CPS: TTP Option: Medium: Multi-objective Control of Catoptric Systems

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1. INTRODUCTION

Energy consumption due to buildings (both residential and commercial) is estimated to be 20% to 40% of the total energy usage in developed countries [41], and lighting and heating are two significant components of this demand [29]. Natural light (i.e., sunlight) is a readily available resource that can contribute both to the illumination [32] and to the heating [35] of structures, yet in the vast majority of circumstances, its use is limited to passive modalities. For example, ***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 illumination and heating of buildings. Through computer-based control of the dynamic positioning of individual mirrors, and cyber-physical integration of the mirrors, the devices that orient them, and customized lighting and heating objectives and constraints, we propose to enable fine-grained management of sunlight as a resource throughout a building.

Figure 1a shows a prototype catoptric surface (called AMP) that was designed, fabricated, and installed during an undergraduate architecture studio taught by Co-PI C. Ahrens. The installation redirects light from gable ends of an existing building into the darker recesses of the atrium to create better natural lighting where it is desired. In that installation, however, the mirror positions are fixed.
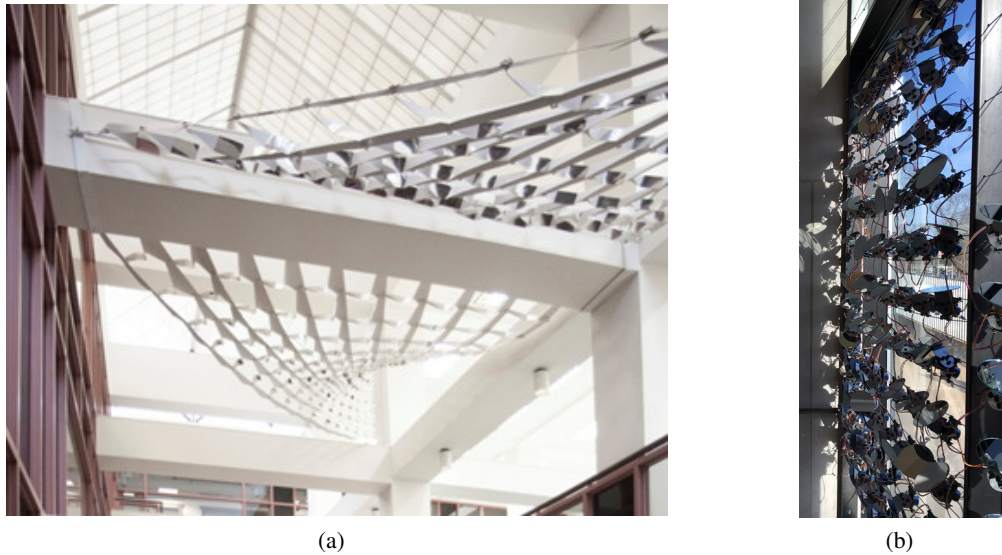

(a)   (b)

Figure 1: Catoptric system prototypes. (a) *AMP*, TRex building, St. Louis. (b) Steinberg Hall, St. Louis.

Based on that fixed design, we are now developing a transformative new version of this approach in which over 600 mirrors are under active, 2-axis, microprocessor-based control and therefore the mirrors can be pointed in different directions dynamically as desired over time. This next-generation installation is currently under construction within the south wall of the Steinberg Hall atrium on the Danforth Campus of Washington University in St. Louis; a subset of the mirrors in this new installation is shown in Figure 1b.

The ability to control the position of each mirror actively and dynamically offers an unprecedented capacity to direct available natural light to where it is most needed. The appropriate positioning of the mirrors can easily change over time, as the usage of the physical space changes, or as cloud cover, temperature, or other environmental factors change.

Our proposed research will advance the state of the art in cyber-physical management of reflected light, by allowing specific intensities to be achieved in some areas while dissipated lighting conditions are achieved in other

areas, according to pre-determined, yet adjustable, image-based maps. These maps may use any raster image to generate the target positions for the reflected light in a space. The image is sampled according to intensity (ranging from black to white) to determine the density of target points (the higher the intensity, the denser the resulting field of points.

Using an image-based map also allows users of our system to visualize zones of intensity in an interior space prior to the mirrors reflecting the daylight. Users also will be provided interfaces for supplying or creating the images to be used for the map, thus encouraging user-based control of, and interaction with, the system. 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 natural light (sunlight) via a catoptric surface, and also repurposing it for illumination and/or thermal management, a number of crucial cyber-physical systems issues must be addressed. This research will investigate the following questions:

1. ***What are the qualitative and quantitative benefits that can be achieved for building daylighting and thermal management through the use of catoptric systems?***

    Research challenges involved with this question include the ability to articulate different benefits, objectives, and constraints, and to quantify them effectively. Clearly, doing so falls within the domain of multi-objective control, so the relationships among potentially competing goals also must be articulated and quantified. We intend to investigate the use of Markov Decision Processes (MDPs) as an approach to the multi-objective control problem, 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 stochastic in nature).

2. ***How do we provide for the safety, reliability, maintainability, and continued efficacy of these systems?***

    Even with a suitable multi-objective control approach in place, the system as a whole has limited usefulness if each requirement is not addressed in an effective way. For example, consider the question of safety: highly concentrated sunlight aimed at a heat collector (important when harvesting energy for thermal management purposes) could be harmful to a person who inadvertently contacted the beam of light.

    Each system-level requirement thus must be included appropriately within the control problem formulation, either as constraints (e.g., for safety) or as additional objectives (e.g., reliability and/or maintainability). Fortunately, the MDP formalism is well suited to the addition and integration of concerns such as these (especially those with a stochastic nature, as reliability and maintainability tend to be).

3. ***Can we design abstractions that encapsulate subsystems for effective reuse?***

    Separating the concerns of low-level control (e.g., of mirror positions) from the concerns of high-level system management (how the available light resource should be allocated) is one way to approach this question. The low-level control subsystem can be encapsulated into reusable components that may be applicable to any number of physical positioning applications, and that can be substituted as needed to address new design constraints that may emerge for an installed catoptric system over time. Similarly, high-level management components (e.g., based on different MDP models) also can be encapsulated, in a manner that allows them to be re-used in different kinds of cyber-physical systems or substituted to address different combinations of constraints and objectives within an installed system as its requirements evolve.

About us: Our group is uniquely qualified to address the questions we pose above. We have significant expertise in the areas of computer engineering, architecture, and computer science that are relevant to this proposed research. We are already collaborating as an integrated team [10], with one prototype system completed and installed and a second nearing completion. We also have significant experience building cyber-physical systems [12, 52] and collaborating in MDP-based design of multi-objective resource management [36]. Co-PI C. Ahrens serves on the Board of Directors for the Association for Computer Aided Design in Architecture (ACADIA). In the past two years, Co-PI C. Gill has served as both program chair and general chair of the ACM/IEEE International Conference

on Cyber-Physical Systems (ICCPS) and is currently serving as an Associate Editor for ACM Transactions on Cyber-Physical Systems. PI R. Chamberlain is co-author of an introductory text entitled *Computing in the Physical World* [11].

2. BACKGROUND AND RELATED WORK

This research proposal builds on ideas, models, and techniques pioneered in two previous projects. The first project, titled **AMP**, created a prototype to redirect daylight deeper into specific locations with a lightwell. The building in which the prototype was installed is an 8 story factory building built in 1895, in which a 5 story light well was cut out of the floors. A skylight was located above the lightwell and provided the daylight source. The primary goal of the project was to develop and use computational techniques to be able to reflect the rays of light into the darker recesses of the lightwell. Figure 2 shows an example output from the resulting software system (analyzing a hypothetical location). A secondary goal of that work was to develop a catoptric surface that connected to existing columns and beams, which was divided into 300 reflective sub-surfaces to achieve the goal. The project verified that the 300 custom geometrical sub-surfaces could be designed and fabricated (see Figure 1a). Though successful in its aims, an important limitation of the project was that each reflective sub-surface had a fixed geometry.
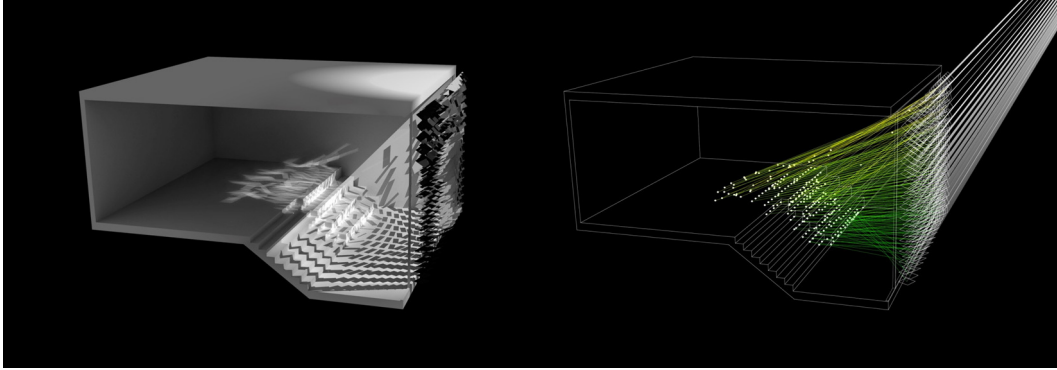

Figure 2: Ray tracing analysis of daylighting design.

The second project, titled **Catoptric Surface: Steinberg prototype**, addressed that limitation of fixed geometry in AMP. The goal of this second prototype was to create a series of mirrors that were independently adjustable according to both the sun's position throughout the day and the desired location within the building towards which to reflect the light. The ability to vary the intensity of reflected daylight within the interior of a building provides the occupants control of the light level for varying tasks such as a lower light level required to read from a screen versus higher light level for reading physical paper. This increased level of control was enabled via the development of units providing 2 axes of rotation of each mirror independently under software control. This second prototype provides a proof of concept that individually controlled mirrors can effectively direct daylight in a very controlled geometry. Figure 3 shows a CAD illustration of the prototype, and Figure 1b shows a photograph of a small number of the installed mirrors.

Leslie [32] and Alrubaih et al. [3] provide a pair of review articles that effectively summarize current approaches to daylighting in modern building design. For the most part, these are passive systems, or might include active control of shades [28], with a strong emphasis on achieving uniform, homogeneous illumination [5, 17]. Our emphasis is on dynamic control of the light position, with the explicit intent to support inhomogeneous as well as homogeneous illumination patterns.

There have been a number of efforts to quantitatively model, and empirically measure, prototype daylighting systems [5, 16, 31, 50, 51]. A pair of studies, first by Lee and Selkowitz [31] and followed by Fernandes et al. [16], initially evaluated the potential for energy savings in the New York Times Headquarters building and then measured the actual realized savings.
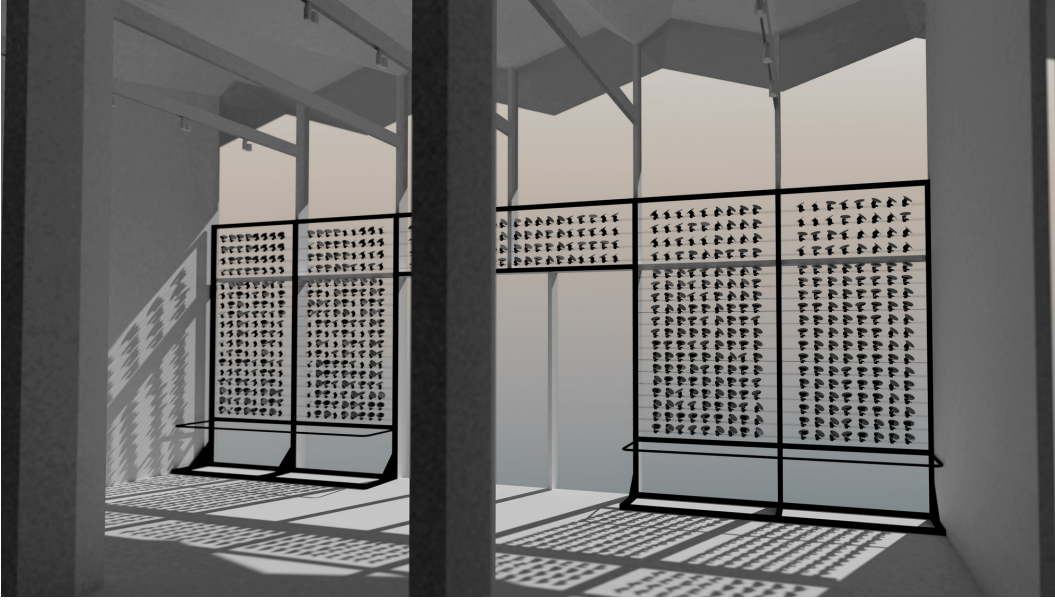
Figure 3: CAD drawing of the Steinberg Hall prototype catoptric surface.

In this work, we will exploit Markov Decision Process (MDP) theory [43] as a formal approach to optimize catoptric surface control. MDPs represent a general approach to modeling optimization problems and have been applied in a diverse set of application areas [55]: examples include robotics [1], economics [4], experiment design [27], medical decisions [2], manufacturing [58], agriculture [30], and our own group's use in real-time scheduling [21, 48] and wireless spectrum management [36].

Our prior research has used Markov decision process models [21] to generate resource management policies off-line [18] for non-preemptive sharing of a resource among multiple purposes at once on-line. For example, a meter-tall robot's camera (oriented by a pan-tilt unit similar to the ones we propose to use in our multi-mirror catoptric installations) may be directed downward to identify wire-frame chairs and other obstacles to navigation that other sensors on the robot may have difficulty detecting, or it may be directed upward to identify faces of people at a social event whose images it can then capture. Given distributions of the durations of intervals during which the camera would need to remain pointed in a given direction to complete an individual task, standard policy iteration techniques then can be used to generate run-time policies that in expectation maximize an objective such as adherence to a strictly proportional allocation of the resource over time [21], or even a more general definition of the utility of completing the different tasks at particular times [48]. We also showed that when different distributions of task completion intervals can occur in different modes (e.g., when a robot moves from room to room), it is possible to learn on-line what mode the system is in, or if the mode is known what the distributions are, but not both [19].

However, policy iteration is exponentially expensive in its computational requirements, and even the memory requirements to store complete policies for on-line use may be prohibitive in resource-limited systems. We therefore focused next on the policies that were being generated from the models, and discovered consistent structure in those policies that allowed a reasonable heuristic approximation. For simple proportional sharing, a single geometric partition of a simplex could be calibrated to encode the appropriate policy accurately [20]. For utility-based resource sharing multiple disjoint heuristics were needed but the most effective one to use was clearly defined by problem parameters [47].

As a further illustration both of the applicability of MDP-based policy iteration to generate effective resource management policies, we applied similar techniques to manage another dissimilar resource: the transmission spectrum in wireless networks [37]. Although the semantics of that resource differed radically from the pan-tilt camera, the MDP models were reasonably similar. We extended the basic model to include modulation as well as admission decisions, discovered and characterized common structure among the policies that were generated, and again

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obtained efficient and effective heuristic policies for on-line use [36].

In this proposal we adopt the definition used in our prior work [21] of a (discrete-time) Markov decision process as a 5-tuple $(\mathcal{X}, \mathcal{A}, T, R, \gamma)$, with **states** designated as $\chi \in \mathcal{X}$, **actions** designated as $a \in \mathcal{A}$, and a transition system, T, which gives the probability $P_T(\chi' \mid \chi, a)$ of transitioning from state χ to state χ' on action a. The reward function $R(\chi, a, \chi') \in \mathbb{R}_{\geq 0}$ describes the reward that accrues when transitioning from state χ to state χ' via action a, under a discount factor, γ, to ensure convergence of the long term reward. In what follows, we will explain how we plan to exploit the formal theory of MDPs as an approach to optimization of the configuration of catoptric surfaces.

3. RESEARCH DESCRIPTION

Our proposed research will address each of the specific questions posed in the introduction, as follows.

3.1. Question 1 – What are the qualitative and quantitative benefits that can be achieved for building daylighting and thermal management through the use of catoptric systems?

The benefits of natural light in human-occupied spaces are well documented both in the research literature and in the popular press [22, 32, 33, 34, 42, 49], and yet thermal effects also may be significant [6] (e.g., too much sunlight can increase temperature to unacceptable levels). While many studies focus on the benefits of homogeneous light levels within a space [3, 5, 17], appropriate light levels may differ based on user needs. The increased range of lighting effects offered by the independent positioning of mirrors can provide functional benefits for people who need more or less light, e.g., due to the age of the occupant or the task she or he is performing. For example, someone using a computer may want less light, since the screen is a source of artificial light and glare from outside may make it more difficult to see, while someone reading from unlit physical media like a book may require higher light levels. Similarly, light levels required for vision may vary with the ages of the occupants: as people get older, they tend to need higher light levels and increased luminous contrast. Furthermore, regardless of age, different people tend to have have different visual acuity. Thus, developing a system that can provide a wide range of lighting effects using daylight rather than artificial light to accommodate these varying requirements is beneficial.

For thermal management, the literature on harvesting sunlight for space heating is substantial (e.g., [13, 23, 26, 35, 46, 53], and we will simply leverage such well-understood techniques. As many sunlight-based heating systems already use catoptric mechanisms (though primarily for sun tracking), our primary interest and contributions here will be to integrate a sunlight harvesting system to investigate and demonstrate dual-purpose use of catoptrics in a single cyber-physical system, both for illumination and for heating.

In addition to investigating how (1) natural light can be redirected to achieve different lighting effects using programmable dynamic orientation of mirrors on pan-tilt units, and (2) to what extent those lighting effects can achieve diverse objectives such as energy collection, temperature control, and people's quality of experience in a space, we will also explore (3) how Markov decision processes (MDPs) can be used to generate policies automatically for multi-objective control of catoptric systems. The choice of MDPs to generate such policies is motivated in part by the influence of stochastic factors such as wireless network packet loss between a high-level controller and the units that control the mirrors themselves, and environmental effects such as transient cloud cover on the natural light that is available.

Another motivation for using MDPs is their efficacy in generating highly regular policies that can be implemented efficiently at run-time. For example, policies for proportional sharing of a non-preemptive resource [18, 21] can be approximated efficiently on-line with high accuracy [20]. Scenarios that are relevant to this research, such as using multiple catoptric arrays to provide even and consistent lighting of a collaborative work area, or to generate an inhomogeneous pattern according to an input image, have similarly regular structure that an MDP-based approach can exploit. Our prior work also shows that custom policies can be generated [47, 48] that account for

various nuances (e.g., in this proposed research, individual variations in visual acuity and thus lighting needs, as well as constraints to keep thermal effects within desired ranges).

We will start with a single objective, matching a provided image map that represents a desired illumination pattern, and then generalize this to include the separate goal of thermal energy harvesting while keeping room temperatures within a specified range. To illustrate what we mean by an image map, Figure 4 shows a set of arbitrary example images, associated with the mirror positions that will create those images. The forward problem is determining the resulting image given the mirror positions. The optimization problem is determining the required mirror positions given the desired image.
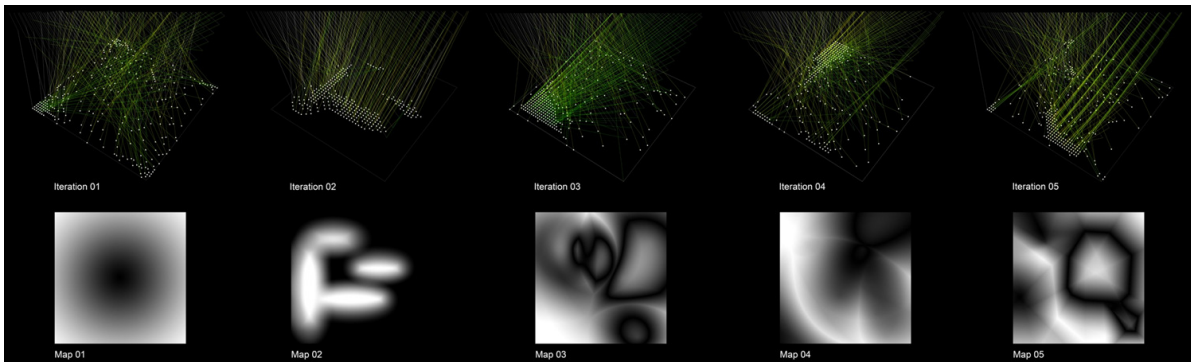

Figure 4: Example image maps (bottom) and associated mirror positioning (top).

For the purpose of designing an MDP, we will leverage the ability of the low-level control mechanism to position each individual mirror as desired. The MDP state-space will model higher-level management issues, e.g., which mirror should be pointed in which direction at which time, using distributions of mirror positioning latencies (based on the previous positions of the mirrors, network latency including delays due to wireless network packet losses, etc.) and variations in natural light that we will capture through profiling studies. We also will further refine these models, which initially will be based on simply commanding the pan-tilt units to point to specific *locations* in space and allowing the lower-level controllers to enact those commands separately, to a more complete cyber-physical model in which positioning commands may include specific *trajectories* for each pan-tilt unit including its initial and final position, and the ranges of accelerations, velocities, and/or orientations it should remain within during its trajectory along that path – this cyber-physical refinement is important both in its ability to enact more rapid adaptations to environmental variations and to perform dynamic lighting effects (e.g., to get the attention of the people in a space if an emergency alert were issued), and also in terms of tracking the wear-and-tear on the pan-tilt units and how that affects longevity and reliability of the catoptric arrays.

With a low-level controller in place, the state space, $\mathcal{X}$, can encapsulate the set of mirrors pointed at each position in the image map. The set of actions, $\mathcal{A}$, will embody the movement of one or more mirrors from their present position to a new position, and the transition system, T, will encode the probabilistic variations present in the available sunlight. In the simplest case, this allows the reward function, R, to be a quantified match between the desired image map and the resulting daylight that is directed to each position in the physical space (e.g., using existing image comparison quantification techniques [14, 39, 57]). For more complex cases involving different individualized lighting requirements, multiple objectives, etc., we will *convolve* the different objective functions to achieve a single common reward function, as we have done in our prior work [47, 48].

After an initial exploration of the MDP formulated as described above, we will then proceed to expand the framework to include the additional objective of harvesting heat. We will quantify the benefits of each objective using general utility functions [48] in a manner previously explored by our group. One candidate set of utility functions we will investigate will be to prioritize daylighting performance, and only allocate *excess* sunlight to the HVAC subsystem. A second alternative will be to proportionally provide sunlight to each goal up to the point that the illumination can no longer benefit, at which point all additionally available sunlight would go into heating.

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In each of the above MDPs under investigation, we will use policy iteration to capture a ***value-optimal*** solution (which maximizes accrued value in expectation and is guaranteed to exist within Markov decision process theory); however, this solution typically must be computed off-line, since it is, in general, exponentially expensive to compute. In parallel, we will also explore the space of value-optimal solutions and seek to formulate a computationally inexpensive heuristic that closely approximates the true value-optimal solution.

3.2. Question 2 – How do we provide for the safety, reliability, maintainability, and continued efficacy of these systems?

The ability to control mirror positions over time is only useful if the additional considerations of safety, reliability, etc., are managed properly for the system as a whole. To address these issues, we will investigate the degree to which they can be handled within the context of each low-level controller versus being dealt with by higher-level system-wide control. We anticipate some of these considerations being incorporated as constraints within the optimization process and others as additional goals that we wish to maximize during the multi-objective optimization itself. Let us first consider those that will be addressed as constraints (e.g., safety).

Constraints. A commonly used safety constraint on a positioning subsystem is to specify hard limits on the range of motion (e.g., of each mirror, individually). This kind of limit can be imposed by the physical design of the pan-tilt mechanics, simply by adding physical stops at the limit positions.

The more interesting constraint systems occur when the safety considerations are no longer locally determinable, but are dependent upon context. An example that is relevant for our catoptric surfaces is a limit on the total light intensity that can be supported at various positions in the field of view of the mirrors. When providing heat into the HVAC system, we desire a high light concentration delivered to the heat transfer point. When illuminating a physical space for human occupants, levels of light concentration above a certain threshold are not only undesirable, they may be patently unsafe.

These context-sensitive constraints add two additional requirements for our proposed research approach. First, the higher-level management system must be responsible for addressing them. In our MDP formulation, we may either adjust the feasible state space, $\mathcal{X}$, so that they are unreachable, or adjust the reward function to give sufficiently negative rewards so as to preclude the policy violating them [47, 48]). Second, we must also ensure that whatever choices are made by the optimization system (whether it be via MDPs or some other approach), the actual mirror positions are still constrained so as to not result in an unsafe condition. This will require feedback of some form on the actual mirror positions and the ability to determine whether or not the actual positions differ from the controlled positions. This may be accomplished either locally (e.g., via shaft encoders on the pan-tilt mechanism) or globally (e.g., via a visual monitoring system and appropriate image analysis software); we will explore, and compare the consequences of, both options.

Goals. Many of the additional considerations are more appropriately addressed as additional (potentially competing) goals, adding to specific needs for daylighting and heating. An example here would be the impact on reliability of the system when individual mirrors are moved. As with all electro-mechanical systems, the pan-tilt mechanism has a limited lifetime, which can be significantly impacted by its usage duty cycle (i.e., the more it is moved, and the more intense the accelerations and decelerations it experiences, the sooner it will likely fail).

These are precisely the kinds of circumstances in which Markov decision processes are useful. For the initial goals (of question 1), is is quite likely that there are multiple optimal solutions (e.g., simply exchanging where two mirrors point, with the goals unchanged). However, once we add in considerations of reliability, which are impacted by frequency of use and the trajectories used to reposition the mirrors, we now have a much richer search space, whose complexity can be encoded effectively in terms of probabilistic rewards. The MDP-based optimization approach is particularly well suited for this type of problem, and can find value-optimal solutions that incorporate wear-and-tear-minimizing movement of mirrors between configurations, thereby diminishing maintenance costs and downtime during the normal use of the system.

The research task here is to develop, experiment with, and evaluate Markov decision processes that simultaneously deliver daylight where it is most beneficial, maintain the safety of the overall space, and provide for the reliability, maintainability, and efficacy of the catoptric surface itself. For example, when we introduce accelerations of the pan-tilt units into the MDP model as described above, we will bias the reward function to avoid hard stops and rapid accelerations which both can wear out the pan-tilt units and also may contribute to uncertainty in positioning (similar to how wheel-slip must be addressed in mobile robotics [40]).

3.3. Question 3 – Can we design abstractions that encapsulate subsystems for effective reuse?

Layered *system architectures*[1] have proven effective in providing standardized interfaces to support portability and reuse of hardware and software, while allowing new innovations and abstractions to enrich system capabilities. Even when many actual systems don't adhere strictly to official standards (such as the OSI [59] networking model or the POSIX [24] operating systems interface model), system designers, developers, and users still benefit from the overall structure those models provide.

This occurs largely because standardized interfaces establish clear boundaries of responsibility on which other layers may rely, while allowing an essential "permission to tinker" with various implementations between those boundaries. For cyber-physical systems, whose semantics include timing and physical properties not considered in previous cyber-only system architectures, there is significantly less experience with what interfaces, abstractions, and even broad system layers are truly common (and so perhaps could be standardized) versus the question of which other aspects are more likely to diverge between systems, and so should be free to do so [10]. In this research, we will investigate the viability and utility of two candidate abstractions: direct pan-tilt control of individual mirrors and MDP-based system-wide control.

Pan-tilt control.   An initial version of a library (and associated programming interface) for pan-tilt control of our mirror units is already in place [38]. It is based upon an Arduino Uno microcontroller commanding the stepper motors controlling the mirrors (up to 32 mirrors per Arduino), with communication to the Arduino via a USB link. Python software executing on a Raspberry Pi coordinates a set of up to 10 Arduinos using a USB hub.

While the initial implementation simply commands position, it is open-loop and therefore requires periodic resetting (which we accomplish by moving each pan-tilt unit to its stops in each dimension), and only one motor connected to each Arduino can be in motion at a time. As part of the research project, we will extend this positioning control software in the following ways:

1. support closed-loop control, either through the use of shaft encoding sensors or image-based feedback or both; and

2. support path direction (including acceleration profiles) in addition to positioning commands.

We will also extend our current prototype for mirror control to include concurrent positioning of multiple mirrors at once – although positioning a mirror takes only seconds currently, which is appropriate to adjust gradually to the progression of the sun's position throughout the day, for more dynamic lighting effects the latency to adjust an entire row of mirrors in an array may be noticeable, and may introduce undesirable lighting artifacts at least temporarily as mirrors are adjusted.

We also will investigate semi-specular reflective surfaces or a combination of specular mirror surfaces with lenses to diffuse the daylight to reduce the contrast with the surrounding surface that does not have light reflected onto it. We will perform light meter tests to measure the lux and the visual impact of direct versus diffuse daylight reflections.

MDP control.   As is the case with pan-tilt control, we already have an initial functioning piece of software that, given an MDP model, provides both the value-optimal decision at any point in the design space as well as the

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[1]We use the term *system architecture* to denote computer hardware/software architecture, distinguishing it from architecture for the built world around us.

expected value of reward [37, 48]. In the current edition, the user must provide the details of the MDP model by authoring a set of software routines (in C++) that effectively build an in-memory representation of the MDP model.

We will explore alternative interfaces, both textual and graphical, for articulating the details of an MDP model. This is particularly challenging as the models themselves are frequently quite substantial in size.

The MDP models themselves also will be extended to consider concurrent positioning of mirrors, in part to ameliorate wear-and-tear on the pan-tilt units, and in part to achieve new dynamic lighting effects that can include combinations of sequential and concurrent repositioning.

Both of these software systems (and their associated interfaces), constitute abstractions that have strong potential for reuse in other contexts. Pan-tilt positioning control is ubiquitous in imaging for use with cameras (although we have a few features, such as concurrent movement at scale, that are likely unique relative to previous systems), and we have already used the initial versions of the MDP software in multiple contexts [37, 48].

3.4. Intellectual Merit

The intellectual contributions of this project are the investigation of methods for the multi-objective optimization of catoptric systems, i.e., deciding how a collection of controllable mirrors should be installed and how they should be positioned from moment to moment. We will investigate not only the multi-objective control models, policies, and mechanisms, but also issues of design for flexible installation; ensuring safety, reliability, etc.; and exploring in what ways catoptric systems can serve as a guiding example for more general cyber-physical systems development.

4. EVALUATION/EXPERIMENTATION PLAN

We will organize our experimentation and evaluation activities around three prototype catoptric surfaces. The first is the system currently being installed in the south window of Steinberg Hall's atrium (described in Section 2). The second will be designed for and installed at VelociData, Inc., a startup firm in St. Louis that is located in the recently announced *39 North* innovation district. The third will be designed for and installed at BECS Technology, Inc., a local manufacturer of electronic control systems that has recently relocated to a newly redeveloped 42,000 sq. ft. facility. This is followed by a discussion of our software development and assessment plans.

4.1. Steinberg Hall, Washington University in St. Louis

Steinberg Hall is situated on the Danforth Campus of Washington University in St. Louis. It is one of the buildings that houses the College of Architecture, and is within easy walking distance of the Dept. of Computer Science and Engineering.

The catoptric surface that is being installed at the south end of the atrium will be complete by the start date of the proposed research project. We will use it for a number of purposes:

1. Development and calibration of quantitative daylight delivery models. We will evaluate the effectiveness of our current ray-tracing software system in assessing the impact of different configurations of the surface (i.e., various mirror positions). Empirical evaluation will use a number of light meters distributed within the space. The data collected will be compared to our predictions as well as the analytical models of both Bueno et al. [5] and Galatioto and Beccali [17].

2. Practical aspects. We will learn several practical things from this installation, including the positioning precision achievable with our current physical design, the viability of operating the mirror positioning motors open loop (the pan-tilt is stepper motor driven and the current system does not incorporate shaft encoders or other positioning feedback), the benefits (if any) of controlling acceleration in addition to position, the

timing requirements for configuration changes, the ability to effect multiple mirror movements in parallel, etc.

3. Investigation of the ability to provide positioning feedback via image analysis. We will install a camera with the full surface in its field of view and assess the viability of using image analysis techniques to discern the orientation of each mirror. An important component of this will be the degree of precision that is achievable.

4. Quantification of the viable heat transfer. We will perform a controlled experiment in which we will focus varying amounts of sunlight on a vessel of water to determine the temperature rise that is achievable. This will enable us to calibrate heat transfer models that will go into the MDP formulation.

5. Reliability testing of the components. This installation is not permanent. When it is decommissioned, we will setup a representative collection of the mirror components in our laboratory for stress testing (to failure). This will allow us to calibrate our reliability models for inclusion in the MDPs.

4.2. VelociData, Inc., 39 North Innovation District

VelociData, Inc., is located at 10425 Old Olive Street Rd., St. Louis, MO. They are in the *39 North* innovation district, which has the Danforth Plant Science Center, Monsanto, Bio Research & Development Growth Park, and Heliz Center Biotech Incubator as anchors. It is a 10 min. drive from the Washington University Danforth Campus, and they have given us permission to install a prototype at their facility (see letter of collaboration).

There are a pair of potential installation sites at VelociData's location. An east-facing window provides light to an individual's office, and (the more interesting option) a pair of west-facing windows that provide light to a bullpen of cubicles occupied by design engineers.

As we will not be able to tie into the HVAC system at this location, our objectives will be focused on the daylighting benefits, including their impact on the occupants of the space[2].

We will use this installation for the following purposes:

1. Perform safety testing[3]. We will perform stress testing on the installed system, injecting errors so as to intentionally attempt to create unsafe conditions, all the while monitoring to ensure that safety is maintained.

2. Assess utility of non-southern facing windows. Since the windows at VelociData's location are on the top floor, and face either east or west, this gives us the opportunity to explore the viability of exploiting multiple-reflection designs (e.g., a fixed position mirror above the roofline that redirects sunlight to the active catoptric surface).

3. Evaluate human response. While we do not have the budget in this project to perform comprehensive productivity analyses, we will be in a position to query the building occupants about their experience with the daylight effects. E.g., do they see value in the controllability of the quantity of daylight?

4. Iterate the design. As these are prototype systems, we have no expectation that the initial versions will operate entirely as desired. We will redesign and rebuild as needed to make progress on the research questions we are investigating.

4.3. BECS Technology, Inc., St. Louis County

BECS Technology, Inc., is located at 10818 Midwest Industrial Dr., St. Louis, MO. They are a small manufacturer of electronic control systems for a number of markets (e.g., agriculture, aquatics, refrigeration). The unique benefit to this installation is that they have agreed to allow us to have access to the HVAC system in their building (see letter of collaboration).

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[2]All experimentation that includes human subjects will undergo review by the Washington University IRB prior to implementation.

[3]Note: we only operate the Steinberg surface under active human supervision, as the automated safe operation cannot yet be ensured.

The HVAC system at BECS is one in which the hydronic water loop also serves as the fire protection sprinkler system [25, 54]. Individual heat exchangers either deliver heat into the loop (e.g., from a boiler) or extract heat from the loop (e.g., to a cooling tower). An experimental loop that can be the focus point for light from a catoptric surface is readily incorporated into a system such as this. The integration is made even easier because BECS, as a manufacturer of aquatics equipment, uses a controller of its own design to manage the entire system.

We will use this installation for the following purposes:

1. Repeat assessments from initial installations. As each installation will have a unique configuration, we will exploit the latter two installations (at VelociData and BECS) to perform common experiments at each, comparing the results to increase the confidence in any conclusions that we draw based on empirical data. This will include all of the calibration efforts, as well as the comparison of empirical data to the theoretical models (both for daylight delivery and thermal heat transfer). This will also include any human evaluations that are undertaken at the VelociData site.

2. Integration into the HVAC system. We will implement a heating loop that is capable of delivering thermal energy into the building's main hydronic water loop. The temperature of the water in this loop will be logged, and the master HVAC controller (built by BECS) will enable us to determine the effectiveness of the heat transfer. We will also be able to quantify the amount of energy savings that results.

3. Assessment of manufacturability. As described in the Transfer to Practice Supplementary Document, BECS is planning to assist us in evaluating the commercial viability of the catoptric surface as a product. An important piece of this evaluation is the assessment (by design and manufacturing engineers at BECS) of the manufacturability of the system.

4. Iterate the design. Again, we do not expect the initial design to be all that it can be. As for the previous systems, we will redesign and rebuild as needed.

4.4. Software Development and Assessment

The current software for raytracing and physical modeling is within Rhinoceros 3D (Rhino3D), a free form surface modeling system that utilizes a non-uniform rational B-spline (NURBS) mathematical representation. The current optimization (not MDP-based) is coded using Grasshopper, a visual programming language plug-in. Grasshopper has been used in the past for lighting performance analysis [15, 56].

The existing positioning software is written in a combination of Python (executing on a Raspberry Pi) and C (executing on an Arduino Uno). The Rhino3D/Grasshopper output is communicated to Python via CSV files on the filesystem.

The existing MDP model software is written in C++ and is not integrated into the above software components at all.

Clearly, an important software development task in this research project will be to enable each of the above software elements to interact with one another, preferably in a relatively seamless manner.

When our research group develops software that is intended to support the research questions being investigated (as opposed to the software effort being the research question itself), we have a practice of adopting software engineering techniques that closely approximate those used in industrial settings. For example, we have regular code reviews, testing is performed by individuals who are distinct from the developers, the software design is presented to the group and its pros and cons discussed prior to implementation, etc.

The assessment of the software will primarily be embodied in the evaluation of the catoptric surfaces themselves. However, we will evaluate the performance of all of the software, ensuring that execution times are reasonable for off-line tasks and deadlines are met for real-time tasks.

5. PROJECT MANAGEMENT AND COLLABORATION PLAN

We first describe the leadership team, including their primary roles on the project. This is followed by a description of our approach to collaboration and a timeline for the research activities.

Roger D. Chamberlain, PI, is Professor of Computer Science and Engineering in the School of Engineering and Applied Science at Washington University in St. Louis. Prof. Chamberlain will have overall responsibility for managing the research project and will take the lead in development of Markov decision process models, performance evaluation, and electrical engineering design requirements.

Chandler Ahrens, Co-PI, is Assoc. Professor of Architecture in the Sam Fox School of Design & Visual Arts at Washington University in St. Louis. Prof. Ahrens will take the lead in the physical design aspects of the catoptric surfaces, including their shape, configuration, positioning, fabrication, and installation.

Chris D. Gill, Co-PI, is Professor of Computer Science and Engineering in the School of Engineering and Applied Science at Washington University in St. Louis. Prof. Gill will lead the software development efforts, with an emphasis on designing for reuse whenever reasonable. He will also lead our approach to reusable abstractions that can be generalized to other cyber-physical system uses.

All three faculty have worked together in the past, so the organization of the present collaboration will be straightforward. Co-authored publications with two more of the faculty include [10, 36, 37]. Ahrens and Chamberlain collaborated on the design and implementation of the catoptric surface being installed in Steinberg Hall, and Chamberlain and Gill have previously co-advised a doctoral student (J. Meier, currently at Lockheed Martin) who exploited Markov decision processes for RF spectrum management.

We will exploit the fact that the entire team is located on the Danforth Campus of Washington University in St. Louis to organize our collaboration around face-to-face meetings. Our weekly meetings will form the backbone of the collaboration, where we check in each other to update status, plan next steps, and address any issues that have arisen since our previous meeting. We will also gather for the purpose of reviewing the literature (traditional journal club activities), student presentations (frequently practice talks for upcoming conference presentations), and reports to the group from anyone who has recently returned from a conference trip.

Our initial plan for the project timeline is listed below, indicating the primary activities to be pursued in each year of the project.

Year 1

- Perform quantitative measurements on Steinberg catoptric surface.
- Design initial MDPs, incorporating daylighting and heat harvesting.
- Develop initial abstractions for low-level controller software.
- Evaluate imaging approach for positioning feedback.
- Perform initial design work for VelociData installation.
- Submit human subjects evaluation plan to IRB for approval.

Year 2

- Decommission Steinberg surface and re-purpose components for reliability testing.
- Expand MDPs to include additional constraints (i.e., to ensure safety).
- Develop initial abstractions for MDP-based optimization software.
- Install VelociData catoptric surface and perform empirical evaluation.

- Perform quality of experience evaluation for VelociData users.

- Perform initial design work for BECS installation.

Year 3

- Expand MDPs to include additional goals (e.g., to prioritize reliability).

- Install BECS catoptric surface and perform empirical evaluation.

- Perform quality of experience evaluation for BECS users.

- Refine software abstractions for both low-level positioning control and high-level MDP-based optimization, based upon what has been learned from earlier editions.

- Release software under open source licensing terms.

6. BROADER IMPACTS

The research will impact on the built environment. According to the EPA, buildings are responsible for producing 6% of greenhouse gasses and heat and electrical generation produces another 25%[4]. A large portion of the electrical consumption in buildings is used for heating, cooling and artificial lighting. Our proposal addresses the reduction of electricity for artificial lighting to be replaced by reflected daylight and capturing the solar heat. During daytime hours, daylight is a preferred source of light for many people and the proposal directs the daylight deeper into a building. The daylight reflection system provides a more sustainable approach by reducing the required electricity and provides a more desirable quality of light.

At the undergraduate education level, this work is closely related to our second-semester introductory course in computer science and computer engineering. The text (co-authored by PI R. Chamberlain) is entitled *Computing in the Physical World* [11], and the course provides an introduction to cyber-physical systems concepts in a laboratory-based setting.

The computational platform used in the course (an Arduino Uno) is the same one used to control the Steinberg prototype catoptric surface, and it has a very large hobbyist following (in the maker community). We regularly request support for Research Experience for Undergraduate (REU) students, and individuals who have completed the above course will be well prepared to contribute to the research.

At the graduate education level, this work will support 4 graduate students at Washington Univ. in St. Louis. These students will be some combination of engineering students and architecture students, with each community of students learning from the other to broaden their individual horizons of experience to include multidisciplinary work.

The Steinberg prototype was substantially designed by a student pursuing dual degrees in architecture (MArch) and engineering (MEng) [38]. He recently was asked to present to the Washington University Board of Trustees about his experience, and the university is considering offering educational offerings that are tailored to students with similar, cross-disciplinary interests.

We will leverage a pair of existing university programs to help us attract students from traditionally underrepresented groups. The Olin Fellowship Program (for women) and the Chancellor's Fellowship Program (aimed at underrepresented minority students) have had a successful track record of enabling individuals to pursue graduate study. In our experience, the most effective method for attracting students from underrepresented groups is by personal contact with a suitable role model. To facilitate this, we regularly ask the appropriately qualified individuals in our group to be actively involved in the recruiting process. This cohort currently includes two minority graduate

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[4]https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data

students (one African-American student and one Hispanic student). We will attempt to leverage the maker space community as one target for broadening participation from traditionally underrepresented groups.

7. RESULTS FROM PRIOR NSF SUPPORT

CSR: Small: Concurrent Accelerated Data Integration (CNS-1527510, PI R. Chamberlain, co-PI Ron Cytron), 10/2015–9/2019, $519,275.

Intellectual Merit – This project investigates the accelerated execution of data integration workflows, which increasingly are bottlenecks in data science. Execution platforms being targeted include both graphics engines and FPGAs.

Broader Impacts – This research project has supported 3 graduate students and 4 REU students. The applications investigated come from the fields of computational biology, astrophysics, and the Internet of Things, further expanding the scope of the students' experience.

Evidence of Research Products and their Availability – Publications resulting from this work include [8, 9, 36, 45]. A benchmark suite of the above workflows has been released as a community resource [7].

CPS: Medium: Collaborative: CyberMech, a Novel Run-Time Substrate for Cyber-Mechanical Systems (CNS-1136073 and CNS-1136075, Washington University: PI C. Gill, co-PIs Kunal Agrawal and Chenyang Lu; Purdue University: PI Arun Prakash, co-PI Shirley Dyke), 9/2011-8/2016, $1,800,000 total.

This research project developed novel foundations for parallel real-time computing, and used them to demonstrate the first ever real-time hybrid simulation involving a thousand-degree-of-freedom structure.

Intellectual Merit – Results of this research include new methods for parallel real-time execution of control and simulation computations, new parallel real-time scheduling techniques and analyses, and characterization and exploitation of trade-offs involving both high computational demand and stringent timing constraints.

Broader Impacts – This multi-university project involved 7 PhD, 3 masters, and 7 undergraduate students, and 2 visiting scholars in highly multi-disciplinary research collaborations. Results of this research appeared in 10 publications at top-tier conferences and journals.

Evidence of Research Products and their Availability – Data, experiment configurations, platform software, and simulation source-code have been published on-line at Washington University and Purdue University.

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