A METHODOLOGY FOR CONTROLLING SMART HVAC SYSTEMS IN PLANETARY ENVIRONMENT

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Abstract

Before astronauts can launch long-term exploratory missions on planets, they need a habitat where they can reside and perform experiments. Heating, Ventilation, and Air Conditioning (HVAC) units can provide the necessary thermal comfort in these habitats. This study tests whether Earth-borne HVACs can be modified to operate in a lunar environment. Using household data collected in Austin, Texas, to simulate an HVAC on Earth as well as meteorological data collected on the Earth and Moon, we discover that without modification, Earth HVAC technology cannot efficiently heat a lunar habitat to a habitable temperature. With modification, the HVAC system heats the habitat to 23°C. However, the cost of operating an HVAC system on the Moon is significantly higher than on Earth. While this finding verifies that technology made on Earth can be modified to work in planetary environments, it warns researchers that doing so will come at increased energy usage.

Introduction

To explore the Moon and Mars, astronauts need smart habitats that support life in harsh environments and remain operational when vacant. NASA's Habitats Optimized for Missions of Exploration (HOME) is an example of such a habitat, providing inhabitants with a breathable atmosphere, drinking water, and food [1]. Smart HVAC systems are instrumental in these habitats because HVACs maintain healthy indoor air quality levels and thermal comfort [2].

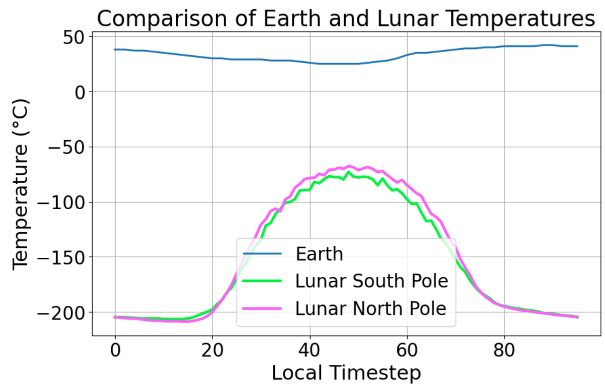

Figure 1: Summer temperatures in Austin, Texas, are significantly higher than that of lunar polar temperatures

When designing smart systems for HOME, scientists must translate their experience operating equipment on Earth to the context of these habitats [3]. However, planetary environments are radically different from Earth's. For example, the Moon's lack of an atmosphere causes extreme temperature fluctuations (see Fig. 1). A model predictive control (MPC) system can potentially remedy this issue as MPCs are a control technique that can optimize energy usage and temperature levels through calculated control actions [4].

This research approach raises the following questions: how might an algorithm driven by data collected on Earth handle the constraints of a lunar environment?

Methodology

Dataset Description

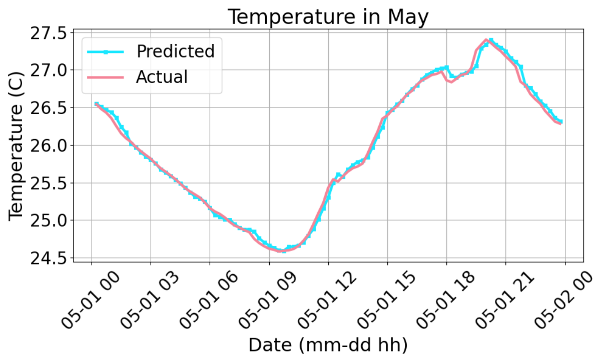

Figure 2: The predictions of the linear regression model closely follow actual values.

- Using Pecan Street's database, HVAC and photovoltaic data were collected in 15-minute intervals from May 1, 2023, to October 31, 2023, from House 4031 in Austin, Texas [5].
- Using Solcast's API, outdoor temperature and Global Horizontal Irradiance (GHI) data were collected in 30-minute intervals from May 1, 2023, to October 31, 2023 in Austin, Texas [6].
- Using data from the Lunar Reconnaissance Orbiter's (LRO) surface pushbroom mapper, bolometric temperature and radiance data were averaged for each local timestep [7]. The same was done for bolometric temperature in the LRO's Polar Cumulative Product (PCP) datasets [8]. The PCP datasets provided winter and summer data at the lunar north and south poles.

Choosing a model

A linear regression model was chosen to model an HVAC's temperature control ability. A series of machine learning models were tested and linear regression produced the best results (see Fig. 2).

Formulating the MPC (MPC)

An MPC that simulated a building with an energy system consisting of a solar panel, battery, and a connection to the grid was modified [9]. Using Pecan Street and Solcast data, the weights of the MPC were reconfigured to simulate a house in Austin, Texas [5, 6]. The formulation of the MPC are discussed in Equations 1-7. The rationale is as follows:

- Equation 1 seeks to maximize thermal comfort while minimizing energy consumption.
- Because the Texan house lacked a battery to store energy, any energy drawn from the grid was immediately used, hence constraint 4 and 6.
- Most commercial solar panels have efficiencies of 17-20%, resulting in constraint 7 [10].

Simulating Lunar Conditions

Bolometric temperature is defined as the temperature of a blackbody having the same mean frequency as the electromagnetic spectrum [11]. Because surface temperature falls within this specturum, bolometric temperature is considered a proxy for surface temperature.

Data collected from the LRO's pushbroom mapper is not stationary, meaning solar radiance and bolometric temperature are not constrained to one area. While the PCP datasets are constrained to each lunar pole, they lack solar radiance data. To address this limitation, solar radiance data collected from the pushbroom data for May 1, 2023, was used as a subsitute. The small coeffcient related to solar radiance–4.69×10^{-5}–may minimize the effects of data scarcity.

In simulating an HVAC under lunar conditions, we assume that the lunar space

Formulation of the MPC

$$J = \min \sum_{t=0}^{N} |\gamma \times \text{HVAC Power}_t| + (\text{room temp}_t - \text{room temp}_{\text{desired}})^2 \tag{1}$$

subject to

$$\begin{bmatrix} \text{room temp}_{t+1} \\ \text{battery E}_{t+1} \end{bmatrix} = A \begin{bmatrix} \text{room temp}_t \\ \text{battery E}_t \end{bmatrix} + B \begin{bmatrix} \text{HVAC power}_t \\ \text{PV power}_t \\ \text{grid power}_t \end{bmatrix} + E \begin{bmatrix} \text{outside temp}_t \\ \text{irradiance}_t \\ \text{internal gain}_t \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} -1000 \\ -500 \\ -1000 \end{bmatrix} \leq D \begin{bmatrix} \text{HVAC power}_t \\ \text{PV power}_t \\ \text{grid power}_t \end{bmatrix} + G \begin{bmatrix} \text{outside temp}_t \\ \text{irradiance}_t \\ \text{internal gain}_t \end{bmatrix} \leq \begin{bmatrix} 1000 \\ 500 \\ 1000 \end{bmatrix} \tag{3}$$

$$\text{battery E}_t = 0 \tag{4}$$

$$-10 \leq \text{HVAC power}_t, \text{grid power}_t \leq 20 \tag{5}$$

$$\text{HVAC power}_t = \text{grid power}_t \tag{6}$$

$$0 \leq \text{PV power} \leq 0.2 \times \text{irradiance}_t \tag{7}$$

where:

- γ serves as the price for powering the HVAC. It is set to 4.322.
- room $\text{temp}_{\text{desired}}$ is the desired room temperature which is 23° Celsius
- A are the weights for the system: room temperature and battery energy level.
- B are the weights for the control inputs: HVAC, PV, and grid power.
- E are the weights for the external disturbances: outside temperature, irradiance, internal gain.
- D and G are weights for the mixed input constraints.

MAPE	RMSE
0.305%	0.138

Table 1: Mean Absolute Percentage Error (MAPE) (see Eq. 8) and Root Mean Squared Error (RMSE) (see Eq. 9).

habitat replicates the configurations of the house whose data was used to calibrate the Earth MPC.

Results

Modeling an HVAC system on Earth

Pecan Street and Solcast data were used to calibrate the MPC (see Eq. 1-7) to simulate an HVAC system on Earth, resulting in the weights listed in Equation 10. These weights accurately simulated an HVAC system, producing the error rates in Table 1.

$$MAPE = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{y_i - \hat{y}_i}{y_i} \right| \tag{8}$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2} \tag{9}$$

where:

- y_i: Actual temperature at time i
- $\hat{y}_i$: Forecasted temperature at time i
- n: Total number of observations

Using the cost function detailed in Equation 1, it was determined that the MPC outperformed the HVAC system (see Fig. 3). For temperatures to approach the desired temperature, more grid and photovoltaic power need to be consumed (see Fig. 4, 5, and 6).

Modeling an HVAC system on the Moon

A Lunar MPC Gone Wrong

Should an MPC use the weights derived from Pecan Street Earth data (see Eq. 10) and be exposed to lunar conditions, the MPC malfunctions. The subzero space is not heated fast enough (see Fig. 7).

Altering the weights

A reliance on heating rather than cooling resulted in matrices B and E's weights to be altered (see Eq. 11). These weights were arrived at heuristically.

While these weights allowed MPCs to heat the space to the desired temperature, the HVAC had to run at 500 kW–a quantity significantly greater than an MPC on Earth (see Fig. 8 and 9). Operating the MPC at the lunar poles required a cost of over a million, an amount significantly greater than the cost of operating an MPC on Earth (see Fig. 10).

Using lunar technology on Earth

An MPC using lunar weights (see Eq. 11) and exposed to Earth conditions also malfunctions: heating the room to a crisp 34°C instead of cooling the space (see Fig. 11).

Discussion

This study demonstrates that the following methodology holds in HVAC management on the Moon:

1. collect Earth data
2. alter the weights of a linear MPC so that it best reflects conditions on Earth
3. alter the weights of an MPC built on Earth so that it satisfies the constraints of a lunar environment

$$A = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} -0.02 & 0.03 & -0.02 \\ 0 & 0 & 0 \end{bmatrix}, \quad E = \begin{bmatrix} -3.7 \times 10^{-4} & 4.69 \times 10^{-5} & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{10}$$

$$A = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0.02 & 0.03 & 0.02 \\ 0 & 0 & 0 \end{bmatrix}, \quad E = \begin{bmatrix} 3.7 \times 10^{-4} & 4.69 \times 10^{-5} & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{11}$$

The transference of technology between the Earth and the Moon might not be one-to-one. An MPC using Earth weights but exposed to lunar conditions is ineffective, and the same can be said for an MPC using lunar weights but exposed to Earth conditions. What this study posits is that planetary technology may be derived from Earth technology.

Once recalibrated, a model driven by data collected on Earth can handle the constraints of a lunar environment but with greater operational cost. Most of this cost could be incurred when heating the environment during periods of extreme temperatures. Figures 1, 8, and 9 provide evidence of this. Temperatures at the lunar north and south poles remain below -200°C until local timestep 20. Up until this point, the HVAC system has not converged to the desired temperature and the HVAC's power consumption remains at 500 kW.

As demonstrated in Figure 10, the lunar south pole during the summer accrues the lowest cost. This affirms NASA's decision to establish the Artemis Base Camp at the lunar south pole, an area prized for its potential access to ice and other mineral resources [12].

Limitations & Future Work

Predicting radiance

A supervised machine learning model trained on LRO's pushbroom mapper data could be used to predict accurate radiance data for polar seasonal data. This model can be used to simulate what temperature and solar radiance levels are at other lunar locations.

Reinforcement learning

The design of this study's MPC was offline. Once the weights of the MPC are adjusted to satisfy the constraints of the environment, the MPC is deployed in a simulation and the weights are never modified. A reinforcement learning-based MPC could eliminate this offline design constraint and achieve superior performance to traditional MPCs [13].

EnergyPlus models

The size of the home, efficiency of the HVAC system, and occupant behavior can influence the energy consumption of HVAC systems, yet are not modeled by the study's MPC. Additionally, the study's assumption that the lunar space habitat mirrors the house that was used to calibrate the Earth MPC may prove to be too rigid to researchers. Adopting EnergyPlus models as a method of MPC and simulation mitigates both of these limitations as various building architectures can be evaluated.

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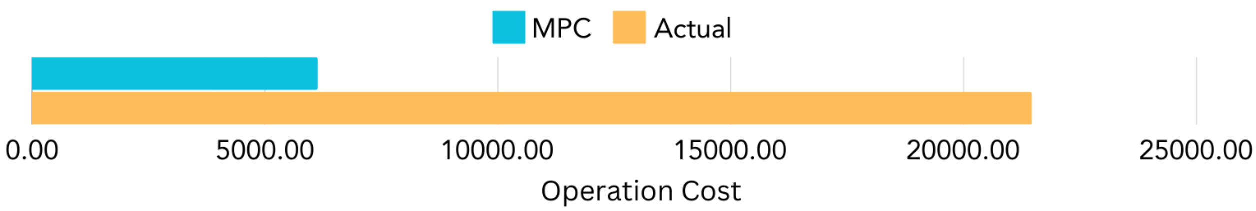

Figure 3: Comparison of operational costs of HVAC systems in Austin, Texas.

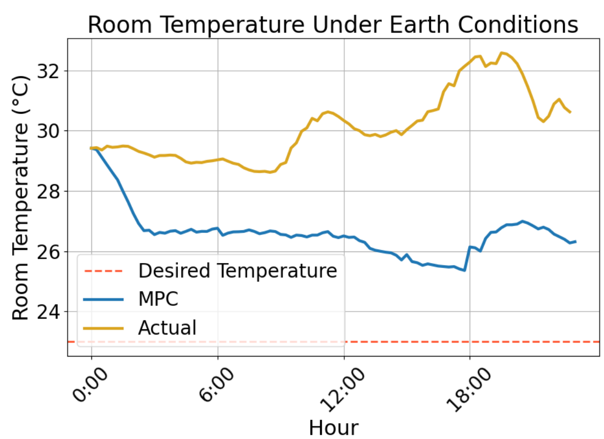

Figure 4: Final room temperature is within 3 °C of desired temperature.

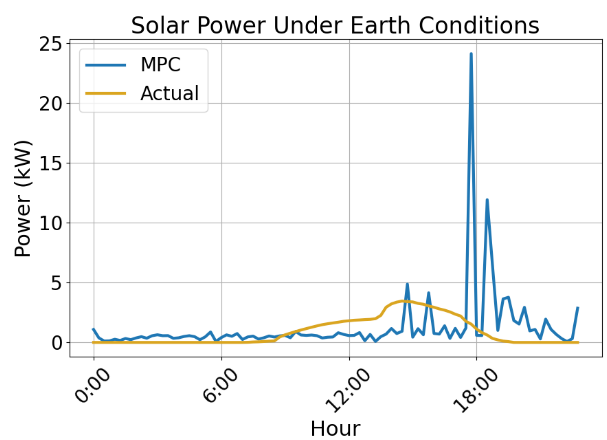

Figure 6: Actual and MPC solar power usage spikes during the afternoon.

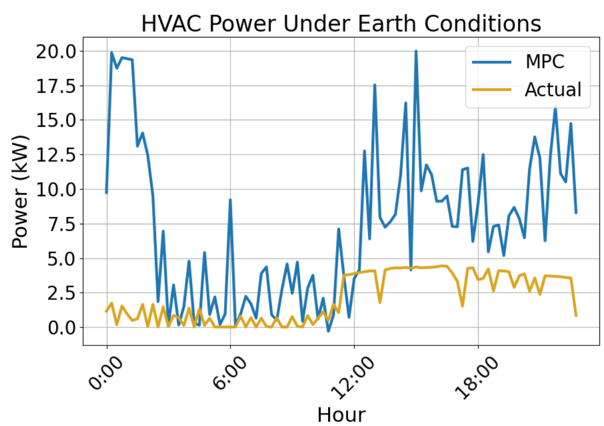

Figure 5: Actual and MPC HVAC usage spikes during the afternoon and evening.

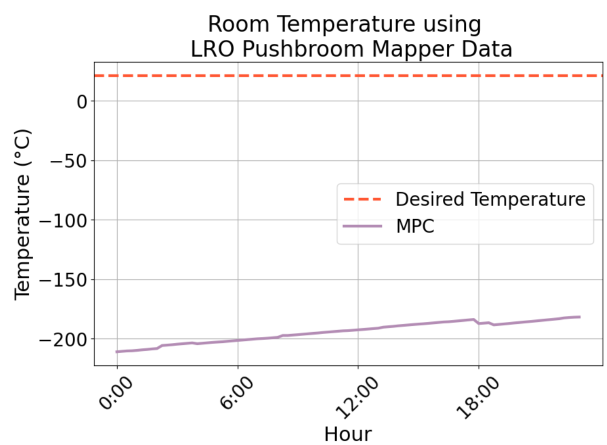

Figure 7: A lunar MPC using weights derived from Earth data.

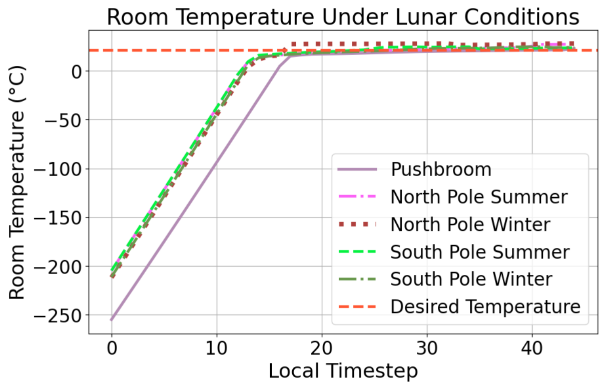

Figure 8: An MPC using lunar weights was exposed to different lunar seasonal conditions, exhibiting similar behavior across all scenarios.

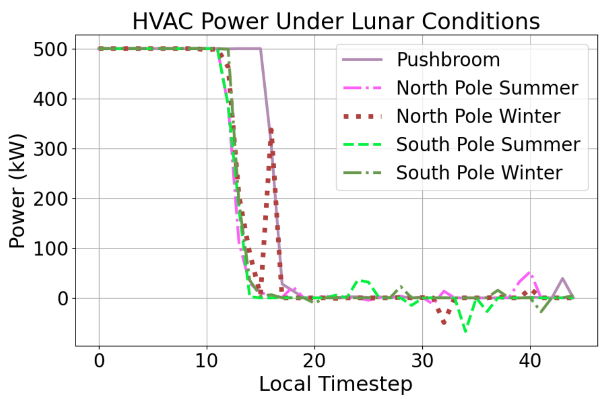

Figure 9: While all HVAC power levels eventually converge to 0, the MPC exposed to pushbroom data took longer.

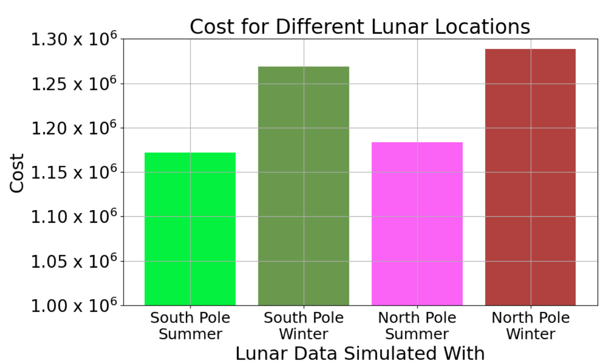

Figure 10: An MPC using lunar weights tested in different seasons.

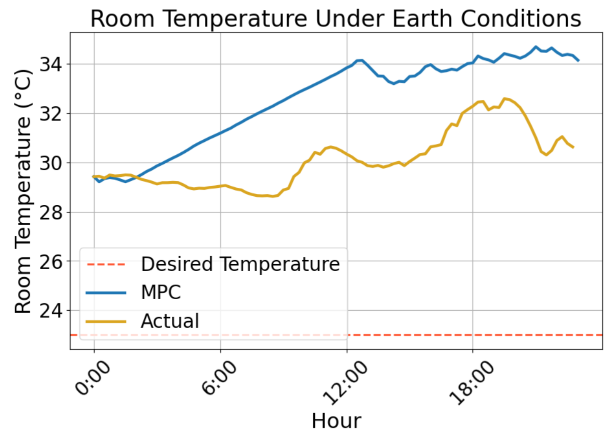

Figure 11: An Earth MPC using lunar weights.

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References

[1] Su Curley et al. "Deep Space Habitat ECLSS Design Concept". In: *42nd International Conference on Environmental Systems*. DOI: 10.2514/6.2012-3417. eprint: https://arc.aiaa.org/doi/pdf/10.2514/6.2012-3417. URL: https://arc.aiaa.org/doi/abs/10.2514/6.2012-3417.

[2] *Heating, Ventilation and Air-Conditioning Systems, Part of Indoor Air Quality Design Tools for Schools*. 2023. URL: https://www.epa.gov/iaq-schools/heating-ventilation-and-air-conditioning-systems-part-indoor-air-quality-design-tools.

[3] Sherry Stokes. *A Smarter Habitat for Deep Space Exploration*. 2019. URL: https://www.cmu.edu/news/stories/archives/2019/september/deep-space-habitat.html.

[4] *What is Model Predictive Control?* MATLAB. 2025. URL: https://www.mathworks.com/help/mpc/gs/what-is-mpc.html.

[5] *Pecan Street Dataport*. Pecan Street. URL: https://www.pecanstreet.org/dataport/.

[6] *Solcast API*. Solcast. URL: https://docs.solcast.com.au/.

[7] *LRO DLRE RDR, calibrated with pointing location geometry*. National Aeronautics and Space Administration. URL: https://pds.nasa.gov/ds-view/pds/viewDataset.jsp?dsid=LRO-L-DLRE-4-RDR-V1.0.

[8] *Collection Information*. National Aeronautics and Space Administration. URL: https://pds.nasa.gov/ds-view/pds/viewCollection.jsp?identifier=urn%3Anasa%3Apds%3Alro_diviner_derived1%3Adata_derived_pcp&version=1.0.

[9] Sergio Lucia. *MPC and Deep Learning*. 2018.

[10] *Photovoltaic Energy Factsheet*. Center for Sustainable Systems, Unviersity of Micigan.

[11] P. C. Myers and E. F. Ladd. “Bolometric Temperatures of Young Stellar Objects”. In: 413 (Aug. 1993), p. L47. DOI: 10.1086/186956.

[12] *Lunar Living: NASA’s Artemis Base Camp Concept*. 2020. URL: https://blogs.nasa.gov/artemis/2020/10/28/lunar-living-nasas-artemis-base-camp-concept/.

[13] Min Lin et al. “Reinforcement Learning-Based Model Predictive Control for Discrete-Time Systems”. In: *IEEE Transactions on Neural Networks and Learning Systems* 35.3 (2024), pp. 3312–3324. DOI: 10.1109/TNNLS.2023.3273590.