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 [24], and lighting and heating are two significant components of this energy consumption [18]. Natural light (i.e., sunlight) is a readily available resource that can contribute to both the illumination and heating 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 [31] rather than active control mechanisms (see [17] for the few counterexamples).

FIXME: What are we doing?

Figure 1a is an image of a prototype catoptric (mirror) surface (called AMP) that was designed, fabricated, and installed through an undergraduate architecture studio taught by 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: Catroptic system prototypes. (a) *AMP*, TRex building, St. Louis, MO. (b) FIXME: name?, Steinberg Hall, St. Louis, MO.

In the next generation of this system, which is currently under construction, the mirrors are under active, 2-axis, microprocessor-based control and therefore can be pointed in different directions dynamically as desired over time.

FIXME: Where (if at all) should we define Open-Source Architecture (OSArc) as distinct from open-source software? How do the notions of OSArc integrate with what we are doing? (This is a Chandler question.) Is [27] a good citation (I just found it on wikipedia)? How about one or more things that Chandler has written?

FIXME: Articulate specific research questions below.

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 clearly 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.

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

3. *Can we design abstractions that encapsulate sub-systems for effective reuse?* 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

FIXME: Describe first two installations.

FIXME: Literature review [3, 5, 11, 17, 20].

FIXME: Describe MDP-based optimization and our history with it.

Markov Decision Processes (MDPs) [26] represent a general approach to modeling optimization problems and have been applied in a diverse set of application areas [32]. Examples include robotics [1], economics [4], experiment design [16], medical decisions [2], manufacturing [33], agriculture [19], and our own group's use in scheduling [15, 30] and wireless spectrum management [22].

In this proposal we adopt the definition used by Glaubius et al. [15] 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.

3. RESEARCH DESCRIPTION

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

There is ample literature that documents the benefits of natural light in human-occupied spaces [20, 21, 25], yet the thermal effects can also be significant [6] (i.e., too much sunlight can increase temperature to an unacceptable degree).

FIXME: We will explore the use of MDPs for multi-objective control of catoptric systems.

FIXME: Describe our three previous uses of MDPs, and how the value-optimal solution can be estimated heuristically in each case. Chris, can you take a first crack at this?

Our prior research has used Markov Decision Process models [15] to generate resource management policies off-line [12] 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 [15], or even a more general definition of the utility of completing the different tasks at particular times [30]. 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 [13].

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 [14]. For utility-based resource sharing multiple disjoint heuristics were needed but the most effective one to use was clearly defined by problem parameters [29].

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 [23]. 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 [22].

FIXME: Describe our approach to applying MDPs to catroptic system control. This includes quantification of benefits, formulation of a combined objective, identifying the control degrees of freedom, encapsulating all of the above in an MDP framework, exploring the MDP state space, seeking to find a heuristic that approximates the value-optimal solution.

3.2. Question 2

FIXME: The interesting thing here is how properties like safety are dependent on context, e.g., we want concentrated natural light when harvesting energy but not when illuminating a human-occupied space.

3.3. Question 3

FIXME: We will investigate the viability and utility of two candidate abstractions: direct mirror control and MDP control.

3.4. Intellectual Merit

The intellectual contributions of this project are FIXME: describe summary of intended intellectual merit [10].

4. EVALUATION/EXPERIMENTATION PLAN

FIXME: Two sites identified:

1. **BECS Technology, Inc.**, 10818 Midwest Industrial Dr., St. Louis, MO. FIXME: BECS Technology is a small manufacturer of electronic control systems in a number of markets (e.g., agriculture, aquatics, refrigeration). We will have access to the HVAC system in their building.

2. **VelociData, Inc.**, 10425 Old Olive Stree Rd., St. Louis, MO. FIXME: VelociData is located in the recently announced *39 North* innovation district, which has the Danforth Plant Science Center, Monsanto, Bio Research & Development Growth Park, and Heliz Center Biotech Incubator as anchors.

5. PROJECT MANAGEMENT AND COLLABORATION PLAN

6. BROADER IMPACTS

FIXME: Describe broader impacts: environmental benefits of energy savings and quality of life benefits to building occupants.

At the undergraduate education level, this work is closely related to FIXME: describe CSE 132 connection.

At the graduate education level, this work will support 4 graduate students at Washington Univ. in St. Louis. FIXME: Expand, including REUs, multidisciplinary angle.

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). FIXME: Can we strengthen the BPC story? Maybe somehow with 132 and maker spaces?

7. RESULTS FROM PRIOR NSF SUPPORT

CSR: Small: Concurrent Accelerated Data Integration (**CNS-1527510, PI: R. Chamberlain**), 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. Publications resulting from this work include [8, 9, 22, 28].

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. A benchmark suite of these workflows has been released as a community resource [7].

TBD - CyberMechProject (**CNS-, PI: C. Gill**), dates and dollars TBD.

Intellectual Merit – TBD

Broader Impacts – TBD

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