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NATURAL HARMONY:

Designing with Thermal Actuators

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ABSTRACT

Building in harmony with nature allows for the comfort and well-being of inhabitants of a home, building, neighborhood, or even a district. In this research, we studied the ways in which harmony is achieved in nature, and the ways in which it is achieved in existing building science. We propose a novel bridge between active and passive mechanical systems, a "semi-passive approach", which requires no external regulation or monitoring, and responds to changing environment conditions. This type of system trades the intelligence and adaptability of traditional mechanical systems for resilience, autonomy, economy, and simplicity. In contrast to simply passive systems, the "semi-passive" approach offers some level of flexibility to changing conditions. To study this concept, we designed a novel intervention that uses thermal actuators that respond to changes in environmental conditions to extend and retract a piston, and collected data regarding its performance in the Vancouver studio of Perkins+Will. The apparatus acts to allow control of ventilation, daylight, and heat gain. While our particular climactic zone may not find year-round applications for such an approach, there are applications for the holistic toolkit of Climate Adaptive Building Skins (CABS).

KEYWORDS: biomimicry, envelope, energy, comfort, passive systems

1.0 INTRODUCTION

An important role that architecture fulfills is to find solutions to accommodate basic human needs while creating deeper meaning and delight. Solutions that work seamlessly with the environment have an elegance that is effortless. Natural systems have this elegance – a sunflower tracks the path of the sun across the sky, animals regulate their temperature through evapotranspiration, exploiting phase change of water to conduct heat energy. In pursuit of this type of elegance, we ask how we can address fundamental needs that we need to recognize as architects, while finding a natural harmony with the basic characteristics that we face. Such solutions require minimal inputs, do not consume energy made through complex means, and are enduring. Primitive buildings, prior to the development of elaborate mechanical systems, attempted to work within these constraints. As buildings became more elaborate, and as technologies developed to enable greater control over comfort, distance emerged between natural harmonious approaches, and the mechanically enabled substitutes.

Our study focused on facade-integrated thermal actuators, aiming to explore how semi-passive technologies can be used to regulate and respond to environmental conditions with minimal energy usage and controls. We designed and constructed a prototype with thermal-actuating pistons, using laser cutting, 3D printing and metalworking. The prototype was evaluated using sensors. The next sections provide background, as well as detailed description of the research methods, collected data and results.

2.0 HOMEOSTATIC MECHANISMS

Animal physiology throughout the phylogenetic tree is filled with mechanisms that exist to keep order within anatomical systems.

One of the most well-known examples of homeostasis is warm-blooded animals' ability to thermoregulate their body temperature. Figure 1 shows an example of this process, particularly focusing on humans. The outcome is not solely based on a physical sensation, as a psychological response is triggered as well. That is, the individual that is in an uncomfortable temperature will try to seek shade or warmth, depending on the situation.

One key thing to note with regard to homeostasis in our own case is that it is usually maintained through the hypothalamus, which processes sensory signals and triggers an appropriate physiological response. This is not unlike the thermostat in a building, which responds by turning on the appropriate boiler or chiller based on a pre-set temperature. Thus, the system has intelligence added to it with an external regulator.

In the case of our study, we argue that removing the regulator adds a layer of resilience to a system by reducing the complexity of it. However, this is at the expense of intelligence, and requires great foresight.

The dwelling unit, building, neighbourhood, or the district can be looked at as units in which homeostasis in a variety of factors can be achieved and is desirable for the well-being of its occupants. If we use the cell membrane or skin as an analogous condition in the natural world, these building blocks of architecture present an opportunity to maintain their own homeostatic balance through this interface. To scale the down the scope of this article, we will look at the homeostatic conditions of buildings alone, and this leads us to Climate Adaptive Building Systems.

As Dewidar et al. explain, a building's envelope is “a complex membrane capable of energy, material and energy exchange”[1]. It is part of a building's metabolism, and contributes to the well-being of its occupants.

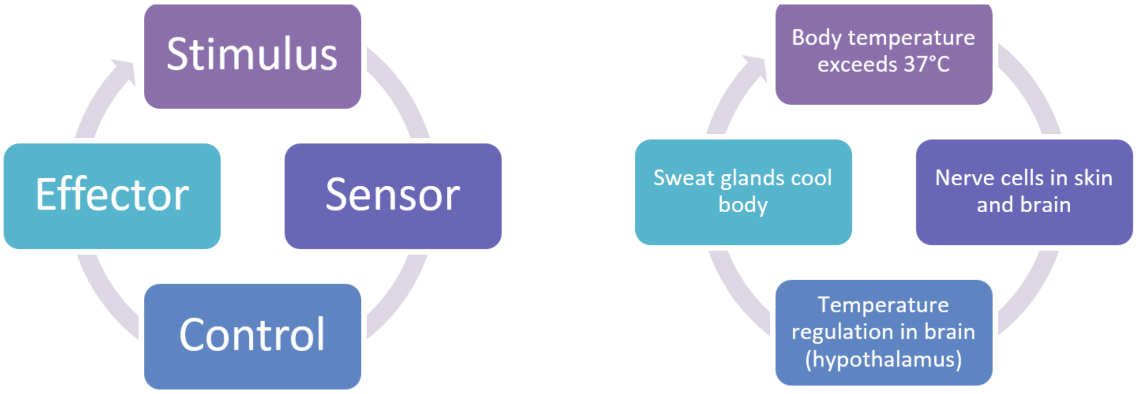


Figure 1: A general mechanism for homeostatic response on left. On the right, a basic model of thermoregulation processes in humans.

3.0 CLIMATE ADAPTIVE BUILDING SKINS (CABS)

Climate-Adaptive Building Skins (CABS) have the potential to reduce energy loss and gain, given the proper design response to climactic conditions and user requirements. There is no silver bullet to this process, and instead what designers need are tools to respond to unique requirements of the conditions that they face, including social, material, economic and environmental constraints. Biomimicry, as in many architectural problems, poses an opportunity to provide solutions for a given region[2].

Adaption of a building skin can respond to the following environmental considerations:

1. Heat transfer
2. Visual light transmission
3. Ventilation
4. Water retention/storage/evaporation
5. Electrical power generation.

A prime example of an active CABS is Jean Nouvel's Institut du Monde Arabe, which has a system of mechanical irises that respond to daylight by either opening or closing. A vast array of these identical units creates unique patterns as clouds pass across the sky, providing both visual interest and improved performance.

To criticize this precedent, the electromechanical action and complexity of the system has apparently resulted in numerous malfunctioning units on the facade[3]. Due to its complexity, a system such as this has not only high start-up costs, but also maintenance costs. From a life cycle assessment perspective, this causes issues that conflict with the sustainable and economic benefits of having an adaptable building skin. The ideas required to achieve a CABS are thus not ones necessarily out of complexity, the ingenuity almost comes from the simplicity of the approach.

Perhaps the best example of a CABS is a manual blind, which can control heat gain and visual glare through human intervention. The effect is the same as that of the aforementioned precedents, but the intelligence is lost (though at an exchange of greater control and manual overrides). In contrast, the passive fixed screens which are increasingly-popular offer a "one-size fits all" solution, which sacrifices intelligence and operability in exchange for robustness, simplicity, and consistency in environmental control.

Actuation of a facade to environment conditions does not need to be expensive, nor complicated[4]. Simplifying the process of actuation has the potential for less maintenance requirements, less opportunity for error, and removing the need for external regulation of the system. This is striking the right balance between "robustness" and "flexibility", a realm of research in which there is still much work to be done[5].

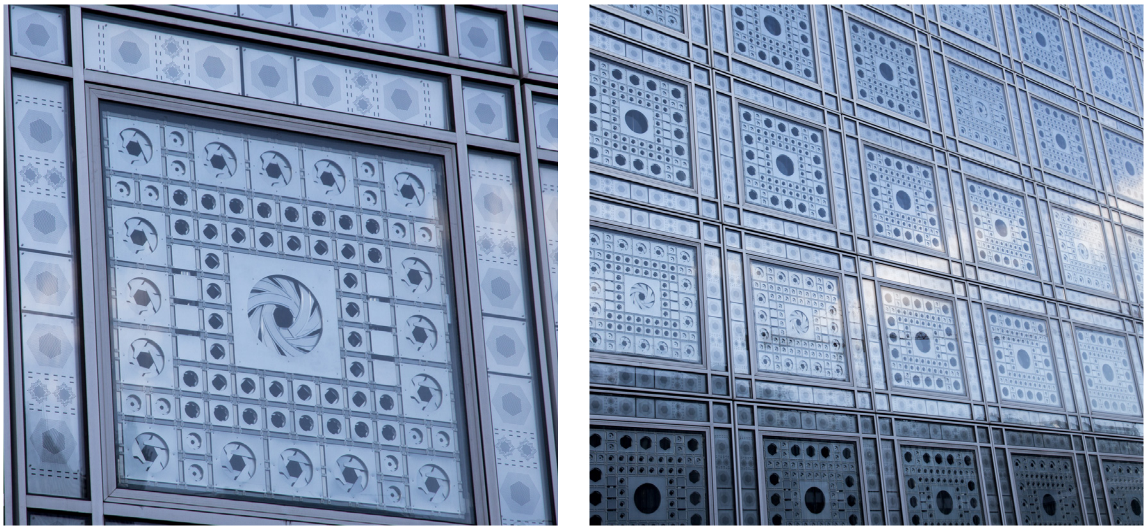


Figure 2: Jean Nouvel's Institut du Monde Arabe's mechanical iris system. Through an array of similar systems, a dynamic change happens as environmental conditions change.

4.0 THERMAL ACTUATORS

A thermal actuator is a device that translates temperature-related changes in matter into movement. Typically, there are two types of thermal actuators: gas-based and wax-based. In each case a medium (either the gas or wax) is contained in a housing, coupled with a single outlet where the expansion or contraction may be relieved. Heat gain causes the medium to expand, which is then translated into the linear motion of a piston. This elegant and simple mechanism is utilized in an array of applications related to thermal control, such as automotive thermostats, mixing valves, and controlling vents on greenhouses. Moreover, where reliability is prized such as in aerospace, thermal actuators are used to control valves associated with fuel and hydraulic systems, or in common machines like automatic dishwashers to operate detergent dispensers. Wax-based thermal actuators are also commonly known as wax motors, but are effectively a motor and thermostat in one.

A benefit of gas-based thermal actuators are often capable of being adjusted or "tuned" to a specific temperature range by mechanically increasing or decreasing the volume of the housing. Wax-based thermal actuators are not generally adjustable in the same way, instead, the chemical characteristics of the wax itself can be customized to transition at set temperature thresholds.

Depending on the application, thermal actuators may be activated by the thermal conditions of the atmosphere, of a medium the actuator may be in contact with, or through the introduction or removal of heat via electrical resistance. In the simplest application, relying on atmospheric conditions alone to initiate activity may allow a system to be resilient, autonomous, and reliable – but at the expense of intelligence and adaptability. To minimize inputs in the applications envisaged in this study, the only input we foresee is atmospheric heat imposed by the sun. In the purest form, the system uses the actuators in a "semi-passive approach", where parts still move in response to environmental conditions, but without the need for external regulation. Figure 3 shows an example of a thermal actuator used in this study, while Figure 4 shows the basic operating principle in a window application.

Figure 3: A thermal actuator, used in this study. The body on the left contains wax or oil that expands when exposed to heat. The piston on the right creates a "stroke", pushing out due to this expansion.

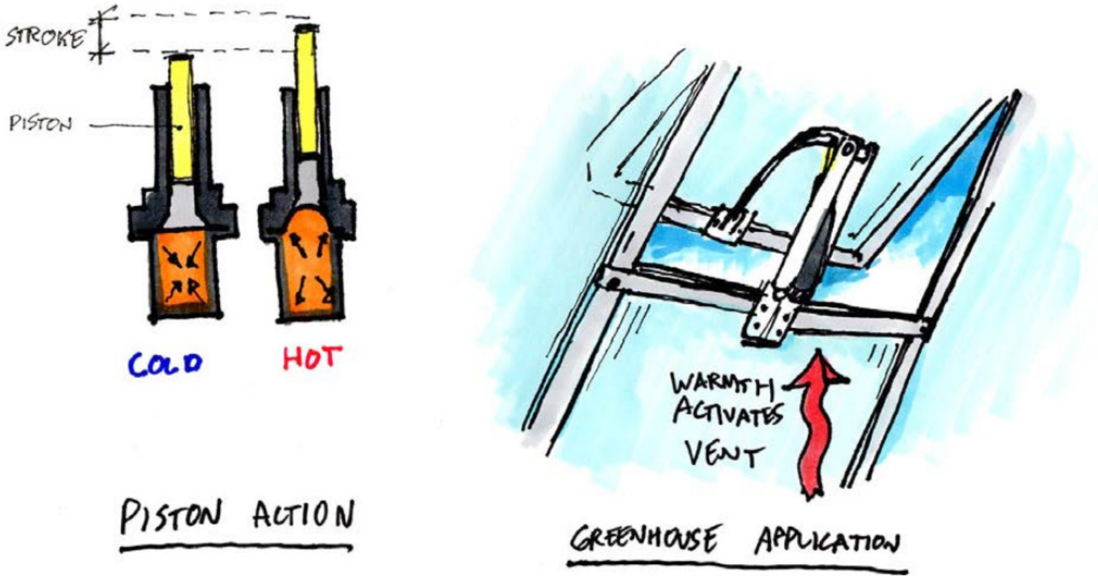


Figure 4: Action of thermal actuators in response to heat load. A typical greenhouse application is depicted on right, where the load of the window causes the actuator to retract as it cools.

In order to rely on the simplicity which this approach implies, the desired action must have a simple correlation with temperature increase or decrease. The characteristics of the actuator must therefore be matched with the conditions targeted. The cylinders as tested in this project have an expected service life of at least 10 years[6].

5.0 ARCHITECTURAL OPPORTUNITIES

Passive architectural features have advantages over complex electromechanical systems. Less usage of energy, ease of use, and fewer moving parts (which results in a more resilient system) characterize passive responses. While overhangs, thermal separation, and improved glazing performance are all indicative of passive features, motion in architecture is largely controlled by active electromechanical systems. "Semi-passive" thermomechanical systems thus provide an opportunity for improvements in reliability and energy usage, as well as responding in harmony to natural forces without the need for complex computation or motors[7]. Figure 5 shows potential options for application of thermal actuators.

Passive solar shading can be achieved by properly orienting the building in response to solar exposure, and by using exterior shading devices. The appropriate application of these methods depends on the climate, region, building site and type, social expectations and economic impacts. Figure 6 shows external shading for the NMAAHC building, located in Washington, DC. Figure 7 shows building envelope design for a transit station, where transparency of the shading screen corresponds to the orientation of the panels.

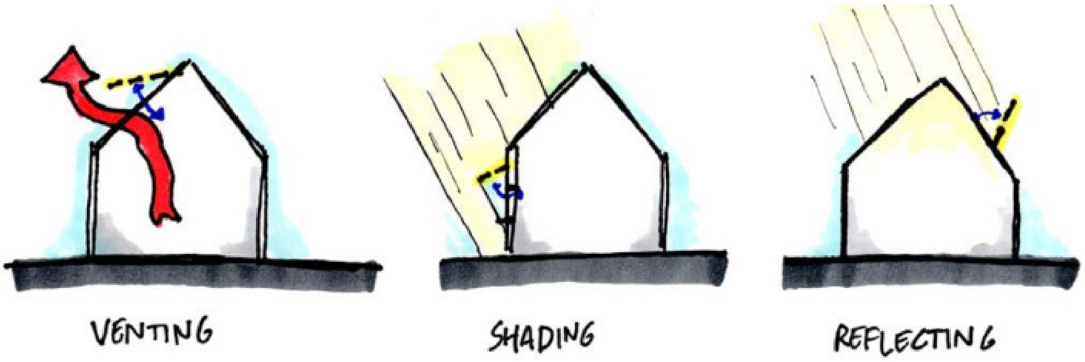


Figure 5: Potential options for applications of thermal actuators.

Figure 6: External shading through a screen defines the form of the NMAAHC. This application balances views and solar performance.

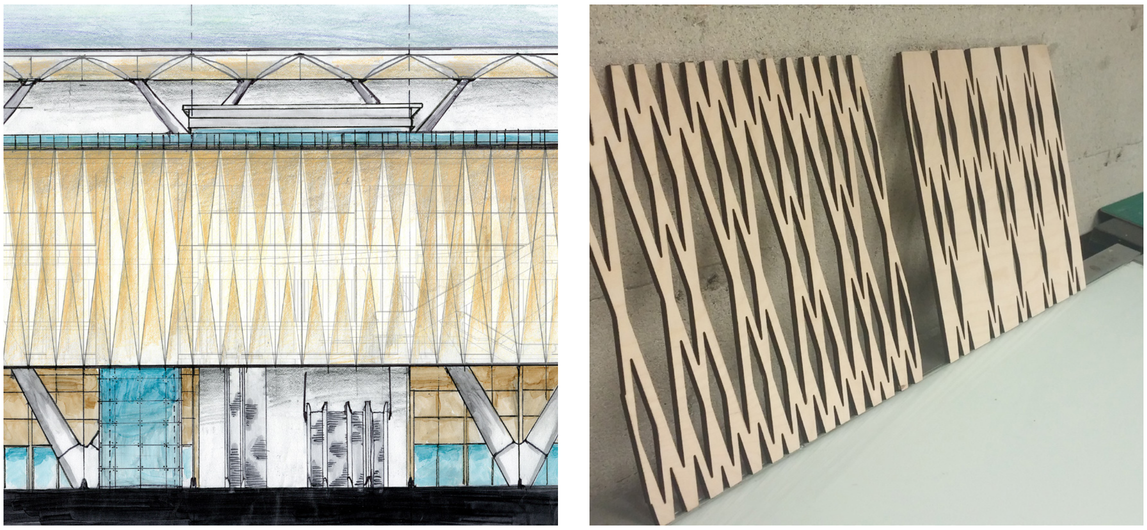


Figure 7: The screen on this transit station proposal floats above the plaza below. Depending on the solar orientation of the panels, the screen is modified in transparency (right). A semi-passive variant of this facade could adapt to changing conditions.

A previous study has focused on the architectural application of thermal actuators for facades at length, identifying several important caveats when deploying this technology to the built environment for climate control[8]. Most important is the difference between surface temperature of the actuator in direct sunlight, and ambient temperature. Actuators are often painted black to absorb heat from direct sunlight, but this impacts how they are "tuned" to their environment. To work around this constraint, miniature greenhouse enclosures were constructed for the actuators that stabilized solar gain. The second major innovation in that research was the use of a self-latching mechanism that holds the actuator. The result of the latch is an actuator that can remain open at a consistent extension for a longer period, versus responding to temperature fluctuations in a smooth gradient[8].

6.0 DATA

An assessment of potential interventions was completed using a portable temperature logger. By taking linear records of temperature over time, the location where actuators could be installed to affect internal comfort was inferred to be in a skylight frame over the main atrium of Perkins+Will's Vancouver office. This data also allowed us to customize our selection of actuators by tuning the threshold and speed at which they activated in response to heat gain. Figure 8 shows ambient temperature collected over time for two locations, while Figure 9 shows surface temperature for interior side of the roof. Figure 10 shows temperature range and response profile for the thermal actuator used in this research.

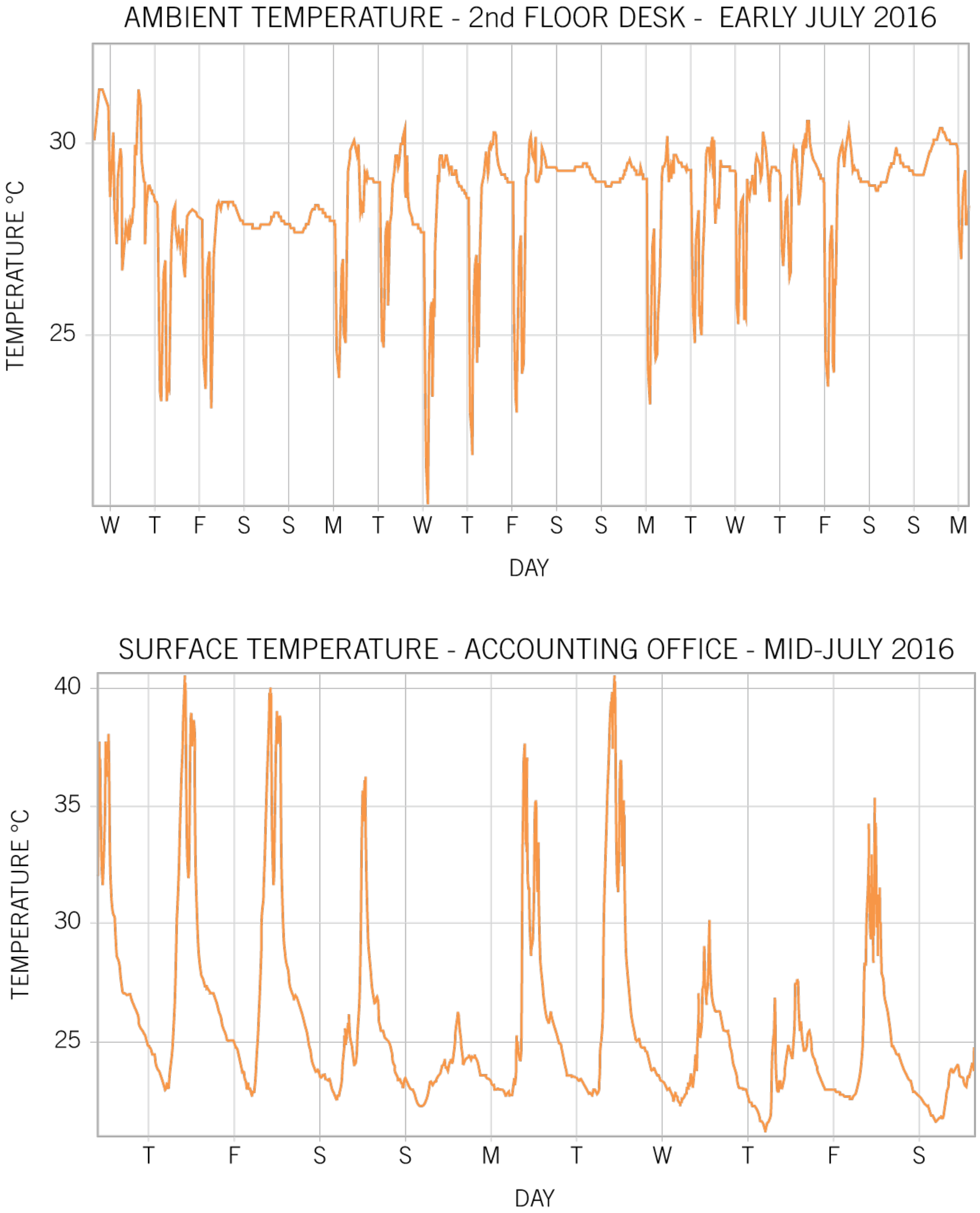


Figure 8: Collected temperature data over time from a desk and accounting office in the Vancouver studio of Perkins+Will. The troughs during the week are the building exhaust flushes, which influence only ambient temperature and not areas exposed to direct sunlight.

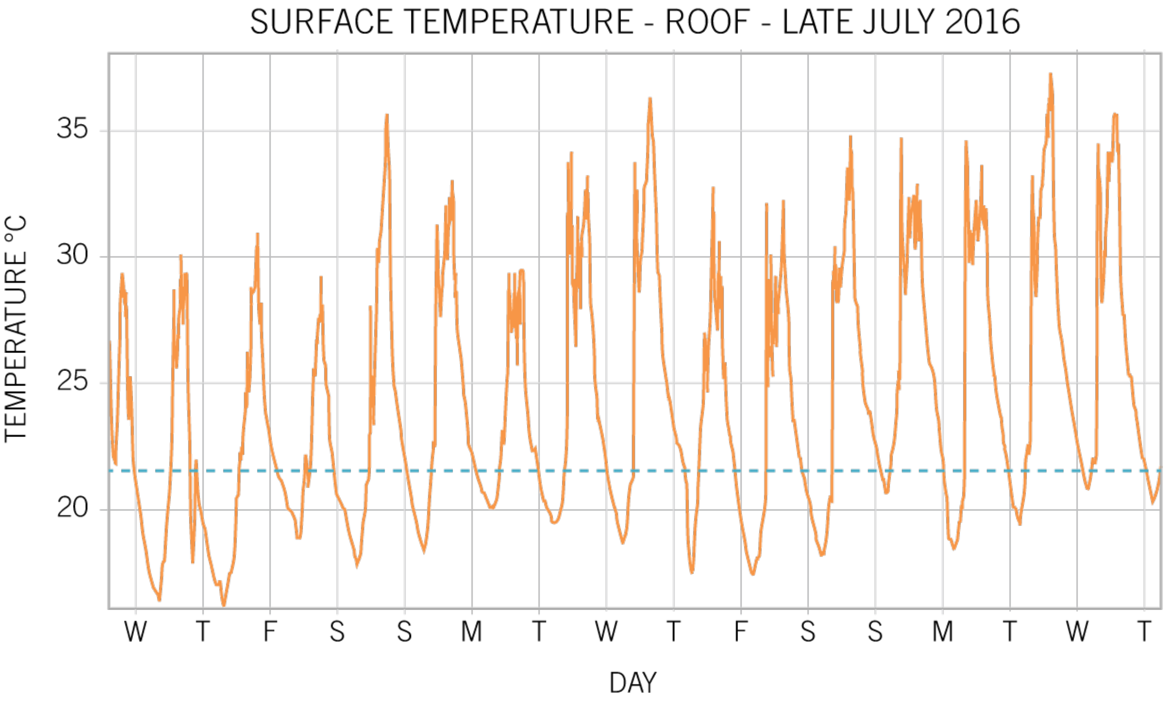


Figure 9: Surface temperature data from the roof of the Vancouver studio of Perkins+Will. The area above the line demonstrates where the actuator profiled below would be mostly closed.

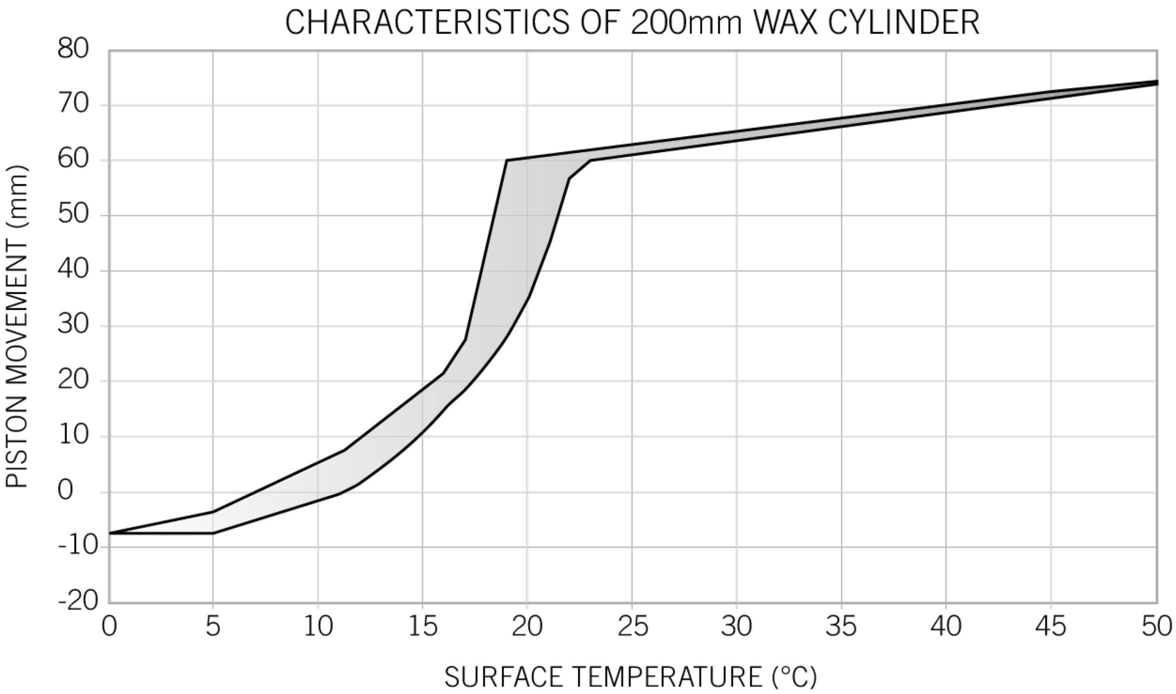


Figure 10: A sample response profile for a thermal actuator given in a temperature range. The response can vary, and is represented by an area (Adapted from E20D profile)[6].

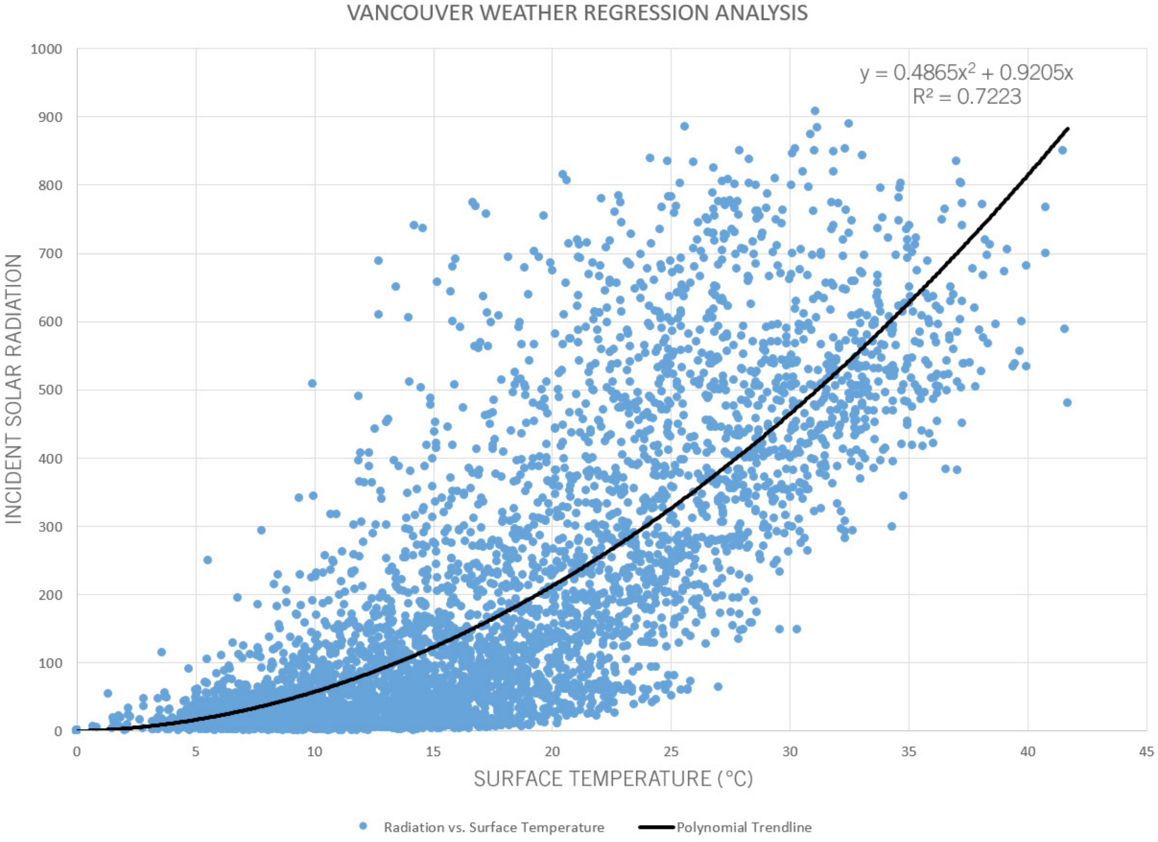


Figure 11: Coefficient of determination between incident solar radiation and surface temperature for Vancouver climate data.

An energy model study was conducted to understand how to properly utilize thermal actuation technology. Using Vancouver climate data, the model demonstrated a polynomial coefficient of determination (R^2) or 0.7223 between incident solar radiation and surface temperature, as seen in Figure 11.

This relationship implies that the surface temperature increases as solar radiation increases. An actuator that expands when temperature increases could reliably assist in blocking solar gain, if the mechanism itself impedes solar access.

Thus, the proposed apparatus was designed with the intent of shielding an opening as temperature increases, with the intent of improving thermal comfort using an autonomous semi-passive system.

7.0 PROTOTYPE CONSTRUCTION

The prototype as studied to test the principles of thermal actuation uses three layers of screens to respond to heat. One layer is fixed, and the other two layers respond to ambient temperature using two different degrees of actuation and piston movement. The result is a screen that is completely open when below approximately 8 degrees, and completely closed when above 20 degrees using the response curve in Figure 10.

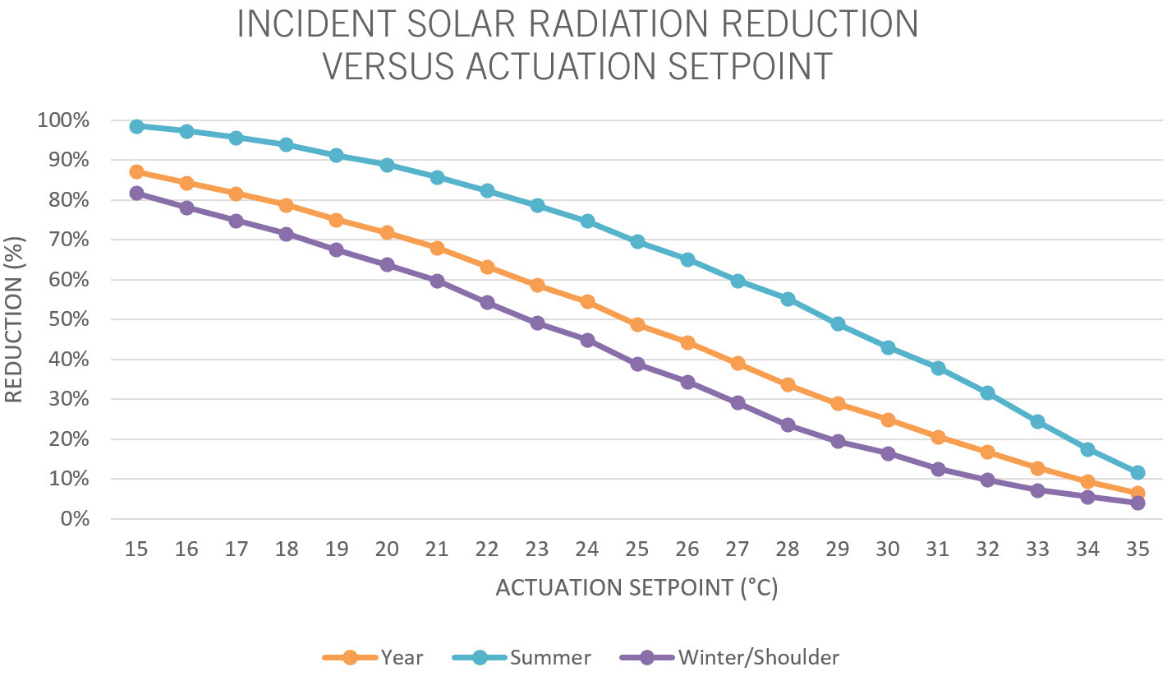
Positioning the prototype horizontally and in direct sunlight carries with it some unintended consequences. As previously mentioned, the actuators were exposed to direct sunlight, and were thus not responding to the ambient temperature. The result was that it closed quicker than anticipated. Tuning of the actuators is key to any environment and orientation, and for this reason, expanding the installation to a permanent and generalizable building component may benefit from using adjustable gas cylinder as opposed to our set wax cylinders.

Figure 12: The completed prototype placed in position on the test site. Bottom Left: Temperature above 20°C (59°F). The ambient air temperature closes the shutter and limits solar gain. Unfortunately, Vancouver has not had a sunny day in over two weeks at this point. Bottom right: Apparatus installed, visible from below. Temperature below 15°C (59°F).

8.0 POST-CONSTRUCTION ANALYSIS

The installation functioned as expected, however, in the temperate climactic region of Vancouver the technology only applies at certain times of the year. In regions closer to the equator, the range of use becomes more of a year-round consideration, and thus a greater return on investment. As expected, the ease with which thermal actuation is integrated into a basic shading strategy and the reliability of the system could see this potentially applied to building facades with relative success.

A simple model of the actuation strategy is reflected in comparing the potential reduction in incident solar radiation to a space using Vancouver's weather data, as shown in Figure 13. Its reveals that our model will be partially active year-round. Tuning the actuation to the climate is of the utmost importance, and designers need to evaluate if a sacrifice of radiation gain is acceptable during the winter. In northern climates, this may not be the case.



		ACTUATION TEMPERATURE (°C)																				
		15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
INCIDENT SOLAR REDUCTION	Year	87%	84%	82%	79%	75%	72%	68%	63%	59%	55%	49%	44%	39%	34%	29%	25%	21%	17%	13%	9%	6%
	Summer	99%	97%	96%	94%	91%	89%	86%	82%	79%	75%	70%	65%	60%	55%	49%	43%	38%	32%	24%	18%	12%
	Winter/ Shoulder	82%	78%	75%	72%	68%	64%	60%	54%	49%	45%	39%	34%	29%	24%	19%	16%	13%	10%	7%	6%	4%

Figure 13: Energy model results illustrating the reduction in incident solar radiation (Y axis) versus the theoretical set-point at which the actuator triggers (X axis), using Vancouver's weather data assuming a south orientation.

Figure 14: A prototype for a manually-actuated solar cell facade[3].

These results indicated several important considerations for this particular apparatus and technology:

1. A facade orientation that is more likely to receive direct sunlight would allow for greater temperature spikes and more ability to "tune" the actuators to their particular siting.
2. The apparatus would be appropriate for climactic regions with more consistent temperature swings.
3. Passive House design methods, which eponymously focus on systems that are passive, such as shading and envelope improvements, could benefit from this "semi-passive" approach. Instead of fixed overhangs which continually block solar gain, there is a potential application for deployable awnings that do not block out the much needed light during winter months in northern climates.
4. There is also great potential for expression and articulation of the actuation process. It would be an interesting experiment to combine collapsible membranes with the automatic actuation technology, as seen in Figure 14. Theoretically, the expansion of the actuator could be used to deploy solar panel collectors during the day and retract them at night. Tuning of the actuators is key, and so climates that are much more consistent (such as equatorial climates) would be better applications for this approach.

9.0 CONCLUSION

This study was an endeavor to think differently about our energy consumption and use existing technologies in a new way. Thermal actuators offer the potential for buildings to operate in tune with nature's cycles, in a way that requires less maintenance, parts, and monitoring of activity. The proper utilization of these components implies an understanding of the local climate and its variations, as well as the ability to model the response and tune it on site. In a theoretical sense, being able to balance all the variables would result in improved energy performance, but tradeoffs need to be balanced against occupant comfort, security, and daylighting.

The prototype confirmed this proposal by responding in the expected way, although there is much room for the aforementioned tuning. Being only one panel, the opportunities and gains obtained by operating at scale are unrealized. The current architectural exploration in screens could have their efficiency bolstered by responding to thermal conditions. During darker, colder, days the screen could be more permeable, allowing for a clearer view out of the building. The key is intelligence and planning for peak demand. Computational modelling of daylight can provide for the resources needed to understand where thermal actuation technology would be an appropriate response for a particular CABS.
Once the ability to properly model expected thermal conditions is achieved, and actuators are able to be properly tuned and controlled, it is viable that this type of system could see permanent physical installations in the near future.

Acknowledgements

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