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ECO-MACHINE: A GREEN ROBOTIC ECOSYSTEM FOR SUSTAINABLE ENVIRONMENTS

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Abstract. This paper focuses on developing a kinetic system with responsive solutions for sustainable environments. The emphasis of our work is to develop a zero-energy interactive ecosystem called an "eco-machine". We setup a conceptual framework and investigate how to integrate sensors and actuators into green building tectonics to achieve a sustainable kinetic system. The operational scenario and prototype implementation are reported in this paper.

Keywords. Eco-machine; sustainable environment; interactive architecture.

1. Introduction

There has been an increasing interest in developing interactive architecture that can dynamically alter the physical space in response to changing needs. An interactive architecture system is sought to be achieved by embedded sensors and actuators that continuously interact with the surrounding environment. Research work in interactive architecture has developed embedded sensors or actuators in buildings components that transform its shape and physical properties in response to change (d'Estrée Sterk, 2005; Oosterhuis and Biloria, 2008; Fox and Kemp, 2009). While interactive technology has been investigated, many recent works have focused on the design of kinetic machines and networked sensing systems for combining sensing, computation, and physical interactions (Pan and Jeng, 2012; Rossi et al, 2012; Thün et al, 2012; Bohnenberger et al, 2012). Less effort has been made to design an eco-friendly machine that is driven by nature (e.g. air, water) and interacts with other creatures (e.g. plants, organism) as a whole ecology.

The objective of this research is to develop the concept of *eco-machine* that is able to provide sustainable solutions for moderating energy use, spatial design, and user activities. The fundamental question is: "How to achieve a green robotic eco-system that is self-sufficient and driven by natural forces?" Toward the goal of sustainability, interactions among human, machine, and environment should be concerned with the manipulation and transformation of energy, materials and information. Therefore, we propose a conceptual framework for green robotic eco-system and develop an eco-machine prototype in this paper.

2. The Eco-machine

The term "eco-machine" is commonly defined as living machine for clean, green waste-water recycling. In this paper, we define eco-machine as an ecosystem that seamlessly integrates natural resources with embedded computational devices for sustainable environments. It is argued that people need to view species, nature, and technology in a radically new way (Odum, 1971). An approach is the design of living technologies for ecological engineering (Todd and Josephson, 1996). We were inspired by the design of living technologies and attempted to develop an eco-machine using biomimic power and renewable energy self-produced by the system. To design prototypes of eco-machine, three major perspectives are considered: "Autonomous control", "Kinetic mechanism" and "Interactive materials". Combining autonomous control, kinetic mechanism and interactive materials open up new strategies for developing an eco-machine for sustainable environments.

3. Literature Review

This section provides a literature review of eco-machine with respect to autonomous control, kinetic mechanism and interactive materials for sustainable environments

3.1. AUTONOMOUS CONTROL

The concept of combining machine and living systems can be traced back since 1970s; Architect and MIT Media Lab founder Negroponte proposed "soft architecture machine" concept, and predicted that physical building will produce new form when computing technology involved (d'Estrée Sterk, 2005). However, the system integration work of former discuss are partial works of combining machinery and building systems. There is little research to cope with architectural machine as a part of ecosystem.

Contrast to the architectural machine discussed above, we try to expand the scope of research into hybridization between machine and ecological environment. To make up a hybrid system, the operation of eco-machine should have series of environmental sensors, active actuators, and digital signal processors. These embedded computations will accommodate natural resources and adaptive functions and respond to climate change. Each autonomous entity may assemble together to become a larger organism and to share energy.

3.2. KINETIC MECHANISM

In the book "An Evolutionary Architecture" by John Frazer (1995), a set of modular intelligent blocks is developed, which outlined eight aspects of evolution system, including development through natural, self-organization, metabolism, thermodynamics, morphology, morphogenetic, symmetry breaking, and the prevalence of instability.

The book revealed the design of robotic modules for kinetic systems. In this paper, we adapt the idea of evolutionary architecture to develop kinetic robotic modules that can maximize the energy efficiency through the kinetic mechanism. The module then has functions of active control to modify the structural behaviour and generate power for maintaining the kinetic movement of the system; hence toward a new way of "zero-energy architecture".

3.3. INTERACTIVE MATERIALS

Recently, many kinds of innovative materials have been developed and integrated into the built environment. The innovative materials should be applied to a larger integral component of responsive kinetic system. The kinetic structural solutions may also include pneumatic, chemical, magnetic, natural or mechanical materials. The computation embedded into the materials and transformable objects can change the atmosphere of space through adaptable spatial configurations. Thus, the system may no longer be passive, but actively responsive to the surroundings with environmental and social adaptabilities. For instance, some newly-developed textile materials can automatically transform to adapt to the changes in temperature and lighting levels" Such developments are confirming that the surface, structure and form are becoming more interconnected, interdependent and interactive. It requires a multi-disciplinary approach in design process. The paradigm shift from mechanical to biological in trends of architectural evolution has emerged.

4. Design Methods

In order to understand the concept of eco-machine, it is better to develop a scenario in the context of sustainable environment. The scenario is useful to demonstrate the sustainable relationships between ecology, water supply and user-lifestyles. In the scenario, eco-machine will become an important component for energy saving in future environments.

4.1. A SCENARIO

In the scenario (Figure 1), a set of kinetic physical structure is built along the seashore. The kinetic structure is actuated by hydropower and changes its form according to the sea level. We design rainwater storage and water-detecting system in order to utilize the water resource in generating the power for kinetic structures and also for flood-prevention in climate change. The water can also be collected for later use in cooling the interior or irrigating the plants on hybrid surfaces.

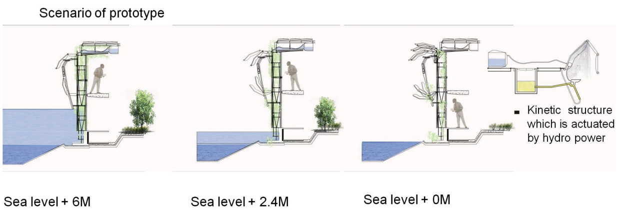


Figure 1. The kinetic structure is actuated by hydropower and changes its form according to the sea level.

4.2. DESIGN CONEPTS OF THE PROTOTYPE

In the above eco-machine scenario, two contradictory requirements have to be fulfilled: (1) enough renewable energy supplied for self-sufficiency; (2) adaptable kinetic structure for environmental change. However, renewable or biomass energy can produce very limited energy in each conversion and far beyond the ability to directly actuate a kinetic surface structure. The mismatch between the low energy production efficiency and high energy consumption for powering a structure is a crucial problem to be solved in this study. Therefore, we need to seek solutions by developing an embedded actuator system with minimal electronic energy consumption.

Based on the conditions above, the prototype design will follow the natural law of energy conservation and the method of potential-gravity energy storage. The prototype will gradually accumulate the potential-gravity energy, and release it at once while the amount is enough for actuating the kinetic structure. The implementation strategies include:

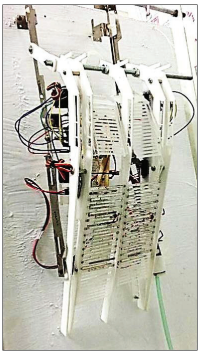
- **Physical kinetic mechanism design:** with emphasis on the character of “potential-gravity energy storage as the main design concept
- **Autonomous control design:** by choosing the water-detecting signal as the triggering variable in the computation algorithm.
- **Innovative material design**: by designing a layer of water-detecting modules on the façade surface as a new hybrid tectonic.

The design strategies above will bring advantages on: (1) balancing the mismatch between the low power production efficiency and high energy consumption from the kinetic structures; (2) lessening the complexity of linkage components and preserve a more usable space inside the eco-machine; (3) integrating with currently existing hydro-power network with the rainwater recycling system to set up sustainable relationship between ecology, water supply and environmental tectonics.

5. The System Implementation

The implementation will focus on demonstrating the eco-machine as a sustainable interactive component which sensitively responds to the environmental variation. The eco-machine prototype (Table 1) consists of three sub-systems: (A) Hydraulic transmission mechanism, (B) Smart surface, and (C) Embedded control systems.

Table 1. The structure profile of the Eco-machine prototype.

The Eco-machine prototype	Structural Profile
	

5.1. HYDRAULIC TRANSMISSION MECHANISM

We utilize the mechanism of potential-gravity energy accumulation. The hydraulic pressure will be accumulated to a certain extent, and then it will be released and transmitted. As depicted in Figure 2, the assembly of the hydraulic transmission mechanism includes: (A1) Liquid containers, (A2) Controllable floodgates, (A3)

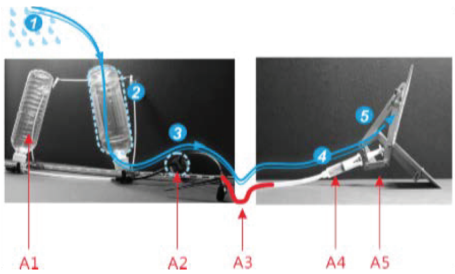


Figure 2. Hydraulic pressure transmission mechanism.

Connecting tube, (A4) Buffering component, (A5) the movable lever. The liquid container is used to accumulate the rainwater or the seawater. The controllable floodgate decides whether to release the liquid or not. The buffering component is used to prevent the over-speed releasing rate of the dynamic potential energy.

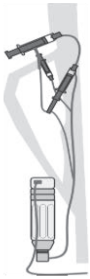
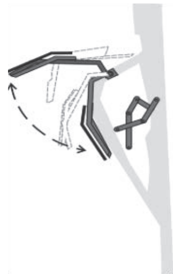
The processes of hydraulic transmission mechanics are as follows: (1) The mechanism is prepared for the collection of rain-drops or ocean water liquids; (2) The liquid collected would be kept in a container in order to accumulate enough potential-gravity energy; (3) When the controllable hydraulic floodgate is open, the liquid flows to the operational locations via the tube. (4) A syringe as a buffering mechanism is installed at the front-end to gradually release the hydraulic pressure for this kinetic structure; (5) the hydraulic pressure will push the movable lever steadily, and cause the movement of the kinetic structure. When the liquid in the container is released completely, the surface then restores to the shutting state.

5.2. SMART SURFACE

As listed in the item (B) of Table 2, there are two main topics related to the smart surface to be discussed:

- **(B1) kinetic structures:** in the prototype implementation of this study, many operable surface modules are manufactured by CNC machines to be the kinetic components in building facade. We also used the PCB (printed circuit board) process to customize circuit board in special shapes and with electric wires and circuit elements embedded into the tectonics of the surface.
- **(B2) smart materials:** we develop a layer of water-detecting surface which is easy to be integrated with the building envelop. As depicted in Figure 3, the plural electrode array with opposite polarity plants in alternating position and maintains proper intervals between electrode arrays. Once the water simultaneously covers both of the opposite electrodes, it will arouse short-circuited occurrence and trigger the water-detecting signals for reporting the environmental event as "rainfall" or "sea-level ascending".

Table 2. The system framework of the Eco-machine prototype.

Sub-Systems	**A- Hydraulic transmission mechanism**	**B- Smart surface**	**C- Embedded control systems**
Assembly diagram			
Elements	A1. Liquid container A2. Controllable floodgate A3. Connecting tube A4. Buffering mechanism A5. Movable lever	B1. Kinetic structure B2. Water-detecting module algorithm	C1. Micro controller C2. Autonomous computing C3. Servo motor

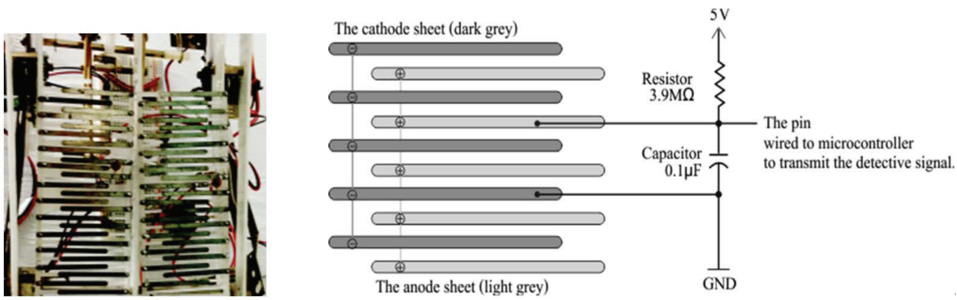


Figure 3. The photo and circuits of the water-detecting module.

5.3. EMBEDDED CONTROL SYSTEMS

As listed in Table 2, microcontroller, autonomous computing algorithm and servo motors are the three elements considered in the embedded control systems. "Arduino Mini" is the microcontroller used in this prototype. It can receive the signals from a water-detecting module and send pulse signals to a pair of servo-motors to actuate the floodgates and kinetic surface. In the microcontroller, a "triggering variable" is provided to decide whether the kinetic surface should be actuated.

The “triggering-variable” is affected by the sum up of positive and negative factors. Raindrops, manually turn-on or higher temperature are the positive factors to bring increment; while a time-based descending rate, or revolving limitation of the mechanism are the negative factors to bring decrement. While the incremental speed is greater than the attenuation speed, the kinetic surface will be actuated at the moment that the trigger threshold is reached.

The triggering-variable is controlled by an algorithm (Table 3). In the loops of computing iterations, the algorithm will repeatedly come up with new values by continuously checking the sensor’s data and the time consumed. The strengths of the algorithm are as follows:

- It ignores partial and short-term effect to prevent the surface from opening up accidentally. For instance, when the surface detects very little water, it will not open.
- It ensures that the operation of the kinetic surface follows not only singular factor but also the overall situations; e.g., a user manually sends an open signal while it’s rainy outside, the surface will keep closed to prevent the rainwater from flooding into the interior.

Table 3. The script of the algorithm.

Script 1: The following example used a simple algorithm to determine whether the alternation of the kinetic surface or not.

```
  int TriggeringVar, Increment, Decrement;
  int TriggerThreshold = 200 ;  // The value is specified on each situation.
  int DecayRate = 10 ;  // A time-based descending rate.
// Token of iteration start.
  LoopStart:
  Increment = 0 ;
  Decrement = 0 ;
//Conditional expressions.
  if LiquidDetect = true                      then Increment ++;
  if TemperatureOverThreshold = true          then Decrement ++;
  if ManuallyTurnOn = true                    then Decrement ++;
  if ManuallyTurnOn = false                   then Increment ++;
//Accounting triggering variable and constraining triggering variable to be greater than zero.
  TriggeringVar = TriggeringVar + Increment – Decrement – DecayRate;
  TriggeringVar = constrain (TriggeringVar, 0, 255);
//Motor Driving
  if TriggeringVar > TriggerThreshold then DrivingMotorOfFloodgate(true);
  else DrivingMotorOfFloodgate(false);
// End of this iteration and go back to starting token.
  goto LoopStart
```

5.4. PROTOTYPE DEMONSTRATION

In the demonstration, the operating sequences of the kinetic component will follow the algorithm listed in Table 3 and perform steps below:

- In the starting state, the kinetic surface is open (Table 1, right).
- Whenever the sensor detects rain-drop or water, the triggering variable starts to change incrementally, nevertheless, if no more rain-drop falls, at certain period of time, the triggering variable will start to decay by a time-based descending rate.
- For the triggering-variable, if its incremental speed is greater than its attenuation speed and reaches the threshold, the controller IC of it will send triggering signal to close the floodgate of the surface (Table 1, left).
- Until no more rain water is detected, the triggering variable will get lower than the threshold because its attenuation speed become greater than its incremental speed. In this state, the controller IC will send triggering signal to restore the floodgate to the starting state.

The components are capable of required functionality to articulate the motion of kinetic elements: (1) to store water in water collectors and pump up to get high potential energy; (2) to use the salt water to activate the motor with metal air fuel cell.

6. Discussion

In this study, we applied the accumulation-attenuation algorithm to the control mechanism of the Eco-machine prototype. The simple algorithm is very suitable for end component of the kinetic systems to improve the environmental adaptability of smart materials. Such control mechanism helps the architectural façade correctly response to the right situation in the complexity of changeable environmental parameters. The result demonstrates a surface prototype which is able to store and to release energy at right situation for operating the floodgate at the right circumstances. The prototype suggests a new direction toward an ecosystem created by a biomimic solution to the interaction between nature and built environment.

Also in this project, we have suggested sustainable strategies to the implementation of eco-machine design. Based on our observation, it is useful to combine sustainable components and embedded computation into the green robotic system. We preliminarily proved that energy consumption can be reduced in interactive systems by installing eco-machine components. Comparing to traditional interactive systems, less sensors and electronic apparatus are required in this project. The eco-machine system can be replaced by advanced tectonic and evolutionary systems to achieve sustainable performance.

7. Conclusion

In evaluating the validity of the eco-machine prototype, the implementation has proved the functionality in the following perspectives:

- **Alternative energy resources:** applying the renewable water power resources to cooling systems in order to reduce energy consumption.
- **Kinetic mechanism:** applying the accumulation of potential-gravity energy to design the kinetic mechanism.
- **Control algorithm:** using the algorithm of accumulation and attenuation to establish a self-adaptive control mechanism
- **Smart material:** developing a simple and analogical rain water sensing surface to trigger the interaction.

The experiment provides a valid proof of the "eco-machine" concept in advanced materials, alternative energy, and environmental responsiveness. However, it still needs more efforts on hybrid façade design and testing as future research direction for interactive systems. The hybrid technique applied to building façade requires totally-interwoven operation of nature materials and controlled systems.

Acknowledgements

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