Passive autonomic computing with 'heat-motors' and their compounds

Christopher Leung
Bartlett School of Architecture
University College London
Gordon Street, London
christopher.leung@ucl.ac.uk

Professor Stephen Gage
Bartlett School of Architecture
University College London
Gordon Street, London
s.gage@ucl.ac.uk

Dr Ben Croxford
Bartlett School of Graduate Studies
University College London
1-19 Torrington Place, London
b.croxford@ucl.ac.uk

PhD Symposium 2010, June 11 – 14, 2010, Copenhagen, Denmark

Abstract

The heat-motor is a simple device that converts thermal-to-mechanical energy, individual heat-motors may be considered as inputs to a 'class of machine' that can perform simple *Boolean* logic operands. This research explores some of the properties of this 'class of machine' and an application that uses multiple heat-motors.

The high mechanical actuation energy that is generated by the heat-motor is inherted by this 'class of machine' and suggests the possibilities for an architecture of reconfiguration in response to different external thermal conditions. The possibility of conditional response to the thermal environment is explored through a case-study project.

Keywords

Autonomic computing devices, Heat-motor, Thermo-hydraulic actuation, Wax phase-change.

ACM Classification Keywords

J.6 Computer-aided engineering.

Introduction

The wax-filled ‘heat-motor’ is a device that can convert a change in ambient thermal energy into mechanical energy from the expansion of wax during phase-change between its solid and liquid state. The properties of the wax-filled “heat-motor” are interesting for a number of reasons. The expansion of the wax has been shown to generate large hydrostatic forces [1] that can be used to reconfigure building components directly. The heat-motor can operate *passively* by harvesting changes in the ambient thermal conditions that are typical around buildings. They do not need electrical power to operate and they produce zero CO_2 in use.

Previous research has reported the potential of heat-motors and how to take advantage of their passive operation [2]. However, the phase-change material that powers the heat-motor has received little attention in the literature for its potential to carry out conditional evaluations. This could be achieved in the form of heat-motors containing varied phase-change materials that are connected by mechanical linkages to perform *Boolean* logic operands.

The theoretical basis for a device *other* than a digital computer to perform conditional evaluations such as logic primitives that can be described by discrete states is well established [4]. This suggests a repertoire of thermally-activated responses can be built with instances of this ‘class of machine’.

The single heat-motor is a ‘open-loop’ stimulus-response device i.e. the state of the output does not influence the effect that the input stimuli has on the state of the heat-motor, there is no feedback as defined in classical control theory [3].

One of the unique properties of a single heat-motor is that it is both the embodiment of logic as well as the mechanical actuator itself. As a consequence, the response of the heat-motor to ambient thermal conditions can be described as ‘autonomic’ because it is an involuntary responsive behavior due to the underlying material properties of the wax used [8]. This is distinct from a conventional deterministic computing using programmed firmware because the ‘program’ that the device runs is the sequential change in wax temperature driven by the exposure of the heat-motor’s to the prevailing weather and available sunlight.

The application of this ‘class of machine’ to operate movable components in an architecture of reconfiguration poses some questions. If we are to match the advantages of the heat-motor’s autonomic open-loop response with the desired positions of the movable component we need to consider the effects that the prevailing weather conditions has on both.

Research question

The repertoire of responses from such a ‘class of machine’ to the prevailing weather conditions suggest that they might be suitable for use in novel applications in the built environment.

Given the expected variations in diurnal and seasonal external thermal conditions when it is desirable to have a well-tempered indoor environment, what would be the approach to reconfigure a building envelope using the passive ‘open-loop’ autonomic responses from an instance of this ‘class of machine’?

Methodology

The heat-motor is a practical technology, it can be studied using empirical methods. A proprietary heat-motor has been tested under deterministically controlled conditions as well as with observational studies in un-controlled outdoor conditions.

Testing heat-motors under controlled conditions has been carried out in a programmable climate chamber. This facility is the thermo-physical analogue of a software development environment, it can be used to interactively test and debug the thermo-mechanics of this 'class of machine' in an runtime environment with run, stop and step-through thermal sequences. This methodology was adopted given that the heat-motor is an example of embodied logic that is only *operational* when it exists in its application environment.

The data acquired from the heat-motors monitored during these tests in the climate chamber could then be used to characterise the heat-motor in a first-order heat-transfer model.

Observational studies were also carried out on the behavior of heat-motors in uncontrolled outdoor in-situ conditions. This is when the heat-motor operates in a 'open-loop' with the external weather and offers the most realistic insight to characterize their autonomic behavior. Monitoring data from the observational studies provides test-case days that can be used to test and verify computer simulations built from the first-order models.

The empirical studies treat the heat-motor as essentially a thermo-mechanical device but individual heat-motors are analogous to the input in a simple logic primitive like *Boolean* AND and OR operands. They can be described as having a state and their state can be defined with respect to the state of their stimuli.

A simulation is developed to model the output of this 'class of machine' as compounds of multiple heat-motors when responding as a passive autonomic computing device to annual weather data for London, UK [5].

This research adopts a working method that observes and monitors the operation of physical models to complement the exploration of the properties of virtual models in simulations. In this way the research can inform the verification of digital models and the validation of their virtual simulation.

A case study

In some cases it is desirable to reconfigure the elements in a façade in response to different thermal conditions. If the duration and magnitude of the thermal conditions that stimulate the autonomic response of this 'class of machine' can be shown to match the duration and resulting state desired for the reconfigured element, then this may be an application to investigate further.

The environmental design of thermally insulated window shutters is an example of a reconfigurable façade element with these responsive characteristics. This is the basis to pursue it here as a case study. It is challenging because it is both a formal and environmental reconfiguration of the façade, this makes its environmental performance dynamic and this has been shown to offer benefits of reduced energy use [6][7].

Figure 1 Technology demonstration pavilion

In summary, the thermally insulated window shutter can be reconfigured in two positions in response to three different thermal conditions:

- It can be closed to provide insulation and prevent excessive heat-loss when it is cold outside
- It can be closed to provide shade when it is hot outside and there is excessive sunlight that may lead to overheating
- It can otherwise open to admit incomming daylight to the interior and provide amenity views to the outside

A full-size pavilion was constructed to demonstrate the operation of nine shutters, each individually operated by an instance of the heat-motor operated machine. The responsive behavior of the passive autonomic machine was operated by two heat-motors and this was investigated to provide a conditional evaluation of cold, moderate and hot conditions.

Figure 1 shows the front of the pavilion with the nine shutters in their open position on a moderately warm day with intermittent periods of direct sun-light. The case-study has tested different aspects of the research question, it is an example of the reconfiguration of building scale elements solely by the passive conversion of the thermal energy in the air and available sunlight into mechanical energy. It also demonstrates the possibility of conditionally evaluating three outdoor thermal environments and responding with a repertoire of two configurations.

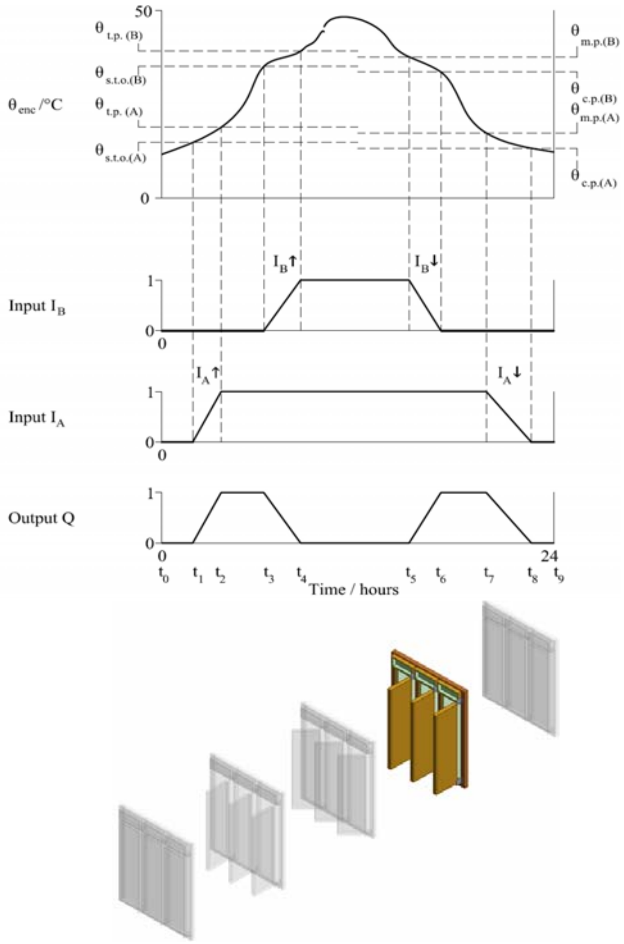

Figure 2 Operating profile of the dual heat-motor on a hot day

Results

Observation studies of the pavilion were carried out over a number of weeks during summer months to capture examples of cool, moderate and hot test-days.

Figure 2 is an example of a test-day during which all three responses occur during the 24-hour diurnal cycle. The time-series at the top of Figure 2 plots the temperature inside a glazed enclosure around the heat-motor operated machine.

The two time-series below this show the response of each of the two heat-motors as inputs A and B. The lower time-series shows the final output and below this is a sequence of stills showing the changing position of a bay of three shutters over 24-hours.

The results show that the mechanism could distinguish between three distinct thermal conditions and respond to them conditionally by reconfiguring the shutters.

The shutters close at night-time when it is cool to reduce heat-loss through the window. During the morning heat-motor A is activated by warmer conditions to open the shutters and admit daylight. During the mid-day period direct sun-light raises the temperature to activate heat-motor B, the machine then closes the shutter to provide shade and mitigate against excessive heat-gains. During the late afternoon and early evening the temperatures drop and the mechanism re-opens the shutters as heat-motor B deactivates and then finally closes the shutters when heat-motor A deactivates during the night.

Discussion

The case-study demonstrates the principals of this 'class of machine' with one instance that embodies the *Boolean* XOR operand.

Figure 3 illustrates another logic primitive the *Boolean* AND operand between two heat-motors containing wax with different activation temperatures. Other logic primitives and their inversions may be embodied by two or more heat-motors connected with mechanical linkages. These instances may be used to further extend the repertoire of responses from this ‘class of machine’ to its thermal environment.

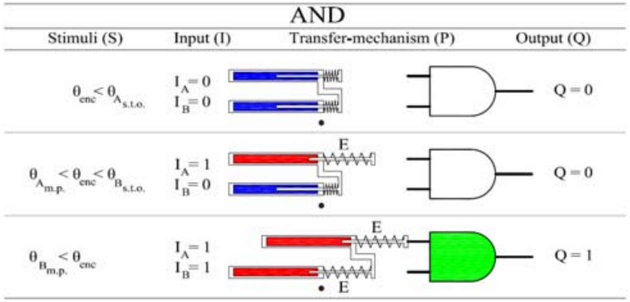

Figure 3 Truth-table of Boolean AND for two heat-motors

A simulation of the annual operation of the machine developed for the case-study is shown in Figure 4. The results of the simulation suggests that there is further scope to design and engineer the repertoire of both instances of this ‘class of machine’ and the building elements it is used to reconfigure. This provides a analytical method to evaluate matches between the result of the conditional evaluation of one with the desired state of the other to shared weather conditions.

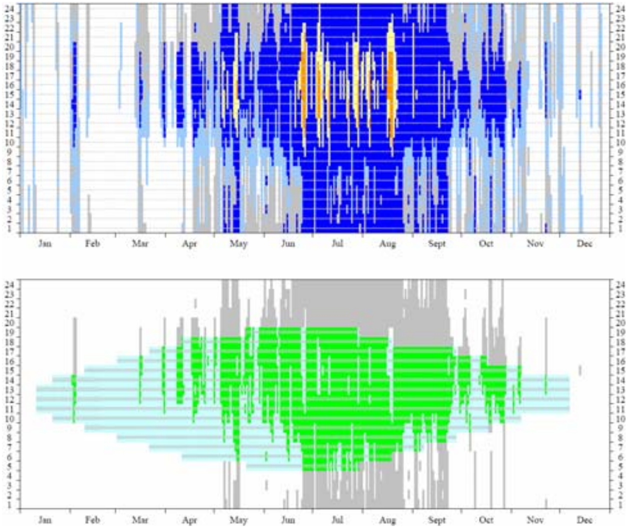

Figure 4 Annual activity of case-study machine in London, UK

The distinction that can be drawn between harvesting passive thermal energy from the ambient air temperature and solar irradiation when available suggest the further development of enclosures used in this ‘class of machine’. This may lead to the further development of heat-motors that differentiate between the two as input stimuli.

It is speculated that while further instances of this ‘class of machine’ may be considered trivial as computing devices because they inherit the simplicity of a *Boolean* logic primitive, their repertoire of responses to the sequence of diurnal and seasonal temperature time-series that they will be exposed to over their operational life may not be.

Conclusion

The 'class of machine' explored in this research suggests that we might reconsider both the embodiment and the integration of computing devices in the built environment for certain types of needs.

This is a shift away from the embedded microprocessor based system that models responsive behavior through sensing devices, symbolic manipulation in processing and the control of electrically powered actuators. Instead, it is a shift toward a 'class of machine' that can sense, can conditionally evaluate and can provide actuation of building-scale components. This is an alternative embodiment with the advantage of a passive response that harvests the changes in the thermal energy available from its surroundings.

It is also a shift away from considering the design of responsive building envelope that is achieved by integrating into it a network of electronics to model its behavior using abstract symbolic representation that consume electrical energy to operate. Instead, it is a shift toward a building fabric that is an integration of the embodied logic and the actuator device within the components of the building that are reconfigured.

This is an alternative where each configuration of the building's envelope is the desired conditional response to the prevailing external conditions, and these are matched with the thermal conditions that stimulate a corresponding result from the repertoire of possible responses of this 'class of machine'.

Both of these alternatives suggest that there is a need for further investigation to consider suitable applications, and quantitative investigations to inform the models and their simulation that would be necessary to support their design.

Acknowledgements

The industry sponsor of this research is Haque Design + Research Ltd http://www.haque.co.uk. This research work has been supported by the UK Engineering and Physical Sciences Research Council (EPSRC).

References

[1] C. S. & Loveday, P. W. (2007), *A thermo-hydraulic wax actuation system for high force and large displacement applications*, SPIE The International Society for Optical Engineering, USA, pp. 99

[2] Tibbitts, Scott (1992), *High output paraffin linear motors : utilization in adaptive systems*, Proceedings - SPIE The International Society for Optical Engineering, USA, pp. 388-426

[3] Weiner, Nordbert (1948), C*ybernetics: or control and communication in animals and the machine*, MIT Press, Cambridge, MA

[4] Minsky, M. (1972), *Computation: Finite and infinite machines*, Prentice-Hall International, inc, London

[5] *CIBSE Guide J: Weather and solar data Test Reference Year* (TRY) and *Design Summer Year* (DSY) weather data for London, Chartered Institute of Building Services Engineers

[6] Langdon, William K. (1980), *Movable insulation*, Knowledge publications, Rodale Press, Pa. USA

[7] Shurcliff, W. A. (1980), *Thermal shutters and shades : over 100 schemes for reducing heat-loss through windows*, Massachusetts, USA

[8] Wigginton, M. & Harris, J. (2002), *Intelligent Skins*, Architectural Press, Elsevier