**Intellectual Merit**

Through this proposed research, we will advance the state of the art in catoptric systems, using two important applications to guide and evaluate the development of prototype systems: community-scale food production, and lighting and thermal management of human-occupied buildings. Our proposed investigations will target three primary objectives: (1) identifying and quantifying benefits that can be achieved by redirecting light (including daylight, incandescent light, light from LEDs, and combinations thereof) for hydroponic and soil-based food production, building lighting and thermal management, through the use of catoptric systems; (2) establishing and evaluating models and methods to ensure the safety, reliability, maintainability, and continued efficacy of these systems, using rigorous methods based in Markov Decision Processes for modeling and policy generation; and (3) extracting common abstractions from the instantiation and evaluation of the approach in three distinct application domains (food production, building lighting, and building HVAC), as a starting point for further application of the approach in other smart and connected communities applications.

In addition to projected broader impacts on community nutrition, illumination of occupied spaces, and sustainable energy use, this proposed research is of significant intellectual merit in expanding and deepening the kinds of cyber-physical systems capabilities that are pertinent to smart and connected communities. Specifically, by introducing active modalities (sensing, control, coordination, and actuation) into historically passive (daylight) or largely static (artificial lighting) modalities, and controlling and coordinating them with respect to well-defined objective functions in each of several distinct applications, we seek to transform how light is used indoors.

For example, while hydroponic food production using artificial light has been shown to be effective [TBD – cite Tuscon AZ truck], examining the effectiveness of redirected natural light in comparison to (and possibly in combination with) artificial lighting is both largely unexamined and well aligned with the expertise and interests of this research group and our collaborators.

Similarly, daylighting (the use of natural light for illumination) design is dominated by passive window positioning and configuration [51] rather than active control mechanisms, except in a few cases [28]. Heating systems that exploit sunlight frequently use actively-controlled mirrors for tracking the relative position of the sun, but there is limited experience with using the same sets of mirrors for both thermal and lighting control.

We propose to investigate how to utilize actively controlled catoptric (mirror) surfaces effectively for improved food production and illumination and heating of buildings. Through computer-based control of the dynamic positioning of individual mirrors, and cyber-physical integration of natural and artificial light sources, the mirrors, the devices that orient them, and customized plant growth, building lighting and heating objectives and constraints, we propose to enable adaptive and fine-grained management of light as a resource throughout a building.

We propose to develop image-based maps and other interfaces to allows users of our system to visualize zones of intensity in an interior space prior to the mirrors redirecting light, and to allow updates to the map to increase or decrease intensity through different modalities of redirection, filtering, or blocking or recruiting light sources. Users also will be provided interfaces for supplying or creating the images to be used for the map, and defining and evaluating different objective functions for lighting intensity, thus encouraging user-based control of, and interaction with, the system in each of several different applications. The engagement of any member of a community in the creation of that image in turn may impact on the entire community

[44] and encourage dialog about the quality and quantity of light within the environment.

Given the desire to control different combinations light (sunlight and different sources of artificial light) via catoptric surfaces, for different plant growth, illumination and/or thermal management objectives, a number of crucial cyber-physical systems issues must be addressed. For example, we will investigate how existing techniques like multi-objective control be applied to manage the relationships among potentially competing goals within each application (which themselves also will be articulated and quantified as a contribution of this proposed research). We also intend to investigate whether Markov Decision Process (MDP) models can serve as a cohesive framework within which each application domain’s distinct multi-objective control problem can be represented, and appropriate control policies generated automatically (e.g., through techniques like policy iteration), recognizing that maximization of an objective function in expectation is a robust way to acknowledge the inherent uncertainty of future events (whether it be sunlight availability, lighting demand, or any other effect that is either stochastic in nature or is sufficiently complex but stationary so that it can be modeled as such).

Constraints for safety, reliability, and maintainability, also will be modeled, alongside the objective functions for the continued efficacy of a catoptric system in each particular application domain. Even with a suitable multi-objective control approach in place, it is essential that such requirements are all addressed together, at once, and consistently. For example, considering safety: highly concentrated sunlight could be damaging either to a plant or a person and so would lead to deterioration of the expected value for the objective function in food production or illumination applications. However, in a HVAC application, such light aimed at a heat collector (important when harvesting energy for thermal management purposes) may need to be limited even if its increase would improve the application’s objective function, as it could be harmful to a person who inadvertently contacted the beam of light. This example in turn reveals the kinds of nuances that may be in play for such systems, which in turn may inform other cyber-physical applications – for example detecting the presence or absence of a person in that scenario could inform sensing, control, and actuation decisions. Reliability and maintainability considerations similarly may span both objective functions and constraints, for example in community food production settings where failure of the system would impair vital nutritional resources on which a community increasingly relies.

Several key considerations for this proposed research will be the effectiveness and ease with which (1) abstract state representations (within the MDPs) can adequately track and manage complex real-world applications, (2) large numbers of mirrors, sensors, and pan-tilt units can be managed over long periods of time as some of them may degrade or cease functioning entirely, and (3) fundamental issues with observability that arise from the first two considerations. We propose to address the first consideration through careful abstraction of each application domain’s most salient features within our models. For example, in the domain of food production, we will work with our collaborators in plant science to identify and/or define initially simplified models for how different illumination patterns may optimize food growth – we will then apply those models to control catoptric surfaces in small-scale physical experiments, and refine the models based on the results of those studies.

The second and third considerations will be addressed by tracking and reporting the potential degradation of individual elements in the prototype test-bed we will develop for each application domain, and examining the uncertainty in sensing, actuation, and control that may occur because of it. Incorporating uncertainty into our MDP-based models, e.g., through developing POMDP models, PAC bounds (as we have done in prior work [TBD – cite Glaubius et al. UAI paper]), and other methods will be another important contribution of this research.