect is independent of and in addition to any uniform level of dimming deemed acceptable.

Qualitative Benefits to California IOU Ratepayers

The primary initial markets that would benefit from the enhanced capabilities and aesthetics of the Glint luminaire would be directional lighting for retail, hospitality, and museum spaces. But with continued development of the control's hardware and software, the cost can be driven

[5] U.S. DOE EERE Report "Adoption of LEDs in Common Lighting Applications" – Jul 2017

down, and the value of the realizable energy and cost savings will eventually bring value to the office and residential markets as well.

The ease of re-directing the Glint luminaires will eliminate the physically dangerous and time-consuming task of workers on ladders manually re-directing a bank of directional lights. Further, in scene change applications a single adjustable luminaire can replace multiple conventional luminaires, saving cost in equipment and installation. Finally, the use of remotely adjustable luminaires makes it easier to provide optimal lighting distributions in any lit environment, which will enhance safety, productivity, and occupant experience.

Additional benefits will accrue from the further development of automated lighting technologies. California is well positioned to be a center of technological innovation and progress in this field, with a willingness to embrace new energy-efficient technologies and a concentration of expertise in connected systems and internet-of-things. With the advances achieved through this project, Glint can help to lead this emerging technology field. Long-term benefits include new well-paying jobs within California and the flourishing of a promising new field of research that can have wide-ranging impact in the day-to-day lives of all Americans.

LIST OF ACRONYMS

Term	Definition
AC	Alternating Current
ADC	Analog-to-Digital Converter
BLE	Bluetooth Low Energy
CCT	Correlated Color Temperature
CEC	California Energy Commission
CRI	Color Rendering Index
DC	Direct Current
DMX	Digital Multiplexing
DOE	Department of Energy
EERE	Energy Efficiency and Renewable Energy
FCC	Federal Communications Commission
GWh	Gigawatt-hours
IOU	Investor-Owned Utility
IR	Infrared
K	Kelvin
LED	Light Emitting Diode
Lm/W	Lumens per watt
mm	Millimeter
MRD	Market Requirements Document
PC	Personal Computer
PRD	Product Requirements Document
PWM	Pulse-Width Modulation
SSL	Solid State Lighting
TAC	Technical Advisory Committee
TSD	Technical Specifications Document
TWh	Terawatt-hours
UL	Underwriter’s Laboratory

Term	Definition
U.S. DOE	United States Department of Energy

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APPENDIX A: Technical data on prototypes

Demonstrator prototype

The design of the demonstrator prototype uses two stepper motors to drive motion in the two axes (longitudinal and transverse) via crankshafts. The control system did not use a custom circuit board but instead several off-the-shelf boards wired together. Motor control is implemented using a Raspberry Pi microcontroller board connected to a STMicroelectronics L6470 motor driver board. The Raspberry Pi was also wired to a Casambi communications module for Bluetooth mesh communication. The full demo system is shown in Figure A-2. It included a large external control box that holds the luminaire driver and all the control electronics.

A simple user-aimed beam pointing control capability was implemented within the Casambi platform using the interface shown in Figure A-3, which includes four pushbuttons to control forward and reverse motion in the two axes. The motion continues as long as any button is pressed.

Figure A-1: Demonstrator prototype control architecture schematic

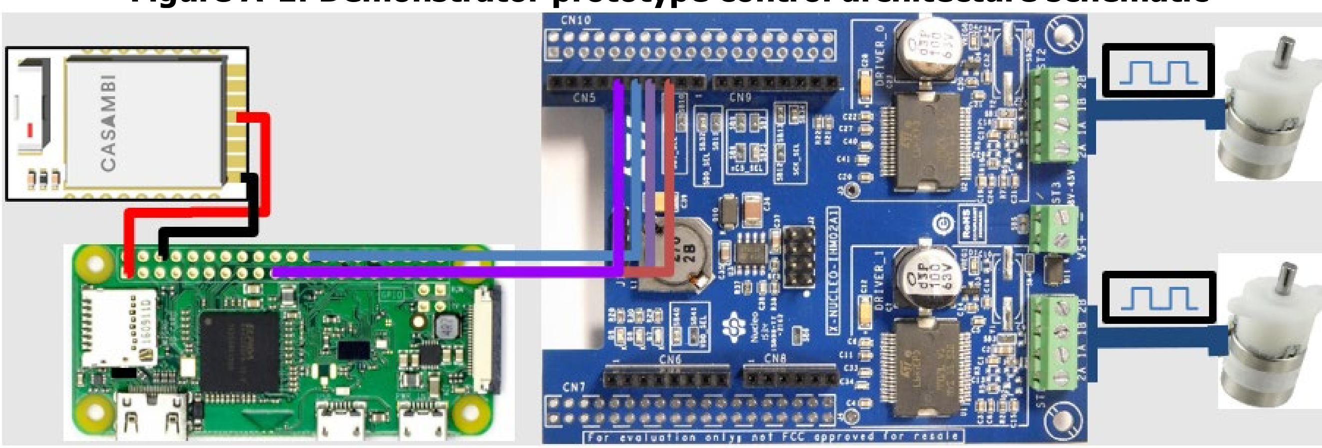


Figure A-2: Photos of demonstrator prototype with control electronics

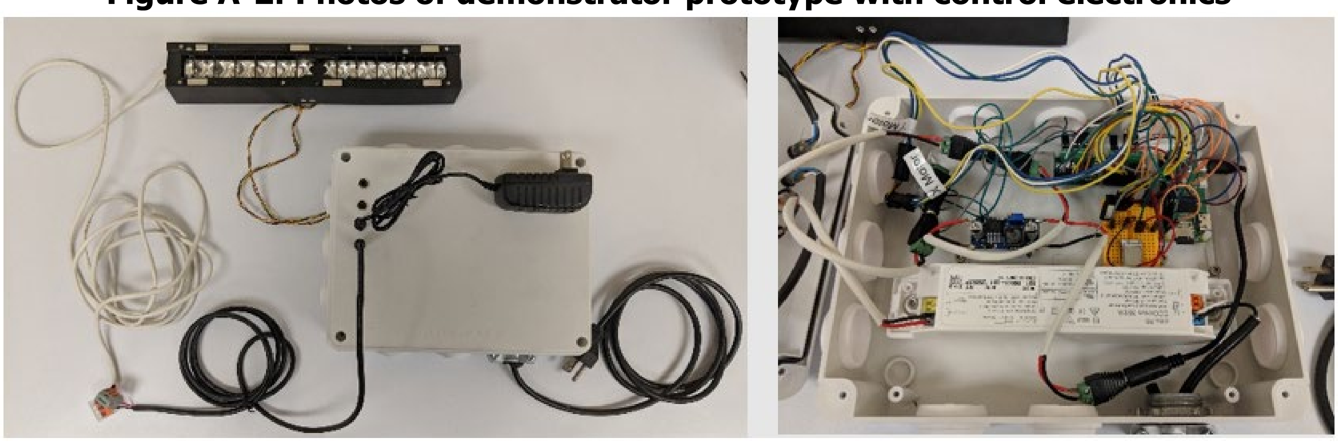
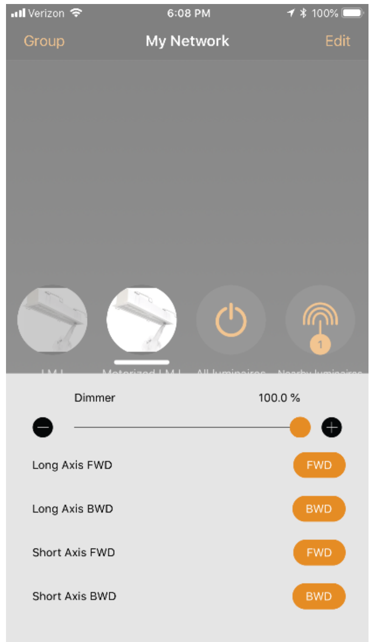


Figure A-3: Screenshot of Casambi interface for demonstrator prototype



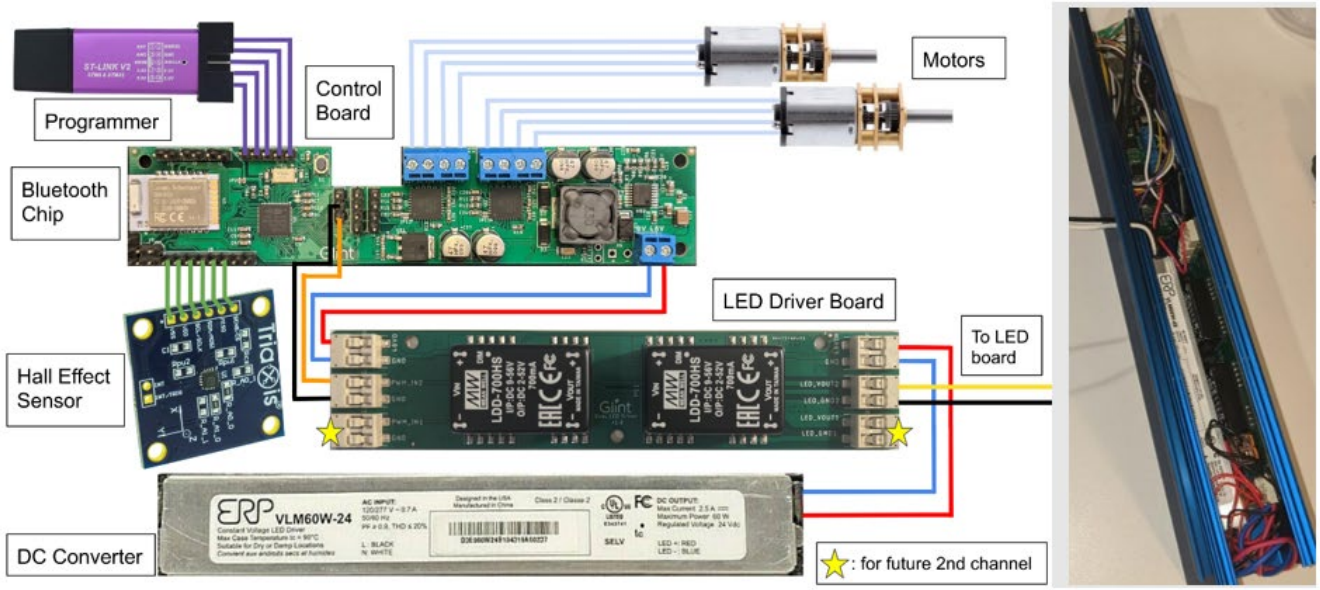
Scene-based prototype

The scene-based luminaire featured new control circuitry, shown diagrammatically in Figure A-4. A custom control board includes the Casambi Bluetooth module and a STMicroelectroncis microcontroller, linked by a communications channel. The microcontroller communicates with the offboard Hall Effect sensor and controls two onboard stepper motor drivers. A separate board included two direct current (DC) drivers, with dimming controlled by pulse-width modulation (PWM) signals from the microcontroller on the control board. A 48V DC Converter power supply provided power to the LED driver board as well as the control board. All the circuitry and wiring could be contained within the top compartment of the fixture, with careful arrangement.

Control firmware was written for the microcontroller to provide the following functions:

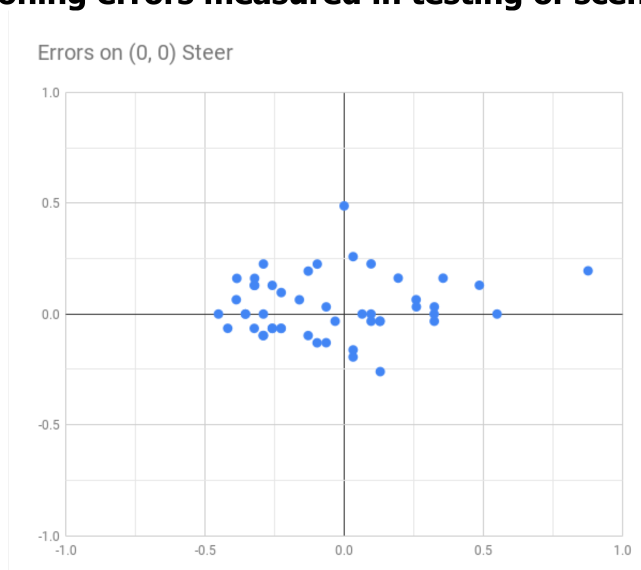
- Initialize the Casambi module on startup
- Accept, buffer, and process communications packets from the Casambi module
- Perform calculations to determine required lens *x* and *y* position for beam pan and tilt angles requested by the app user and transmitted to the control board in Casambi communications packets
- Monitor the Hall effect sensor and apply appropriate scaling factors to determine current lens *x* and *y* position
- Control stepper drivers to move lens to target position in *x* and *y* using feedback from the Hall effect sensor
- Produce dimming PWM signal with duty cycle determined by the dimming level requested by the app user and transmitted to the control board in Casambi communications packets

Figure A-4: Scene-based prototype control architecture schematic



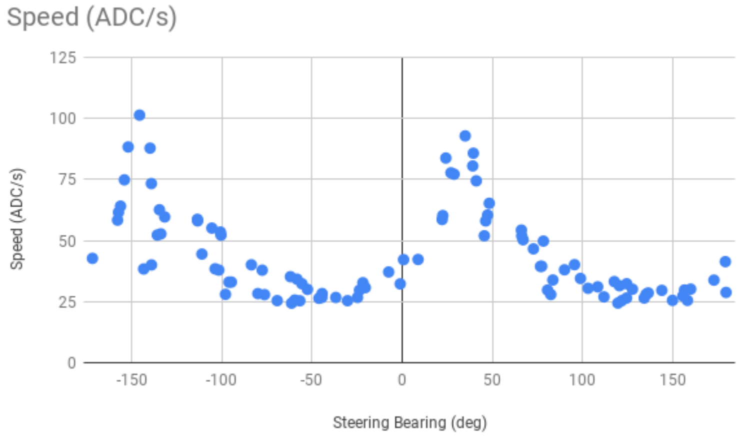
Slew rate and pointing accuracy were tested using the following algorithm. First, a random pointing angle was chosen, and the unit was steered to that angle. Next, the unit was driven back to a straight-down pointing angle. The deviation of the final pointing angle (as determined by the Hall sensor reading) from the straight-down pointing angle target was used to quantify the positioning error, which is less than 0.5° in all but one case, as shown in Figure A-5. The time required for the motion back to the straight-down pointing angle was used to determine the slew rate. This slew rate shows a dependence on the initial pan angle, as shown in Figure A-6, which is a direct consequence of the mechanical design. The minimum slew rate measured is 18°/sec and the maximum is 70°/sec.

Figure A-5: Positioning errors measured in testing of scene-based prototype



Each point represents positioning error at the conclusion of a movement sequence. Coordinates are in ADC units, each of which corresponds to 0.7 degrees.

Figure A-6: Measured slew rate of scene-based prototype

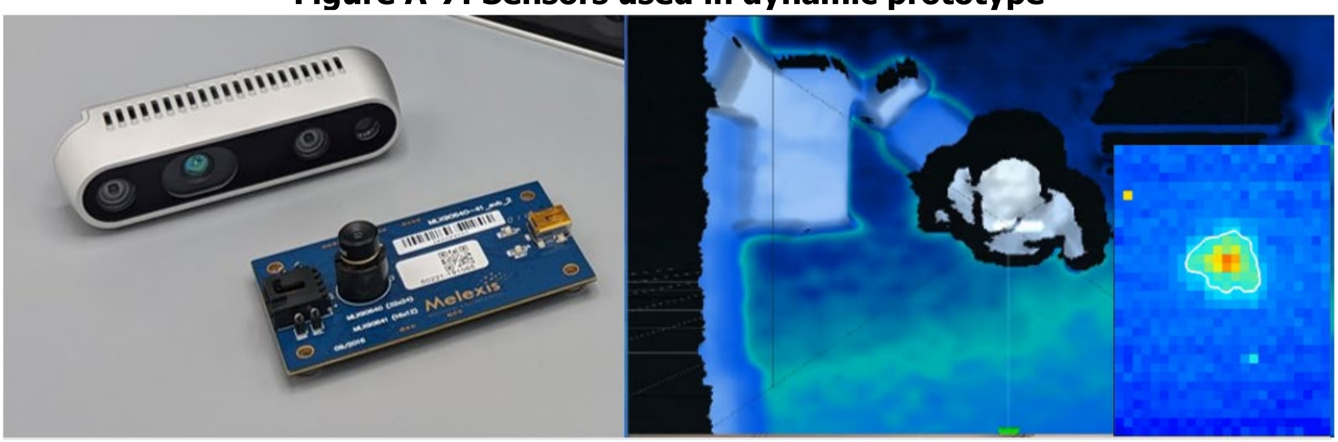


Slew rate to straight-down position from random initial pointing angles, plotted as a function of initial pan angle (plotted in ADC units/second, each ADC unit is 0.7 degrees)

Dynamic prototype

Many potential sensors were evaluated for use in the demonstration. The different technologies under consideration included traditional RGB cameras, thermal IR cameras, LiDAR, stereo depth cameras and RF beacons. For the prototype system, Glint chose a thermal IR camera from Melexis (MLX90640) and a stereo depth sensor from Intel (D435) (See Figure A-7). These sensors were chosen for their impressive capabilities at reasonable costs.

Figure A-7: Sensors used in dynamic prototype



Left: Intel RealSense depth sensor (upper left) pictured with the Melexis 90640 thermal IR sensor and board (lower right). Right: Depth frame capture of a person looking up at the sensor with thermal IR false-color frame of the same event inset.

An important requirement of the system is a large field of view to track people and events in a space with a low number of sensors. Appropriate resolution was another critical parameter for sensor selection. As seen in Table A-1, the thermal IR sensor has very low resolution compared to the depth sensor. This low resolution is well-suited for a system that can track people in a space, as the IR sensor will only pick up large objects (people) that warrant tracking. The Intel depth sensor enables future improvements in tracking performance. A higher resolution depth sensor not only gives the system a 3D representation of space, with proper data analysis it can also provide detail about the events, tasks, and occurrences happening in a space. Lastly, high accuracies and refresh rates ensure the system can operate on low-noise data and process it in real-time.

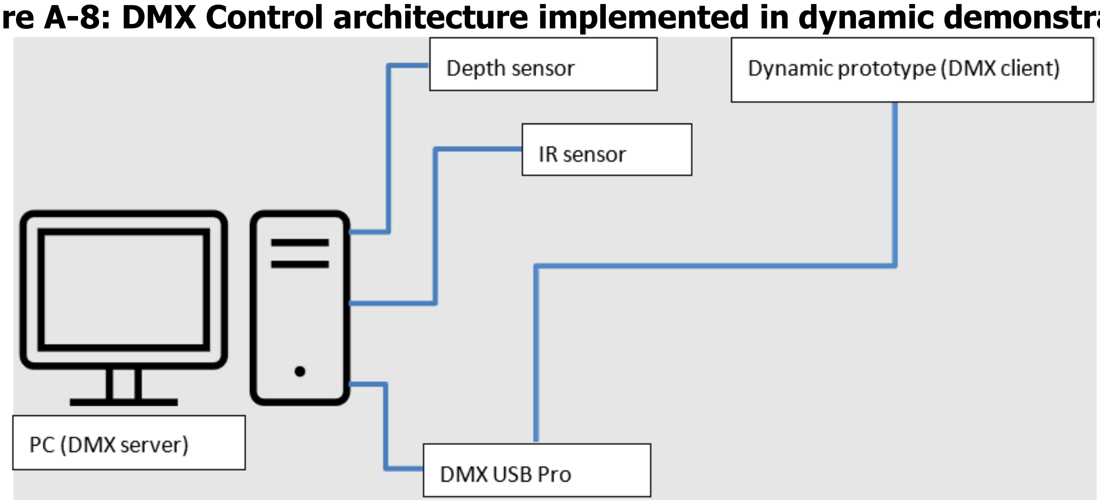
Table A-1: Key parameters of sensors used in dynamic prototype

	Melexis thermal IR	Intel RealSense depth
Field Of View (W° x H°)	110 x 75	86 x 57
Resolution (pixels)	32 x 24	1280 x 720
Range	-40 to 300°C	0.3 to 10m (< 3m ideal)
Accuracy	<1° C	<2% at 2m
Refresh rate (fps)	up to 64	up to 90
Extras	Software support	Software support, RGB incl.

To enable dynamic control, the prototype included additional hardware, firmware, and software running the DMX512 protocol. DMX was implemented on the control hardware and firmware, and a wired connection established to the microprocessor on the control board. This was connected through the data bus on the track to an Enttec DMX to USB control box, which is compatible with many DMX libraries and simple to program with a computer.

Using a computer as the server in the control network allows control software to be developed and debugged with familiar tools, without having to worry about the constraints of an embedded system. In addition, a central server provided a simple way to incorporate sensor data into the control loop. While controlling the luminaire, the server simultaneously listened for sensor data and determined whether the data contained information pertinent to the control of the luminaire. With the thermal infrared (IR) sensor, this information was in the form of 'heat blobs', or large continuous regions of the image that radiate within a certain band of temperatures.

Figure A-8: DMX Control architecture implemented in dynamic demonstration



The PC acts as the central control system, receiving sensor data and controlling the luminaire

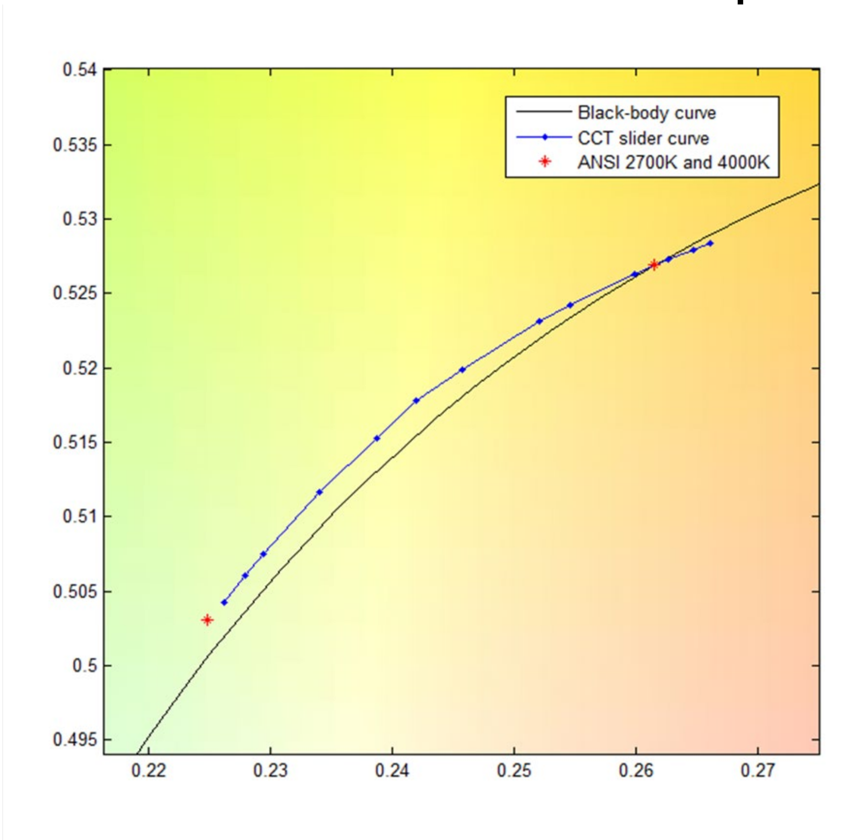
The full control loop included the following steps:

- Sensor outputs a frame
- Frame is transmitted through USB connection to the server
- Server parses sensor data at frame rate to determine presence of people
- If people present, calculate their positions and appropriate settings (dimming, steering) to send to dynamic luminaire; if no people present, wait for another frame
- Settings intended for dynamic luminaire are sent to Enttec control box via USB
- Enttec control box translates settings to DMX512 data
- Settings in DMX512 are sent to dynamic luminaire via cable
- Settings are parsed by luminaire firmware and converted into motor and dimming control commands
- Motors in the luminaire steer the beam according to control command
- LED drivers dim the light according to control command

Pilot prototypes

The pilot prototypes contained a new variable CCT light engine. As shown in Figure A-9, this provided effective control over temperature from 2700K to 4000K with close adherence to the black-body curve over the entire range. Overall flux from the luminaire is lower than in the fixed-CCT implementations since at the CCT extremes only half the LEDs are lit. The flux is 700 lumens at 2700K and reaches 900 lumens at 3500K – 4000K, with a system efficacy of 60 Lm/W.

Figure A-9: Color coordinate chart for CCT-tunable pilot fixtures

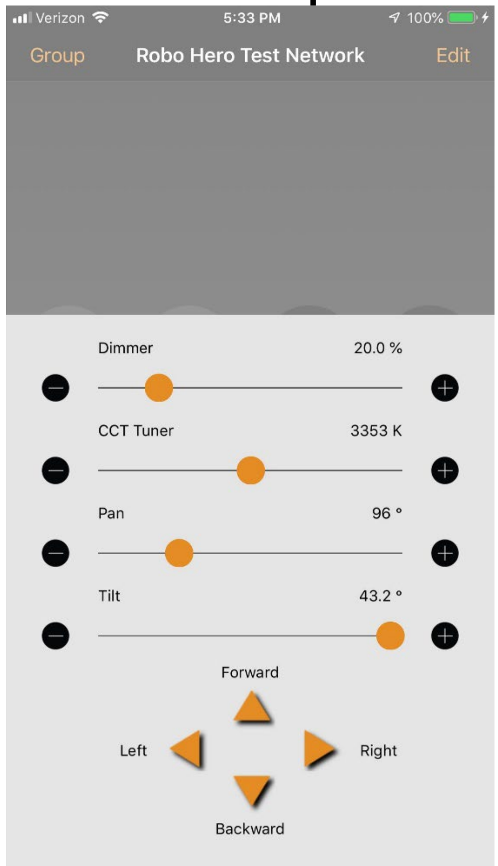


The mechanics in the pilot prototypes permit beam steering over the full design range of at least 40° tilt in any pan direction (in practice, the system typically permits about 45° tilt). Units were built and evaluated at all three planned beam angles (13°, 22°, 32°). In all cases, beam shape maintenance over steering was carefully assessed for quality performance on par with the manual Hero product. Binding and other mechanical failures present in the scene-based and dynamic prototypes were successfully addressed in the pilot design. Motion is quiet and smooth, and the driver hum is greatly reduced.

The Casambi control system was also updated in the pilot generation of prototypes. The new control screen is shown in Figure A-10. It provides a slider for CCT adjustment and includes both directional arrows and pan/tilt sliders for adjusting beam aiming. If the directional arrows are used, the pan/tilt slider positions update automatically to show the new orientation.

The interface also offers new functionality when multiple pilot fixtures are in use in a single Casambi network. Individual fixtures can be aimed so that their beams produce a certain overall pattern, and then grouped together for further adjustment. If the group is adjusted with the directional buttons, then the overall projected pattern will be maintained as it is steered. If the group is adjusted instead with the pan and tilt sliders, then all fixtures in the group will adopt the same pan and tilt settings.

Figure A-10: Casambi interface as implemented in pilot prototypes



Reliability testing was performed in a thermal test chamber held at 30°C. One of the pilot fixtures was driven in continuous cycling between aiming positions. The cycling followed a pattern that consisted of 145 evenly spaced positions that sampled the full travel range (10° increments in pan, 10° increments in tilt) and every direction of movement. The pattern of the 145 positions is shown in Figure A-11. The entire pattern was repeated approximately 82 times over the course of two days, yielding 11,800 aiming cycles in total.

Figure A-11: Steering path of fixture during cycling testing

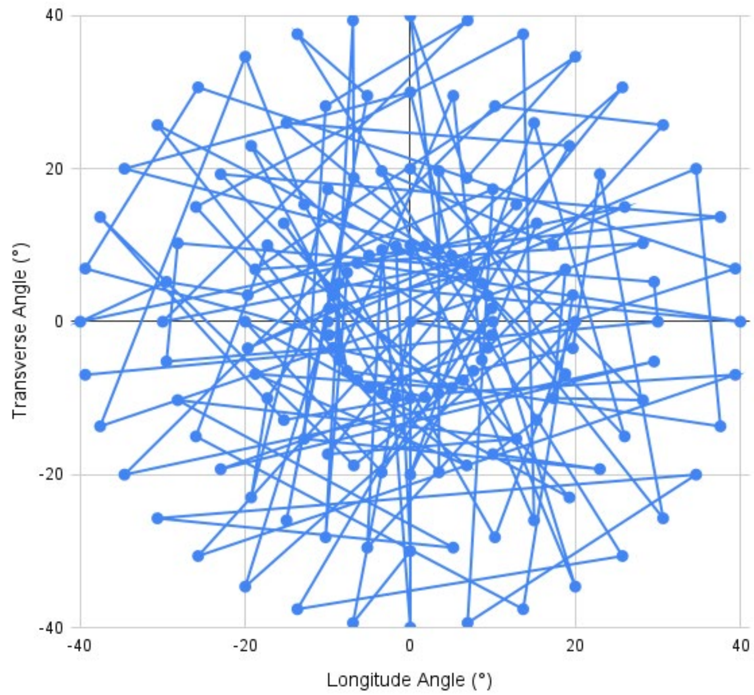
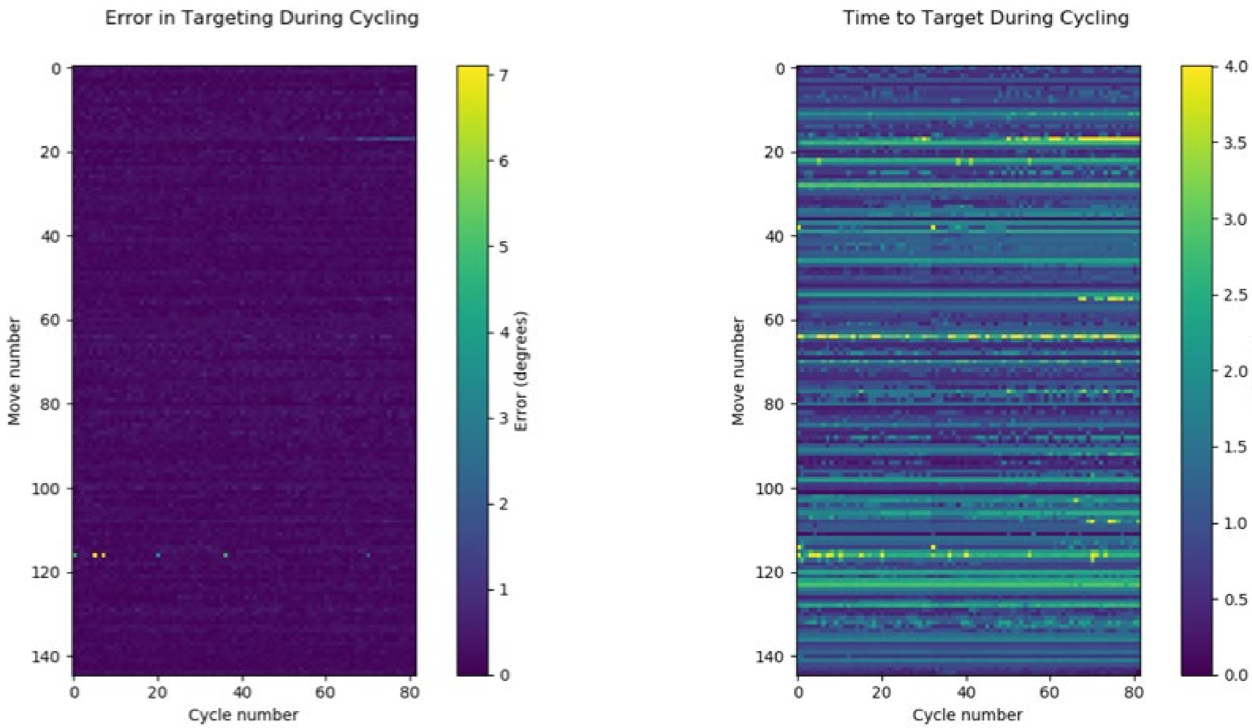


Figure A-12 shows the error in angular targeting (derived from Hall sensor measurements) through the 82 cycles tested and the 145 positions per cycle. The positioning remains highly accurate over the entire 11,800 cycles, except for two positions: positions 18 and 115. Both positions are near the edge of travel, where the mechanical system would occasionally stall. This stalling was traced to a calibration issue and addressed before the pilot fixtures were released for the demonstration installation.

Figure A-12 also shows the time it took to move to each of the positions during the cycling test. Cycle times are generally stable for almost all moves, with a few at the edge of travel showing cycle times increasing to the timeout limit of 4 seconds, indicating the stalling behavior described above. It is also possible to discern a subtle but abrupt reduction in cycle time at the interruption that occurred between testing on day 1 and day 2, this is indicative of faster actuation in the fixture at startup, with a minor slowdown associated with heating to steady-state temperatures.

Figure A-12: Error in targeting (left) and time to target (right) during cycling



Thermocouples were attached from a measurement board to various parts of the test fixture to monitor the operating temperature of the parts. Steady-state temperatures are shown in Table A-2. We note that Motor 1 ran quite hot, 20 degrees above Motor 2. This is because the mechanical design does not provide good heatsinking for Motor 1. Although failure of the motor was not observed in our testing, the high temperature is surely detrimental for long-term reliability and was identified as an element of the design needing revision for production designs to be appropriate for dynamic use cases.

Table A-2: Steady-state temperature of luminaire components during cycling

Mechanical Cycling Steady-State Temperatures (°C)	
Ambient	30
Hall sensor	47
LED circuit board	54
Motor 1	70
Motor 2	50