Optimization of Thermodynamic Balance Control in LEO – Biosphere 2

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Introduction

What is the Biosphere 2?

Biosphere 2 is the World's largest laboratory experiment in the interdisciplinary Earth Sciences. Constructed from 1984 to 1986, Biosphere 2's initial goal was to research a self-sustaining ecosystem with inhabitants to study the possibilities of space colonization technologies. This program was mired in controversy, which led to multiple changes in ownership before the University of Arizona took partial control of the site in 2007, and then full control in 2011. Now it is a University of Arizona funded research site with public educational tours and multiple ongoing research projects. One of the current projects at Biosphere 2, and the focus of this paper, is the Landscape Evolution Observatory (LEO).

LEO? Who's that?

LEO consists of three adjacent bays greenhouse-like bays, each containing their own artificial landscape. Each bay is closed system with unique properties. LEO contains 1800 sensors which monitors the water, carbon, and energy cycles, as well as the physical, chemical and biological evolution of the landscapes. Additionally, data on the water and soil chemistry, the temperature both inside and outside, and other weather conditions are documented. The landscapes are 30-meters x 11-meters in area, and each contains 500 metric tons of soil. The landscapes are at a slope of 10 degrees with a uniform depth of 1 meter consisting of crushed basalt soil from a Northern Arizona crater. Each bay houses pure mineral and abiotic substrate, in addition to living microbial communities. The goal of LEO is to document how changes in soil, topography and biological communities affect the water. Carbon and energy cycles within the landscape and atmosphere. See Fig. 1 and 2 for pictorial representations of LEO.

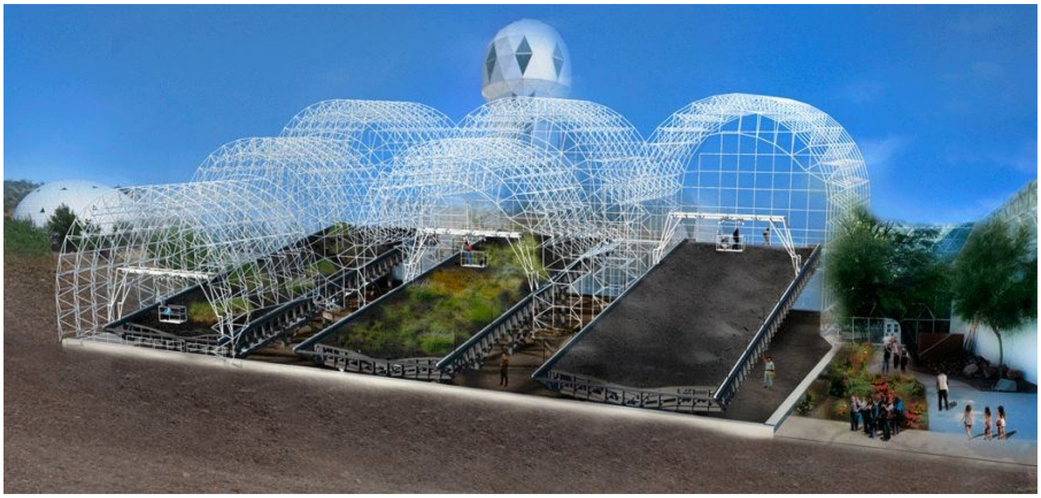


Fig. 1 The Three Adjacent Bays of LEO.

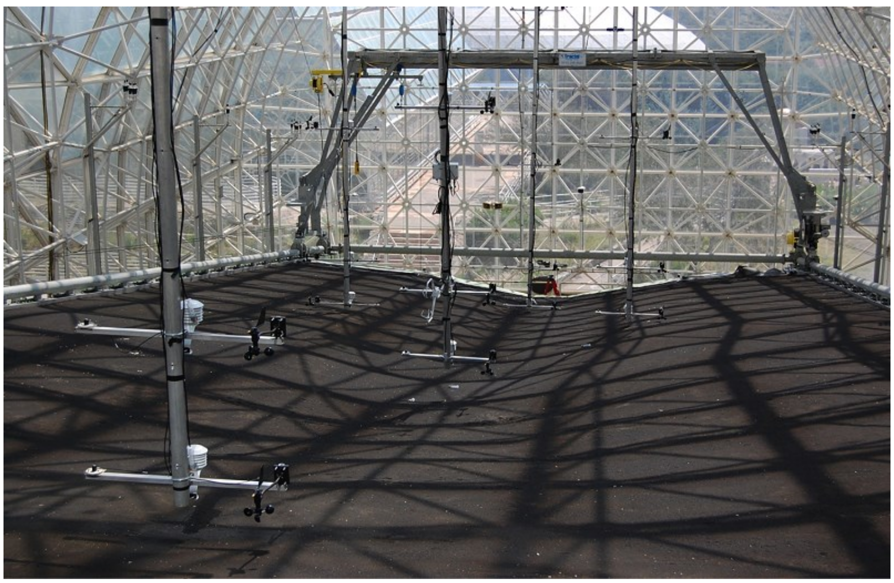


Fig. 2 One of the Slopes of LEO with Various Sensors.

Our Task

The Problem

In LEO, temperature of the soil is one of the hardest things to control. Currently, temperature of each bay is controlled manually, and the process is not systematic: it is at the technician's discretion. In order to control temperature, the technician can control up to three air handlers under each bay which vary in temperature, airflow, capacity, and orientation. The amount of solar radiation that enters each bay has the greatest impact on the soil's temperature; i.e., cloud coverage has more impact on temperature than ambient temperature. Our main task is to create a model to optimize the thermodynamic control system of LEO to provide a stable temperature range for all three bays. See Fig. 3 for the thermodynamic illustration of a bay.

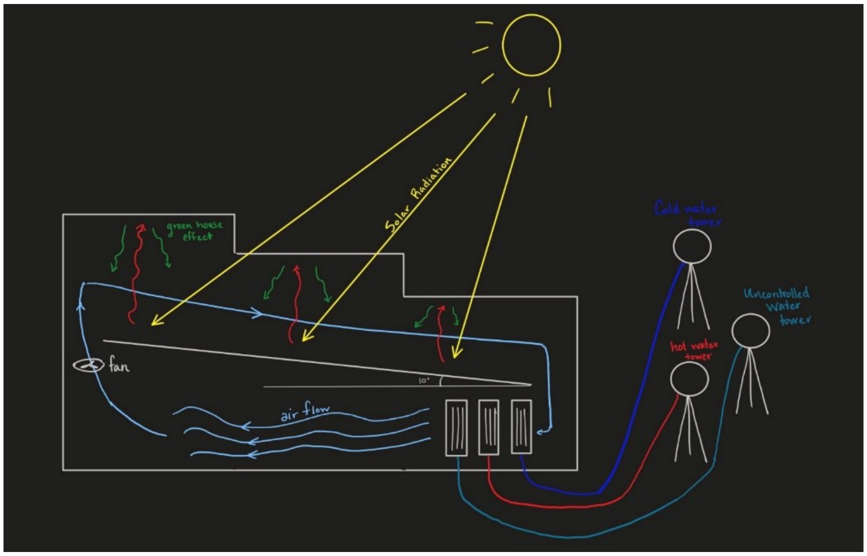


Fig. 3 Thermodynamics of a Bay. The yellow rays represent solar radiation which get absorbed by the landscape which is at an average 10-degree slope. The energy is converted to heat which dissipates through the air (red arrows). This heat is trapped in the enclosure (green arrows) which can be modelled as a greenhouse effect. The only way to control the temperature is by moving the hot air with the use of air handlers, which moves throughout the system (light blue line). Each air handler is connected to a random configuration of water towers. The water towers send water through the air handlers to control the temperature at which air comes out of the handlers. There is a cold-water tower (dark blue line), a hot-water tower (red line), and an uncontrolled water tower (cyan line).

Our secondary task is to optimize the system in order to minimize the energy consumption of the air handlers. The bays can be kept at a range of temperatures so instead of the air handlers being continuously turned on and off to maintain a constant temperature, alternative solutions will be analyzed to see which is most energy efficient.

Variation

Once a solution is formulated for one bay, this solution will likely not be adequate for the other two bays. This is due to variation of various parameters between the bays. Each bay gets different amounts of solar radiations from the sun as the bays are not facing directly south and each is shaded from a multitude of various sources. In addition, each bay has a different configuration of air handlers that have a random configuration to the water towers and have different obstructions for the air flow.

Approach

Step 1: Simplify the problem into just a blackbody radiation problem on a given area

Blackbody radiation refers to an object or system which absorbs all radiation incident upon it and re-radiates energy which is characteristic of this radiating system only, not dependent upon the type of radiation which is incident upon it. The radiated energy can be considered to be produced by standing wave or resonant modes of the cavity which is radiating. An approximation could be made based on the following laws that will allow us to explore the relationship between radiation and temperature

Planck's law of blackbody radiation gives us the spectral radiance density by the following equation:

$$B_\nu(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1};$$

Wien's displacement law shows how the spectrum of blackbody radiation at any temperature is related to the spectrum at any other temperature:

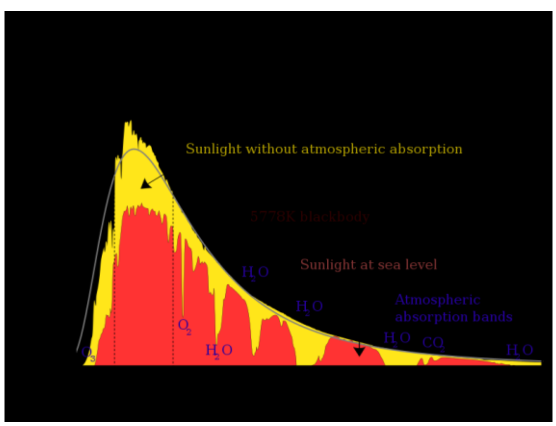
$$\lambda_{\text{peak}} = \frac{b}{T},$$

Finally, Stefan-Boltzmann law gave us the relationship between radiance L (integration of spectral radiance density) and surface temperature:

$$L = \frac{2\pi^5}{15} \frac{k^4 T^4}{c^2 h^3} \frac{1}{\pi} = \sigma T^4 \frac{1}{\pi}$$

Step 2: Import complex relations into the problem (i.e. Greenhouse effect, soil absorption)

The actual problem in reality is much more complicated than just blackbody radiation, we first need to take considerations that the solar radiation on earth has a different spectrum which at each wavelength associate with a different energy that can be absorbed.



Additionally, it is challenging to take account of Greenhouse effect since our soil sample are stored in a closed area. The problem here is twofold, first being solar radiation is absorbed and emitted by material (i.e. wall, temperature detector); and second, there is energy lost due to glass interference (i.e. reflected radiation, absorbed radiation). The temperature of the soil is also will be affected by the ambient air temperature. To start, we can just assume the in-door air temperature will change uniformly, so there is no gradient of temperature changes based on its location of the room. Since the temperature detectors are buried just underneath the surface of the soil, hence we can also just assume that surface soil temperature is our only consideration. We then used the Newton's law of cooling to model the effects on how temperature of the soil changes with the temperature of the ambient air throughout the day. Newton's law of cooling is given by,

$$\frac{dQ}{dt} = -h \cdot A \cdot (T(t) - T_{\text{env}}) = -h \cdot A\Delta T(t),$$

Step 3: Build the mathematical model to simulate air handler effects

This is where we move from concrete and complete progress into speculation. The next step requires we consider how the air handers effect the indoor air ambient temperature. From our research the best approach for this effect is to use Newton's Law of Cooling. Newton's Law of Cooling is generally used on temperature exchange between solid object and surrounding media, at this stage of study, we do not need an extremely precise mathematical model. Additionally, as our simulations improve, we intend on using machine learning to help calibrate the model with live data, so using Newton's Law of Cooling is appropriate. This approach will be used on all three air handlers and their corresponding water loops. Verification of the results from this step will be tested by manually inputing a certain period of time to turn on each individual air handler, then use different combinations (i.e. cooling and heating at the same time) for different testing scenarios.

Step 4: Come up with a mathematic model on how temperature changed as a function of the above variables

Once our basic simulation can effectively illustrate the black body dynamics coupled with the more complex elements like the greenhouse effect and soil absorption, we will create a mathematical model to help describe LEO's behavior. This will fuse together the blackbody radiation and complex elements from previous steps into one place to help guide us in how we can better our existing simulations. Using this model, we then will create several ordinary differential equations with time multiplexing in Matlab that connects time, air, temperature of the day, and temperature of the water loops connected to each air handler, as well as how long that those air handers will be turned on. This gives us a single, cohesive picture at how the system behaves in our idealized scenario.

Step 5: Fit the mathematic model with live data provided by Bio2 through machine learning

After we have our model describing the thermodynamics of LEO, we then want to tune the parameters of the model with live data from Biosphere 2. We will first need data from their outdoor weather station to get precise information on ambient temperature throughout a period of 10 days with precision to a minute. Then we will import the actual temperature data into our mode. We will also need the soil surface temperature data from one of the sample slopes, with hopefully the same level of accuracy. After obtaining enough data, we will use the Evolutionary Programming (EP) method for optimizing PID parameters. PID is the most common type of regulator within control theory because it's relatively simple and yields stable results for most applications. EP is a derivative-free optimization algorithm which makes it suitable for PID optimization in this specific case. Using this type of machine learning, we expect to be able to train and optimize the parameters of our equation to best match the information coming from Biosphere 2. This should give us, albeit simplified, a comprehensive look at how the temperature, time, radiation, and any other factors are related within LEO.

Step 6: Find the optimized solution for minimum power consumption

Finally, after the model has been trained to match the LEO data, we then plan to further optimize it with respect to power consumption of Biosphere 2 for LEO. The power consumptions to keep each water supply tower running will be vary throughout the day. It is clear that the uncontrolled water tower will consume the least power, so it would be ideal to have it turned on as much as possible. However, we are also dealing with multiple inputs with multiple dimensions (which water tower/air handler to use and how long to use them), the best solution seems to be through machine learning again. We can use the same approach in Step 5 of EP for optimizing PID parameters, but with different parameters for this specific optimization application.

MATH 485 and COVID-19

Unfortunately, with the impact of COVID 19 on the University of Arizona, our initial goals are somewhat ambitious. Currently, we are working towards establishing the mathematical model in step 3. This step requires a massive amount of research and presents a huge challenge in integrating the necessary elements to accurate portray LEO. Optimistically, we think getting to step 5, optimization through machine learning, is possible, but we are tempering our expectations for just a set of differential equations and a working MATLAB simulation. Hopefully, we will find more success than that, but given the chaotic nature of the world right now, we are not confident in proclaiming we can do much more right now.

Works Cited

- https://online.arizona.edu/news/join-biosphere-2-research-team-free-online-course
- https://biosphere2.org/research/projects/landscape-evolution-observatory
- https://biosphere2.org/research/leo-data
- Specifications of Photovoltaic Pumping Systems in Agriculture
    - https://www.sciencedirect.com/science/article/pii/B9780128120392000028
- https://es.wikipedia.org/wiki/Archivo:Solar_spectrum_en.svg
- https://en.wikipedia.org/wiki/Stefan–Boltzmann_law
- https://en.wikipedia.org/wiki/Idealized_greenhouse_model