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

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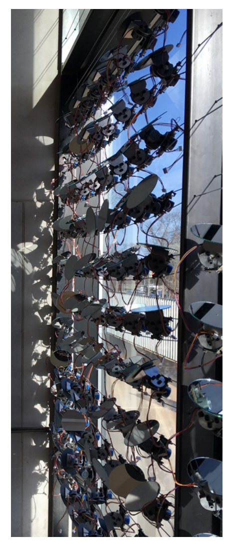
1. INTRODUCTION

The energy consumption due to buildings (both residential and commercial) is estimated to be 20% to 40% of the total energy usage in developed countries [37], and lighting and heating are two significant components of this energy consumption [26]. Natural light (i.e., sunlight) is a readily available resource that can contribute to both the illumination [29] and heating [31] 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 [45] rather than active control mechanisms (see [25] for the few counterexamples). Heating systems that use sunlight do frequently use actively-controlled mirrors for tracking the relative position of the sun.

We propose to investigate the ability to effectively utilize actively controlled catoptric (mirror) surfaces to benefit the illumination and heating of buildings. Computer-based control of the dynamic positioning of individual mirrors, and computer-based management of the sunlight (as a resource), clearly put a system such as this within the scope of traditional cyber-physical systems.

Figure 1a is an image of a prototype catoptric surface (called AMP) that was designed, fabricated, and installed through 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 this installation, the mirror positions are fixed.

(a)



(b)

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

In the next generation of this system, which is currently under construction, over 600 mirrors are under active, 2-axis, microprocessor-based control and therefore can be pointed in different directions dynamically as desired over time. This installation is on the south wall of the Steinberg Hall atrium (on the campus of Washington University in St. Louis), and a subset of the mirrors are shown in Figure 1b.

The ability to actively control the dynamic position of each mirror provides for unprecidented capacity to position the available natural light where it is desired. This can easily change over time, as the usage of the physical space changes.

The proposed research advances the investigation of reflected light by designing specific intensities in some areas and dissipated lighting conditions in other areas according to pre-determined, yet adjustable, image-based maps. The maps can consist of any raster image and generate the target positions for the reflected light in a space. The image is sampled according to intensity (black to white) to determine the density of target points where the higher the value, the denser the resulting field of points. Using an image-based map allows users to visualize zones of intensity in an interior space prior to the mirrors reflecting the daylight. Any user is capable of supplying or creating the image to be used for the map, thus encouraging user control and interaction with the system. The engagement of any member of a community on the creation of that image has an impact on the entire community [40] and encourages dialog about the quality and quantity of light within their environment.

Given the desire to control natural light (sunlight) via a catoptric surface, repurposing it for illumination and/or thermal management, a number of cruicial cyber-physical system issues must be addressed. This research will investigate the following questions:

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

   Issues within this question include the ability to articulate the benefits and to quantify them effectively. Clearly, we are in the domain of multi-objective control, so the relationship between the competing goals must also 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 an ideal multi-objective control system in place, the system as a whole has limited usefulness if these additional requirements are not dealt with in an effective way. Initially, just consider the issue of safety: highly concentrated sunlight aimed at a heat collector (important when harvesting energy for thermal management purposes) can be quite harmful if inadvertently aimed at humans.

   Each of these system-level requirements must ultimately be included within the optimization 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 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?***

   A pair of immediate possibilities come to mind. Separating the concerns of low-level control (e.g., of mirror positions) and high-level system management (how the available light resource should be allocated) is one option. The low-level control subsystem can be encapsulated into a reusable component, applicable to any number of physical positioning applications. Similarly, a high-level management system (e.g., based upon MDP theory) could also be encapsulated in a resuable component, applicable to any number of other stochastic optimization problems. Ultimately, we would like to generalize the above into abstractions that can be leveraged more broadly for arbitrary cyber-physical systems development.

FIXME: Brief description of who we are and what we've done.

2. BACKGROUND AND RELATED WORK

The current research proposal was preceded by two 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 the 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). The secondary goal was to develop a 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). The main limitation of the project was that each reflective sub-surface was a fixed geometry.

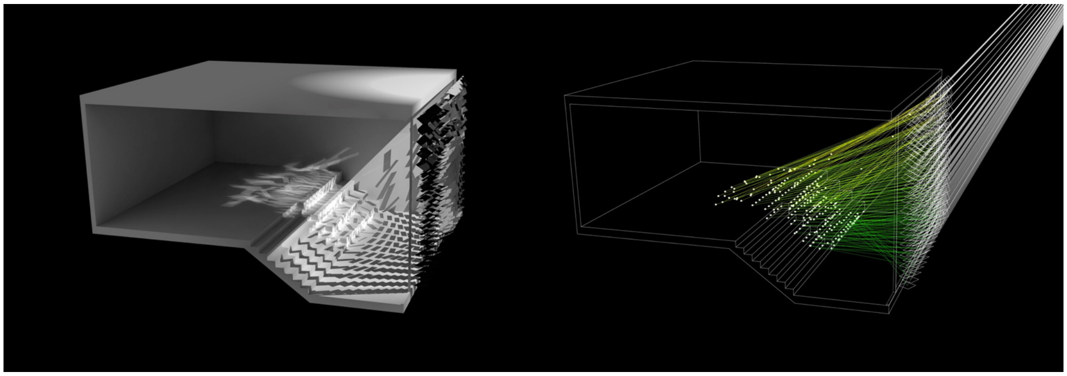


Figure 2: Ray tracing analysis of daylighting design.

The second project, title Catoptric Surface: Steinberg prototype, addressed the limitation of fixed geometry in AMP. The goal of the prototype was to create a series of mirrors that were independently adjustable according to solar position throughout the day and desired location within the building 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. The increased level of control was enabled through the development of 2 axes of rotation of each mirror independently under software control. The prototype provides the 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 is a photograph of a small number of the installed mirrors.

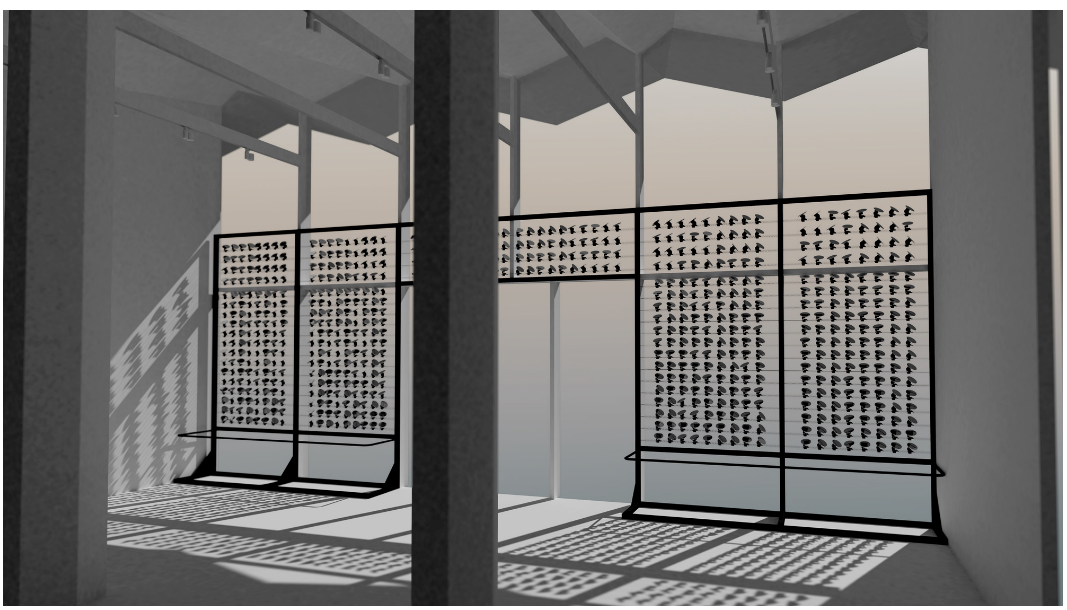


Figure 3: CAD drawing of the Steinberg Hall prototype catoptric surface.

Leslie [29] and Alrubaih et al. [3] provide a pair of review articles that effectively summarize the current approaches to daylighting in modern building design. For the most part, these are passive systems, or might include active control of shades [25], with a strong emphasis on achieving uniform, homogeneous illumination [5, 14]. Our emphasis is on dynamic control of the light position, with the explicit intent to be inhomogeneous in the illumination patterns.

There have been a number of efforts to quantitatively model and empirically measure prototype daylighting systems [5, 13, 28, 45]. A pair of studies, first by Lee and Selkowitz [28] and followed by Fernandes et al.[13], initially evaluated the potential for energy savings in the New York Times Headquarters building and then measured the actual realized savings.

In this work, we will exploit Markov Decision Process (MDP) formal theory [39] an an approach to optimization of the catoptric surface control. MDPs represent a general approach to modeling optimization problems and have been applied in a diverse set of application areas [48]. Examples include robotics [1], economics [4], experiment design [24], medical decisions [2], manufacturing [50], agriculture [27], and our own group's use in scheduling [18, 44] and wireless spectrum management [32].

Our prior research has used Markov decision process models [18] to generate resource management policies off-line [15] for non-preemptive sharing of a resource between 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 reception 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 [18], or even a more general definition of the utility of completing the different tasks at particular times [44]. 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 [16].

However, policy iteration is exponentially expensive, 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 [17]. For utility-based resource sharing multiple disjoint heuristics were needed but the most effective one to use was clearly defined by problem parameters [43].

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 a much different resource: the transmission spectrum in wireless networks [33]. 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 obtained efficient and effective heuristic policies for on-line use [32].

In this proposal we adopt the definition used by Glaubius et al. [18] 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 exploit the formal theory of MDPs as an approach to optimization of the configuration of catoptric surfaces.

3. RESEARCH DESCRIPTION

We will describe the research in terms of our approach to addressing each of the specific questions posed in the introduction.

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 in the literature [19, 29, 30, 38], and yet thermal effects also may be significant [6] (i.e., 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, 14], 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 that 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 while someone reading from physical media like a book may require higher light levels. Similarly, light levels required for vision may vary with the age 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 (see, e.g., [11, 20, 23, 31, 42, 46], and we will simply leverage such well-understood techniques. As many sunlight-based heating systems already use catoptric mechanisms (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 heating and for illumination.

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 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 [15, 18] can be approximated efficiently on-line with high accuracy [17]. Scenarios that are relevant to this research, such as using multiple catoptric arrays to provide even and consistent lighting of a collaborative work area, have similarly regular structure that an MDP-based approach can exploit. Our prior work also shows that custom policies can be generated [43, 44] 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. 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 intially 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, to a more complete cyber-physical model in which positioning commands include specific ***trajectories*** for each pan-tilt unit including its initial and final position, and the accelerations, velocities, and positions it should adhere to in its trajectory along that path - this 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.

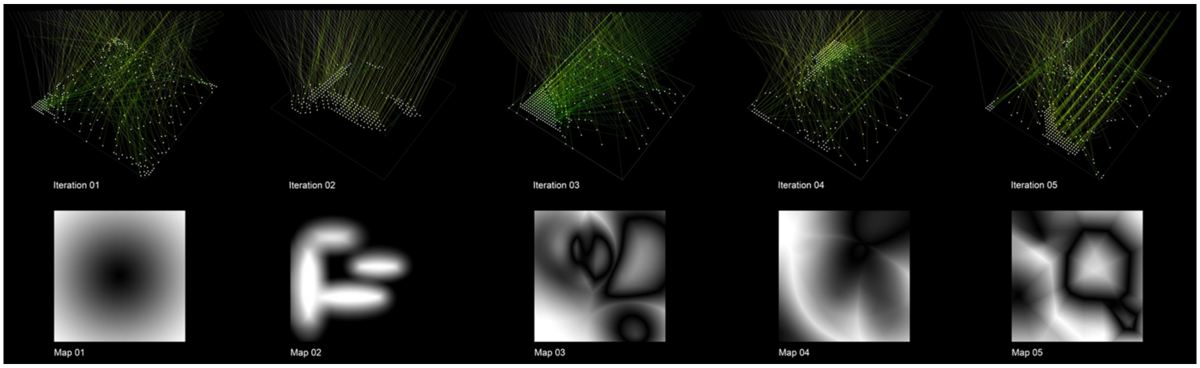


Figure 4: Example image maps and associated mirror positioning.

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 [12, 35, 49]). 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 [43, 44].

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 [44] 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 goes into heating.

In each of the above MDPs under investigation, we will utilize the value-optimal solution (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 explore the space of value-optimal solutions and seek to formulate an inexpensive to compute 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 position is only useful over time 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 the low-level controller versus being dealt with within the high-level complete system 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, the above levels of light concentration are not only undesirable, they are patently unsafe.

These context sensitive constraints add two additional requirements. First, the higher-level management system must be responsible for them. In our MDP formulation, we much adjust the feasible state space, $\mathcal{X}$, so that they are unreachable (or have sufficiently negative reward as to preclude the policy violating them [43, 44]). 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 might 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 both options.

Goals. Many of the additional considerations are more appropriately addressed as additional (potentially competing) goals, adding to the desires of 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, the sooner it will fail).

This is precisely the set of circumstances in which Markov decision processes excel. For the initial goals (of question 1), is is quite likely that there are multiple optimal solutions (e.g., simply exchange to pointing of two mirrors and the goals are unchanged). However, once we add in considerations of reliability, which is impacted by frequency of use, we now have a much richer search space, and a natural fit for probabilitic reward. The MDP-based optimization approach is particularly will suited for this type of problem, and can find optimal solutions that incorporate minimal movement of mirrors between configurations, thereby diminishing the maintainence costs 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 [36]).

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 systems don't adhere strictly to standards such as the OSI [51] networking model or the POSIX [21] operating systems interface model, system designers, developers, and users still benefit from the 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 which other aspects

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

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 mirror control and MDP control.

FIXME: Talk about direct mirror control.

We will extend our current prototype for mirror control to include concurrent positioning of multiple mirrors at once – although positioning a mirror takes only seconds currently, the latency to adjust an entire row of mirrors in an array is noticable, and may introduce undesirable lighting artifacts at least temporarily as mirrors are adjusted.

We also will investigate more general use of light in our approach, by adding lenses as well as mirrors, adding color (e.g., by covering some mirrors with colored film), and other effects. FIXME: Chandler and Roger, please elaborate on this.

FIXME: Talk about MDP control.

The MDP models 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.

3.4. Intellectual Merit

The intellectual contributions of this project are FIXME: describe summary of intended intellectual merit.

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 an 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 [14].
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 imporant 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 Stree 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 stess 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).

The HVAC system at BECS is one in which the hydronic water loop also serves as the fire protection sprinkler system [22, 47]. Individual heat exchangers either deliver heat into the loop (e.g., from a boiler) or extract heat

[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.

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

FIXME: What should go here?

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, 32, 33]. Ahrens and Chamberlain collaborated on the design and implementation of the catroptic 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

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

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*, 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 hobbiest following (in the maker community).

We regularly request support for REUs, and students 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) [34]. 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 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, 32, 41]. 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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