Company Name: MoJo Labs, Inc.
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Principal Investigator: Morgan Jones
Project Title: Daylighting Digital Dimmer
Topic Number: 3a
Grant Award Number: DE-SC0012011

Accomplishments Section

What are the major goals of the project?

The overall goal of the Phase II SBIR program is to develop the novel task-to-wall sensing and control technology into a set of commercial products that enable energy savings via daylighting and market demand through intuitive personal control and light quality through the extension of TTW to color control. The MoJo Remote (formerly referred to as RiteBrite) products planned during the Phase II are part of a low-cost, easy to use solid-state lighting control system that incorporate the novel TTW architecture.

There are four technical objectives to develop, demonstrate, and validate a commercial-ready TTW architecture and related components necessary to interface TTW with current and future commercially available SSL products:

Technical Objective 1: Develop core components - Design and develop the remote and the bridge components of the MoJo technology, the core hardware components of the product line.

Technical Objective 2: Develop bridgeless capability - Enable the task-to-wall architecture within the remote to communicate with existing and near-future commercially available SSL lighting with wirelessly connected lighting without a bridge.

Technical Objective 3: Develop and validate color control - Extend task-to-wall into color control and demonstrate color control in large-scale internal and external test beds using with off-the-shelf color-controllable SSL lighting.

Technical Objective 4: Validate energy savings and performance - Validate the successful operation and energy savings of task-to-wall illumination intensity control in large-scale internal and external test beds with commercial-off-the-shelf wired and wireless SSL lighting.

Six specific tasks (goals) are used to guide the project to meet the overall goal and related technical objectives:

Task 1: Develop the MoJo Remote - Turn the breadboard MoJo components created during the Phase I development into a pre-production MoJo remote product that is ready for market launch and ready to work with the bridge developed in Task 2. Successful completion of Task 1 will partially complete the first and second technical objectives; the MoJo remote will be ready for production and market release with the bridge developed in Task 2.

Task 2: Develop the MoJo Bridge - Create a pre-production MoJo bridge to work with the remote, created in Task 1, to control existing and future commercial wireless and wired SSL products. Successful completion of Task 2 will partially complete the first technical objective.

Task 3: Develop the MoJo Mobile App - Create a pre-production MoJo Mobile App to work with the remote, created in Task 1, and bridge, created in Task 2, to control existing and future commercial wireless and wired SSL products. Successful completion of Tasks 1, 2, and 3 will complete the first technical objective; the MoJo Remote, Bridge, and Mobile App will be ready for production in a configuration to control existing and future commercial wireless and wired SSL products.

Task 4: Create a Bridgeless SSL Lighting Control MoJo MoJo Remote - Research and create a pre-production version of the MoJo Remote, created in Task 1, that can serve as a bridgeless remote to control existing and future commercial wireless SSL products.

Task 5: Extend the Task-to-Wall Architecture into Color Control - Extend the design and capabilities of the task-to-wall architecture, and the MoJo remote, to add light spectral control (red, green, and blue) in addition to light intensity. Add the color enabled TTW architecture to the prototype MoJo components - Remote (Task 1), Bridge (Task 2), and Mobile App (Task 3). Create a pre-production MoJo color system that is ready for market launch. At the conclusion of Task 5, the color capable TTW algorithm will be tested and evaluated for inclusion in the MoJo system. Successful completion of Task 5 will complete the third technical objective.

Task 6: Integration and Test - Validate the MoJo system energy-savings, usability, and lighting quality using internal and external test sites. Successful completion of Task 6 will complete the fourth technical objective.

What was accomplished under these goals?

Overview: The primary focus of the Phase II Development is the implementation of two key technologies, Task To Wall Control, and Wand Gesture light dimming control into an easy to use remote for SSL light control, the MoJo Remote. The MoJo Remote product family includes a battery powered wireless remote, a WiFi gateway as well as Mobile Applications for iOS and Android. Specific accomplishments during the second reporting period include:

1. Finalization and implementation of MoJo Remote Accelerometer and capacitive-touch based UI/UX, referred to as the Wand Gesture UI.
2. Issuance of Patent for Wand Gesture UI.
3. Industrial and Mechanical Design for MoJo Remote and MoJo Gateway.
4. Task To Wall implementation and testing in MoJo Remote.
5. Zooming User Interface (ZUI) for the Mobile App implemented on both iOS and Andriod.
6. iOS Mobile app developed to beta level functionality.
7. Initial Development of the Android Mobile Application.
8. Closed loop color control at task (demonstrated at 2016 SSL R&D Workshop).
9. Task To Wall extended to Color Control, working in simulation.
10. Beta testing begun in Late 2017/Early 2018.

Task 1: Develop the MoJo Remote

In the second reporting period, the MoJo Remote was extended from the initial prototypes to a ready-for-production product. Multiple PCB issues were identified, debugged and fixed, and multiple PCB spins were accomplished during this period. An extensive Industrial Design process was performed, and Mechanical models developed. PCBs were adjusted to fit in the designed enclosures.

Remote PCB Development

Moving the PCB from the initial prototype to product-ready involved the typical set of issues that always occur in an innovative product development. A few highlights include:

- Capacitive touch was changed to Atmel SAMD10 series chips.
- The boost converter used for the light sensor did not function properly over voltage ranges and was replaced with another.
- Power measurements were made of each PCB spin of the MoJo Remote and the design adjusted accordingly.
- Power measurements were made of the pre-production MoJo Remote and matched to the power model developed in the first reporting period.
- A right angle light sensor board was developed and connected to the main PCB via a 4 conductor spring battery connector.
- Multiple PCB spins of the remote were performed to fit into the Enclosure Design.

- A full Industrial Design process was completed resulting in an enclosure design for the MoJo Remote, the wall clip for the MoJo Remote as well as the MoJo Remote Bridge.
- The RF range of the remote was a persistent problem and was gradually improved over each PCB spin.

The RF range of the MoJo Remote was a nettlesome issue worth expanding on. Early on in the project, a module-based approach was taken to simplify the design and accelerate time to market. A Taiyo Yuden module was selected that used a Nordic Semiconductor nrf51 series chip, and this module contains an internal antenna. During the development, this seemed to be an effective choice.

However range testing in mid-2017 revealed that the internal antenna on this module was not effective for the remote to gateway communication and would result in only 10's of meters of range, rather than the 100 meter target range. Because of this, the module approach was changed to a chip-down approach where the Nordic nrf52 series chip, the 52832 was used. Not only did this allow for a custom antenna that improved the range, it also allowed the switch from the nrf51 series to the nrf52 series, which also gained an additional +3dB in receive sensitivity, additionally improving the range of the system.

This was a mid-2017 change, after beta PCB's had already been produced. Unfortunately, this necessitated a delay in external beta testing and inserted unplanned design time and PCB spins into the project schedule. However, this has proved to be time well spent as external beta testing of the previous units would have resulted in user dissatisfaction with the product.

Another difficult design sticking point was how to have the Remote sense light in the upwards direction when it is used in two orientations. Multiple approaches were traded off, including mirrored plastics to accomplish a right angle reflection, however ultimately a two-light sensor approach was chosen that allows a second sensor on a small right angle sensor PCB on top of the enclosure. The connection between the two pcb's was a tricky design decision, but a low-cost 4 conductor battery spring connector was identified that solved the problem nicely.

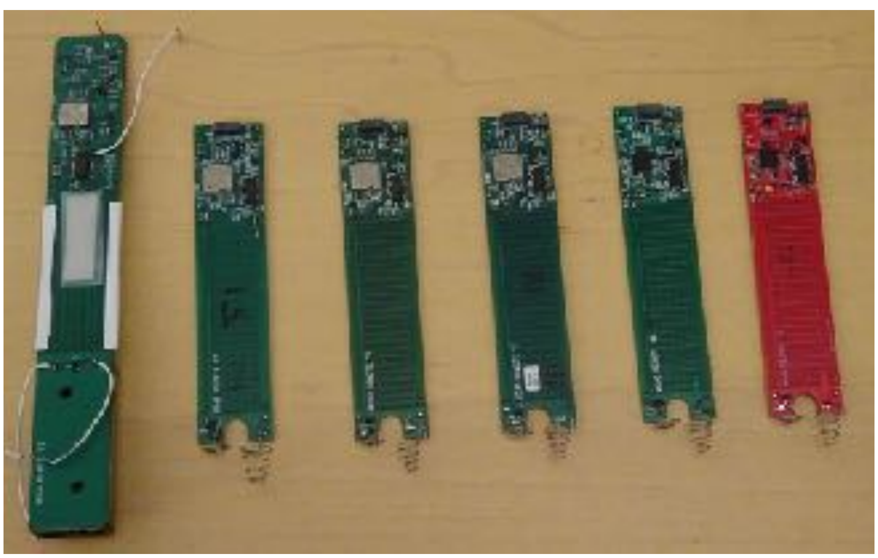

Figure 1: Remote PCB development progression with final pre-production Remote PCB on right.

Remote Industrial and Mechanical Design

A full Industrial Design (ID) process was performed to take the initial MoJo Remote concept to a production-ready state by the end of this Phase II development. At the completion of the first reporting period, rough concepts existed, but the detailed ID process had yet to commence.

The development of the gesture-based UI/UX heavily influenced the industrial design of the MoJo Remote. A "wand" like form factor was chosen, and the ergonomics of a long thin enclosure were studied. The ID factors reinforced the choice of two AAA batteries as they allowed for a more ergonomic, rounded form that fit the hand well for gestures. Additionally, a magnetized clip was defined as a way for people to easily remove the remote from the wall for these gestures. Finally, the MoJo Remote Bridge mimicked the form factor of the Remote to complete the product family design.

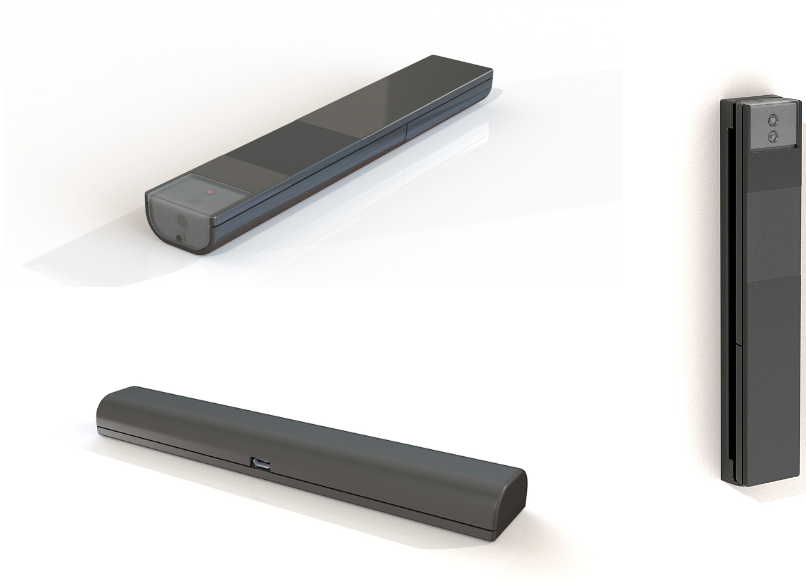

Figure 2: MoJo Remote, MoJo Remote Bridge, and MoJo Remote with Wall Clip

Initial product definition was followed by multiple design concepts, which were then refined, and multiple physical Stereo Lithography were produced and evaluated.

Once the specific design concepts were completed, detailed mechanical design was performed which included solid model development in SolidWorks, custom battery spring development as well as the fabrication of multiple SLA physical prototypes.

The ID/Mechanical Design process concluded with functioning Remote Electronics in SLA enclosures for beta testing.

Remote FCC Testing

The Remote was submitted for FCC testing at NCEE Labs in the fall of 2017 after the above discussed range issue was resolved. Fortunately, FCC testing had not been started on the previous module-based approach. The FCC testing went smoothly both for unintentional radiation as well as intentional radiation. The only significant hurdle in the FCC test involved measuring the 2nd harmonic of the 2.4 GHz fundamental as it was within 6 dB of the limit. Fortunately, multiple additional measurements were provided to NCEE by MoJo Labs and this issue was resolved. The full report was submitted to the FCC in late 2017 with formal approval expected in 2018. Note that the MoJo Remote Gateway was submitted for testing simultaneously, see details below in the Task 2 summary.

MoJo Remote Intellectual Property

As noted in the initial MoJo Remote report, a novel method of interacting with SSL lighting was invented during the performance of this Phase 2 SBIR, called Wand Gesture. Accelerometers and capacitive touch sensors in the remote sense gestures of someone holding the remote and various aspects of SSL lighting are adjusted in a modern-feeling seamless UI/UX. A full utility patent application was submitted in December 2016 and an notice of issuance of this patent application was received in late summer 2017. MoJo anticipates this to be a significant innovation that could enable deeper adoption of lighting controls, which could result in significant energy savings.

Additionally, the MoJo Remote implements Task To Wall translation, and a utility patent for this technology was filed prior to the Phase 1 application. This patent issued during the Phase 2 development, and a follow on Patent covering Task To Wall color control is pending as of the completion of the project.

Task 2: Develop the MoJo Remote Bridge

MoJo Bridge PCB Development

In the first reporting period, an initial PCB prototype of the MoJo Remote Bridge was produced using a Linux-based module for HLK-Tech, the HLK-RM04, as well as a Taiyo Yuden nrf51 based BLE module. The development of the MoJo Remote Bridge continued to evolve during this final reporting period and many adjustments were made to the design during the design process.

As was noted above, the nrf51 based approach using the Nordic Semiconductor 51822 developed issues, and to maximize range a switch to the nrf52 series was made. This change was made for the Bridge development as well, however, unlike the chip-down approach in the Remote, on the bridge the Taiyo Yuden module approach was retained. This decision was enabled by a previous design decision on the Bridge to use stick-on PCB trace antennas that were connected to the main PCB via a u.fl cable, thus side-stepping the Taiyo Yudeo issue with its on-module antenna.

As development with the HLK-RM04 module progressed, multiple issues were found. A lower-cost, follow-on module, the 7688A was released by HLK-Tech, and this module had a number of advantages:

- Faster version of the same MIPS processor.
- More RAM and Flash.
- Surface Mount form factor rather than through-hole.
- Smaller physical size.
- In-system programming for production.

Because of all of these factors, a switch was made to the 7688A module. The smaller form factor played into the Industrial Design approach outlined above in that a very similar form factor to the Remote was enabled by the small size of the 7688A module.

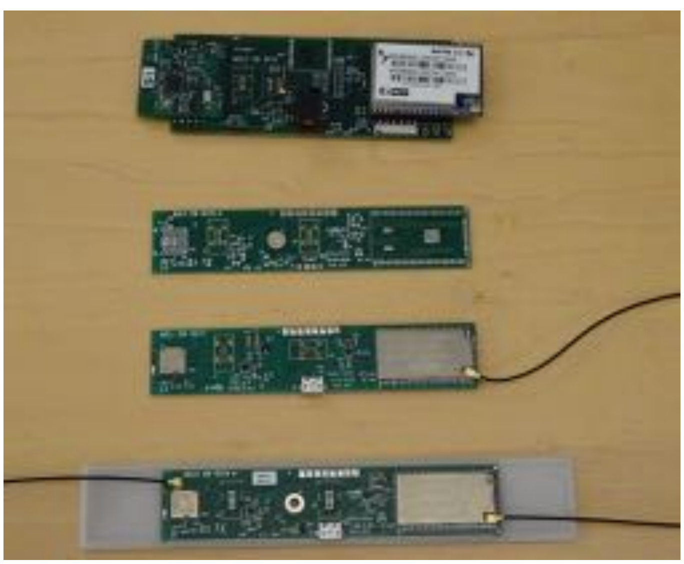

Figure 3: MoJo Bridge PCB Prototypes, with final PCB Prototype on bottom in plastics.

MoJo Remote Bridge Software Development

In the first reporting period, a C-based Linux Application was developed. This application was redesigned and further developed by Adam Boggs, a MoJo employee hired during this project performance. Two areas received detailed attention during this development: the C Application itself, as well as the building of the Linux platform for the 7688A.

The C Application was extended to include the following features:
• Improved integration with the Philips Hue Bridge.
• Smoother dimming with Hue bulbs.
• Cloud interface for Task To Wall monitoring.
• BLE Communication for WiFi Commissioning.

The Linux platform was developed for the 7688A module using the HLK-RM04 distribution as a starting point. Fortunately, Adam Boggs is very experienced in developing for Linux in general and OpenWRT in particular, which is the Linux distribution used for this development. A build system was developed which enabled re-building a production flash image as needed for in-system production programming.

MoJo Remote Bridge Industrial Design

A product family approach was taken for the Industrial Design of the MoJo Bridge that both enabled immediate product family identification, as well as simplified the design process for the MoJo Bridge.

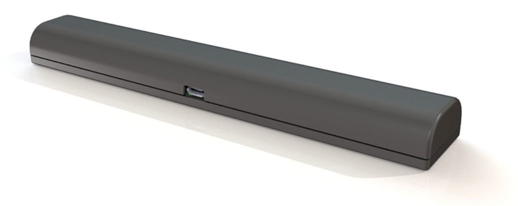

Figure 4: MoJo Bridge Rendering with Micro-USB power connector visible.

The resulting Industrial Design concept transitioned into Mechanical Engineering with the development of a SolidWorks model of the enclosure. Multiple SLA physical models were created, and the resulting SLA enclosures are in use during Beta testing with the Beta-level PCBs discussed above.

MoJo Remote Bridge FCC Testing

The decision to use the nrf52-based Taiyo Yuden module simplified FCC testing in that MoJo could rely on the module's already-completed FCC certification. This meant that only unintentional radiator testing need be done. Because the Bridge had two transmitters on it, BLE and WiFi, a special intermodulation test needed to be added to the FCC testing, but this test proceeded without issues.

This testing was completed in Q3/Q4 2017 and reports submitted to the FCC for approval in late 2017.

Task 3: Develop The MoJo Remote Mobile App

At the end of the first reporting period, an initial iOS prototype application was produced for MoJo Labs under contract to Steamboat Mountain Designs and Fox Apps LLC. While this initial prototype had a subset of the target functionality, much development remained to turn this prototype into a functional App.

In this second reporting period, much development work was spent to move the iOS App to a beta-level, as well as starting and completing a large part of the Android version of the mobile application. For this development, MoJo Labs worked with Codespring LLC and Norvellium LLC as the original developers had transitioned away from mobile application development. The transition was smooth, and the experience of both Codespring and Norvellium proved timely in completing the challenging development.

At the conclusion of this Phase II Development, the iOS Mobile App has no outstanding issues for Beta level functionality, and the Android App is at a feature complete level for Direct Luminaires, with Bridge-To-Luminaire functionality planned for future development (eg Philips Hue).

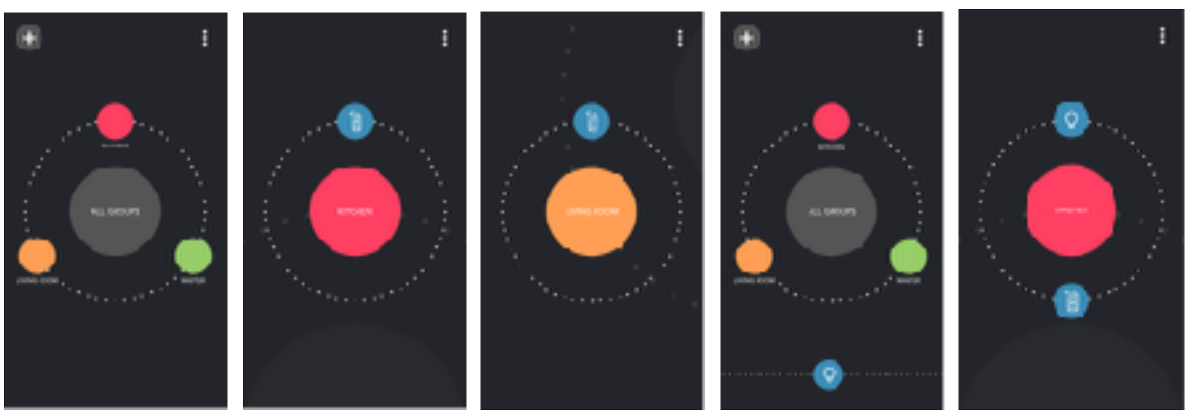

Figure 5: Zooming User Interface: groups, lamp discovery and assignment to group.

Accomplishments during this reporting period include:

- Zooming User Interface (ZUI) development complete on iOS
- ZUI prototype level implemented on Android
- Beta feature level implemented in iOS, including:
  - ZUI
  - Discovery of: Remotes, Direct Luminaries, Hue Bulbs and MoJo Bridge
  - Bridge commissioning onto WiFi
  - Grouping, ungrouping
  - Identification of Remotes, Direct Luminaries and Bridge Luminaires
  - Initial Tip Affordances
  - Direct and Bridged Luminaire control
  - Much more
- Prototype feature level implemented on Android, including:
  - ZUI
  - Discovery of: Remotes, Direct Luminaries, Hue Bulbs and MoJo Bridge
  - Bridge commissioning onto WiFi
  - Grouping, ungrouping of Direct Luminaires
  - Identification of Remotes, Direct Luminaries

- Direct Luminaire control

While the Android Application as yet has not caught up to its iOS counterpart, the Android application has had the benefit of learning from the iOS side development, and has some architectural improvements of the iOS App. In particular, while the iOS side uses a local database on the phone to persist application information such as groups, etc, the Android side uses Google Firebase as a cloud-based realtime database. These architectural improvements will likely find their way into the iOS application in future revisions.

A key goal of developing both Mobile Applications was to enable grouping and commissioning of wireless lighting to individuals not trained in commissioning lighting systems. After much R&D on the UI/UX of the App, MoJo believes that the ZUI UI/UX of the App will enable rapid adoption of wireless connected lighting and should enable easy commissioning and re-commissioning of the Task To Wall daylighting algorithm with only using a smartphone.

Task 4: Create a Bridgeless SSL Remote

This task was originally proposed to evaluate the possibility of embedded a second RF transceiver into the MoJo Remote to enable direct connection of the remote to Zigbee based lamps. As reported in the first reporting period, after the discussion at the project kickoff meeting with Edward Petrow in July of 2015, MoJo has decided to eliminate this task for the following reasons:

• Adding a Zigbee chip would increase power consumption.

• Adding a Zigbee chip would increase system cost.

• While Zigbee LightLink has some market share, the protocol future for connected lighting is very uncertain.

• Maintaining the MoJo Bridge as the method of connection to existing products was decided to be the best strategy.

This has proved to be a solid decision. As expected, Zigbee has not evolved to meet expanding expectations for the emerging Internet Of Things (IoT). However, MoJo has monitored the evolving IoT and protocol market, and in the latter months of this Phase 2 SBIR, two options for possible bridgeless protocols have emerged.

While the Thread protocol has existed for the entire duration of this Phase 2 development, in mid-2017, Google NEST released OpenThread, their open source version of the stack that supports multiple processors and RF platforms. While hardly any products exist with Thread support as of this writing, substantial semiconductor support now does exist, and may spur adoption. MoJo will continue to monitor Thread developments and may produce a follow-on version of the MoJo Remote implementing Thread if the lighting market adopts it in any significant fashion.

Additionally, mid-2017 has seen the emergence of BLE Mesh, the long-anticipated IoT targeted offering from the Bluetooth SIG. While much simpler in concept than Thread, ultimately it requires semiconductors of similar cost to implement, and so will likely be a primary competitor to Thread.

MoJo will monitor the emergence of both protocols and may target a follow-on version of the MoJo Remote as events unfold. Fortunately, a follow-on chip from Nordic Semiconductor is entering production in Q1 2018, and this chip supports both protocols, and so it may be possible to support both with identical hardware.

Task 5: Extend the TTW into Color Control

The ultimate objective of Task 5 is to extend the Task To Wall (TTW) control architecture into closed-loop spectral control. While originally planned for the beginning of year 2 in this Phase 2 development, parts of this were accomplished in the first reporting period, and other parts were delayed to the end of the Phase 2 development by the multiple technical issues identified above during the MoJo Remote development. However, a no-cost extension granted by Ed Petrow enabled the bulk of the intended R&D for this task to be accomplished during this extension period.

At-task color control uses the MoJo Remote to sense the spectral content of light incident at a task location, and then adjusts the spectral output of light from a color control capable luminaire to accomplish control of both total intensity and spectral shape. For this development, a color control capable Philips Hue system was used and integrated with the MoJo Bridge and MoJo Remote/Sensor. The Remote/Sensor senses the spectral content and intensity of the light incident at a task location via its R/G/B capable color sensor, and then uses that information to adjust the light output of the Philips Hue, which is also a R/G/B emitter luminaire.

The Hue has traditional narrow-band LED's in Red and Blue, and a phosphor converted orange LED that produces the green light. The output of the green channel is not narrowband, and overlaps significantly with the red portion of the spectrum which provided unique challenges for closed loop control for to the green channel being heavily cross-coupled to the red channel. A number of solutions to this issue were investigated, but the preferred solution so far is to reduce the attack time of the green channel so that it is controlled less aggressively than the red channel. This allows the coupling to occur between the two control loops without inducing oscillations. A demonstration of this system was shown at the 2016 DOE SSL R&D Workshop in Raleigh North Carolina.

Figure 6: Demonstration of color control at the DOE SSL R&D Workshop

Not only did the demonstration show traditional daylighting in adjusting the intensity of the lamps in the face of the additional light, but it also showed adjusting the spectral content.

The demonstration at the R&D workshop successfully showed many elements of the MoJo Remote system working together to accomplish this control:

- The MoJo Remote/Sensor
- The MoJo Bridge
- The Integration with Philips Hue
- Closed-loop control of spectral content of a luminaire

Additionally, this demonstration simultaneously showed three wireless protocols working to accomplish the simple-looking result: WiFi, Bluetooth Low Energy, and Zigbee. A primary goal of the MoJo Remote system is to tie together complicated technologies to produce simple tangible benefits to people using their lighting.

Additional R&D was performed during the extension period of this Phase 2 development to extend this at-task color control using the Task To Wall architecture so that the spectral content of the task point can be controlled remotely by the MoJo Remote mounted on a wall.

This R&D was performed in simulation to allow for rapid iteration of the development of the algorithm. In simulation, the extension of the Task To Wall architecture was successful, and control of spectral content at task was accomplished.

The following is a visualization of this TTW Color Control simulation:

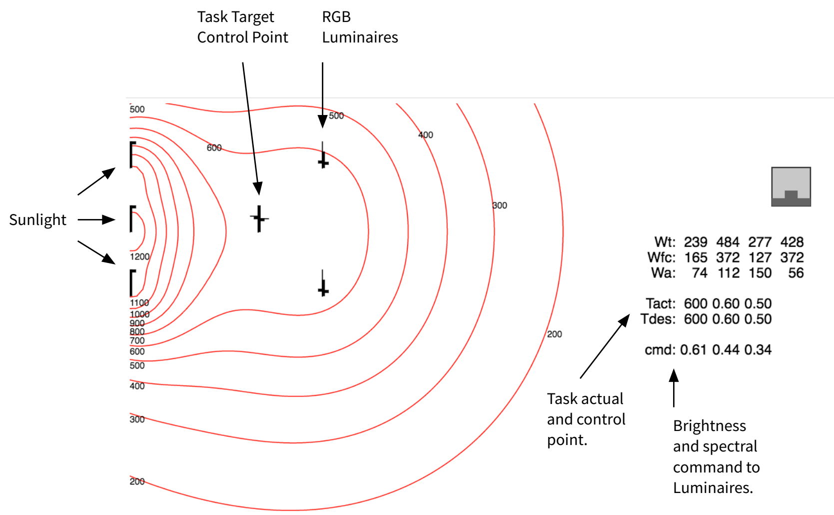

Figure 7: TTW Color Control Simulation showing intensity and spectral control of task location by measuring light only at wall location.

Additional R&D is required to move the TTW Color Control algorithm from the simulation and into the firmware for the MoJo Remote. However, this forward-looking technology has significant potential as a means of task color control without the need for a sensor directly at the task location, but rather by having a sensor on a nearby wall location. The MoJo Remote's spectrally sensitive light sensors provide this functionality.

Task 6: Integration and Test

The goal of Task 6 is to continuously integrate and test the MoJo Remote system. During the entirety of the Phase II project, MoJo has maintained a continuous test of the complete MoJo Remote system as it has evolved, including the Remote, Bridge and iOS App. As new versions of each piece become available, they were inserted into the continuous testbed.

Additionally, at the 2017 SSL R&D Conference, MoJo demonstrated the entire prototype system to multiple conference participants, including Cree, GE, Epistar and multiple DOE participants. This demonstration included the MoJo Remote, the MoJo Bridge, the MoJo Remote iOS App, a Direct Luminaire, as well as a Philips Hue system to demonstrate bridge Luminaire functionality.

However, the goal of the MoJo Remote development is commercialization, and a goal of this Phase 2 development is Beta testing. Entering Beta testing has been delayed by the above mentioned technical challenges, in particular the MoJo Remote range issue and additional PCB spins have delayed Beta into Q4 2017 and Q1 2018. However, Beta testing has begun by the conclusion of this Phase 2 development, and is progressing beyond the period of performance.

As Beta has begun, there are promising initial test results of real-world situations outside of MoJo's testbed. One such installation is a residential kitchen where Philips Hue white bulbs were installed, along with a MoJo Remote, a MoJo Bridge and the Philips Hue Hub. Task To Wall setup was seamlessly commissioned and then used over several days. The following is a graph of TTW data over an afternoon. The kitchen has several south facing windows and receives significant natural light.

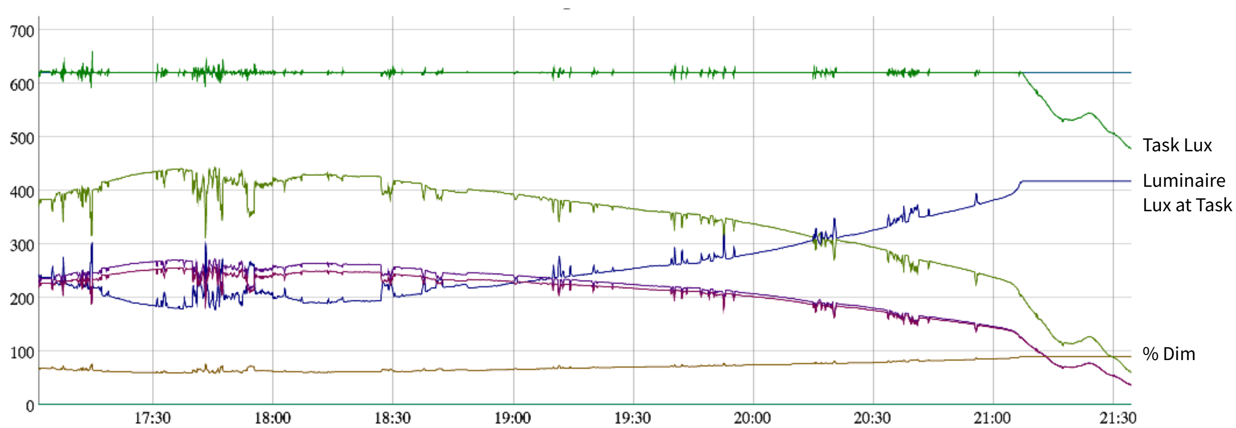

Figure 8: TTW Test Installation In Residential Kitchen

The top line is the control point, the other lines are the constituent pieces of the TTW algorithm, the declining sine wave is the ambient light, the increasing sine wave is the remote adjusting the lights as the sun dims. The dimming command to the luminaries is at the bottom of the graph and shows the TTW algorithm adjusting as the sunlight changes over the afternoon. Finally, at about 21:10, the light output maxes out and the desired task Lux can not be maintained given the light output of the Luminaires.

A second Beta test installation is a small 10x10 office room with Hue White bulbs providing illumination:

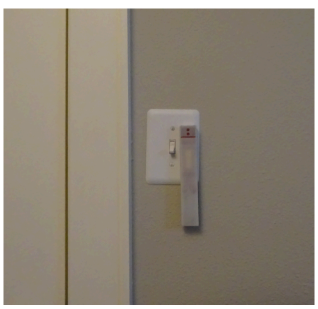

Figure 9: Office room installation with MoJo Remote at Light Switch Location

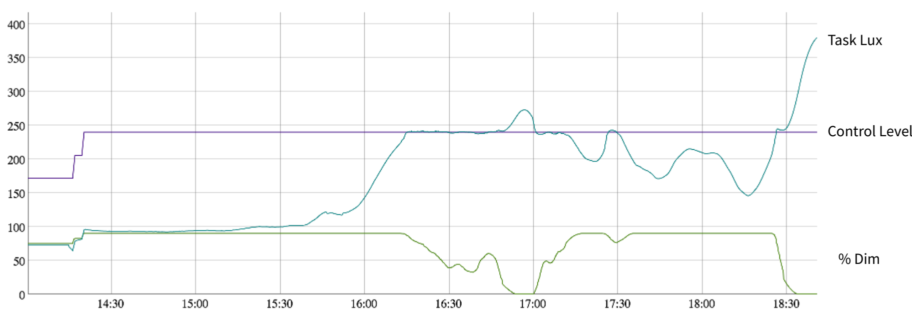

Figure 10: TTW Performance in Office Room

This Office test installation was intended to stress the TTW algorithm by putting it in a challenging environment. The control point was set to control 250 lux at the task location of the desk. This level is well above what the Luminaries themselves could provide. This office has a large south facing window, and on the day of the test shown in the graph above, direct sunlight came in this window. As shown in the graph, when the TTW algorithm could provide the desired lux levels, it did so by adjusting the percent dim. However, significant time periods occurred when accurate control was not possible. Despite this, the TTW algorithm provided usable light levels, either full on when not much light entered the windows, or full off when too much sunlight entered the large south facing windows. Also importantly, the algorithm provided smooth transitions and did not oscillate, which are critical factors for occupant comfort.

These test installations show the benefits of the Task To Wall architecture: a desired light level is maintained while simultaneously saving money and energy. This dual-benefit can not be overstated. TTW allows a "win-win" for desired light levels and energy savings, and the typical tradeoff between results and energy savings does not apply. People using TTW are not asked to sacrifice to enable energy savings, but rather by using TTW they save energy as a side benefit of achieving a very desirable benefit in appropriate light levels.

By integrating both TTW as well as the Wand Gesture control into the MoJo Remote, MoJo expects to enable this "win-win" in a rapidly adoptable product that is currently in Beta Test and on the path to commercialization.

What opportunities for training or professional development has the project provided?

This project has provided considerable professional development in developing wireless communication protocols and working with color control of LED luminaries. While there is a lot of literature on these subjects, the actual implementations are vendor specific and typically not well published. Experimentation and code development has help MoJo develop considerable confidence in the approaches used commercially to develop an architecture and professional skill set that is expected to be competitive.

How have the results been disseminated to communities of interest?

Until the products are released, a lot of information needs to kept in confidence. However, we have submitted two patent applications that will lead to public disclosure and we presented our progress at the 2016, 2017 and 2018 DOE SSL R&D Workshops.