Attractor Dynamics Analysis of Beehive Data from MSPB Dataset
ePortfolio Entry 2 - Module 4

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Abstract

This report analyzes the environmental regulation behavior of a honeybee colony (tag number 202204) based on sensor data from the MSPB dataset (Multi-Sensor dataset with Phenotypic trait measurements from honey Bees). Applying attractor dynamics theory through state space reconstruction, phase portraits, vector field analysis, and topological mapping, we reveal the dynamic characteristics, stable patterns, and self-organizing behavior of the beehive system. Results indicate that the bee colony demonstrates strong environmental self-regulation capabilities, exhibiting clear attractor structures in temperature and humidity dimensions.

Keywords: Attractor Dynamic

1 Introduction

Honeybee colonies, as complex biological systems, maintain stable internal hive environments through collective behavior. This study employs methods from nonlinear dynamics, specifically attractor dynamics, to characterize and analyze the dynamic interplay between temperature and humidity within honeybee hives(Khoury et al., 2011). The concept of attractors provides a framework for understanding system stable states, helping to reveal how bee colonies respond to environmental disturbances and maintain suitable conditions.

The data analyzed in this study comes from the MSPB dataset (Zhu et al., 2023), a comprehensive one-year longitudinal dataset collected between April 2020 and April 2021 from 53 hives in two apiaries in Québec, Canada. This dataset uniquely combines continuous sensor data (including temperature, humidity, and audio features) with expert-annotated phenotypic measurements such as hive population, brood cells, Varroa destructor infestation levels, defensive and hygienic behaviors, honey yield, and winter mortality. Our analysis focuses specifically on beehive 202204, examining the temperature-humidity dynamics from the perspective of attractor theory. The thesis code can be accessed through the GitHub repository at code link.

2 Data and Methods

2.1 Dataset Description

The analysis is based on sensor data from the MSPB dataset (Multi-Sensor dataset with Phenotypic trait measurements from honey Bees), which includes the following key variables:

Table 1: Beehive Monitoring Variables

Variable	Description
`published_at`	Timestamp
`temperature`	Temperature
`humidity`	Humidity
`tag_number`	Beehive identification (analysis limited to beehive 202204)
`hive_power`	Hive power
`geolocation`	Geographic location information
`hz_*`	Multiple frequency variables

Beehive 202204 was specifically selected for this analysis because it contains the most complete and usable data within the MSPB dataset, particularly during the summer months of July and August. With approximately 4,000 measurement points per month (Zhu et al., 2023), this beehive provides a robust dataset for analyzing environmental dynamics. The high temporal resolution of the measurements allows for detailed characterization of the temperature-humidity state space and attractor patterns.

While the MSPB dataset also contains rich phenotypic measurements including beehive population, brood cell counts, Varroa mite infestation levels, defensive and hygienic behaviors, honey yield, and winter mortality, our current analysis focuses exclusively on the sensor data related to temperature and humidity dynamics. The data was collected as part of a comprehensive study conducted between April 2020 and April 2021 across 53 hives in Québec, Canada.

2.2 Analytical Methods

This study employs the following dynamical analysis methods:

- **State Space Reconstruction**: Using temperature and humidity as primary state variables to construct a two-dimensional state space (Deyle and Sugihara, 2011)
- **Phase Portrait Analysis**: Visualizing system trajectories by calculating velocity vectors to identify stable and unstable regions (Eckmann et al., 1987)
- **Vector Field Analysis**: Computing velocity vectors on a state space grid to demonstrate system evolution trends at different state points (Letellier et al., 1995)
- **Topological Mapping (Density Analysis)**: Using kernel density estimation to identify frequently visited regions in state space (attractors)(Deyle and Sugihara, 2011)

- **Regression Analysis**: Building regression models to predict state changes and quantify system feedback mechanisms

3 Results Analysis

3.1 State Space Reconstruction

The state space plot (Fig. 1) provides a direct visualization of the system's trajectory in temperature-humidity coordinates without calculating velocity vectors. A strong inverse relationship between temperature and humidity is evident across most of the state space, appearing as a diagonal trend from the upper left (low temperature, high humidity) to the lower right (high temperature, low humidity). The majority of trajectories follow this diagonal pattern, suggesting a fundamental thermodynamic relationship in the beehive environment. Significant clustering and dense trajectory patterns appear in two main regions: around 32–35°C with 45–65% humidity and around 5–10°C with 75–80% humidity. The trajectories show increased complexity and non-linear patterns at the higher temperature range (30–35°C), with circular and looping patterns suggesting active regulation by the bee colony. Some outlier trajectories deviate from the main diagonal trend, potentially indicating periods of transition or disturbance in the hive environment. This state space reconstruction forms the foundation for the subsequent dynamical analyses and clearly demonstrates that the beehive system does not behave as a simple linear system, but exhibits complex, regulated patterns with preferred regions in the state space.

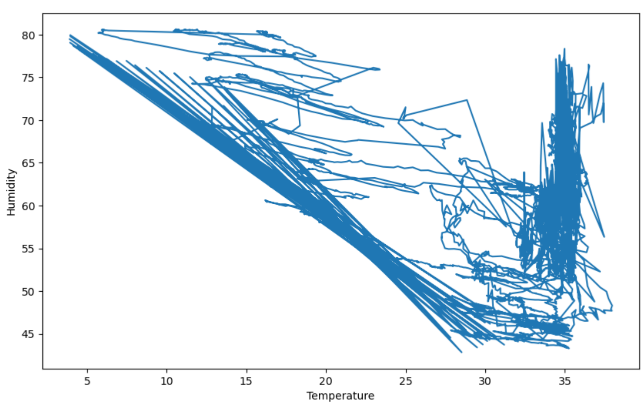

Figure 1: State space plot of temperature-humidity system

3.2 Phase Space Analysis

The phase portrait (Figure 2) displays the trajectories and velocity vectors of the temperature-humidity system. Observations indicate that the system exhibits distinct directional flow, particularly in high-temperature regions (30–35°C). Vector directions indicate multiple convergence zones, suggesting the system has stabilizing tendencies at specific state combinations. Temperature and humidity demonstrate complex nonlinear relationships, with different interaction patterns across different regions. Higher vector density in high-temperature regions (> 30°C) indicates more frequent regulation behavior by the bee colony in this temperature range.

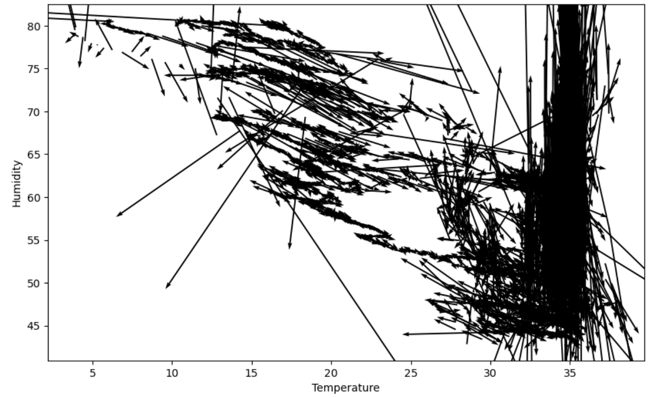

Figure 2: Phase Portrait of Beehive Dynamics

3.3 Vector Field Analysis

The vector field plot (Figure 3) provides a macroscopic view of the system's overall flow tendencies. It clearly shows that the system's primary flow direction converges toward the upper right region (30–33°C, 60–65% humidity). Distinct boundaries exist in the flow field, indicating different dynamical behaviors in different regions. Vector strength (arrow length) varies significantly across regions, suggesting different response intensities to deviations from different stable states. Vectors from peripheral regions (such as high-temperature, low-humidity areas) point toward the main attractor region, indicating the system's tendency to return to typical stable states.

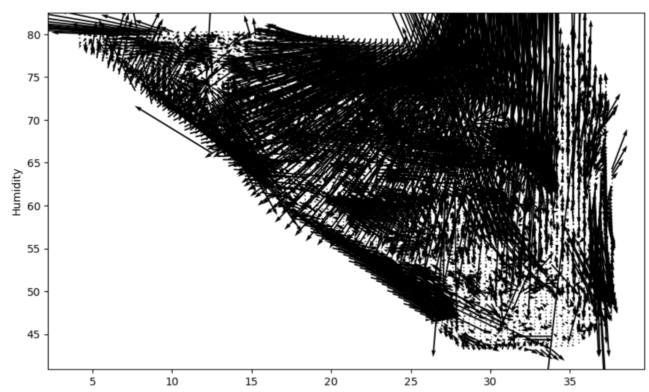

Figure 3: Vector Field of Beehive Dynamics

3.4 Topological Analysis

The topology plot (Figure 4) reveals the probability distribution of the state space through density contours. Two distinct high-density regions (attractors) exist: a primary attractor centered at 32–33°C and 60–62% humidity, with density values up to 0.018, and a secondary attractor located at 33–34°C and 45–47% humidity, with density values around 0.003. Attractors exhibit elliptical shapes with the major axis along the diagonal, indicating correlation between temperature and humidity changes. The primary attractor's area and density are significantly greater than the secondary attractor, suggesting the system preferentially operates in this state. The low-density region between the two attractors suggests potential transition mechanisms between these two stable states.

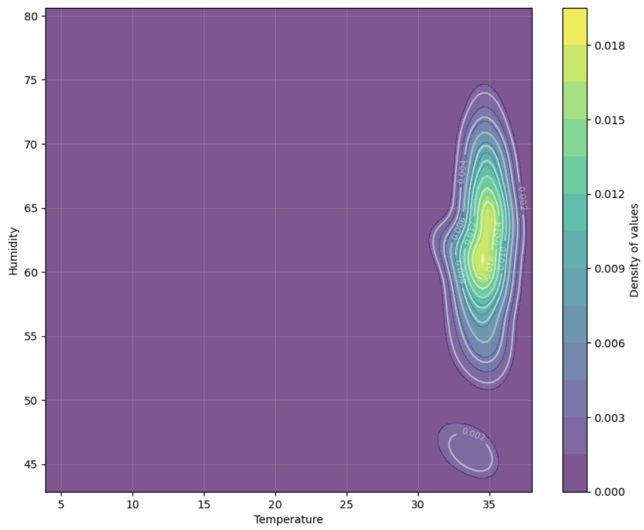

Figure 4: 2D Topology Piloy - Temperature vs. Humidity

3.5 Regression Analysis

The analysis aimed to quantify the influence of current states (temperature and humidity) on future system changes (temperature and humidity changes). The model was developed using a **Vector Autoregressive (VAR)** approach, which is suitable for capturing the dynamic interdependencies between the variables over time. The VAR model estimates how past values of temperature, humidity, and their changes affect future values of these variables. While the model captures significant relationships, the overall explanatory power of individual equations is limited, with relatively low R-squared values for each equation. The VAR results are presented in Table 2.

3.5.1 Model Specification

The VAR model includes the following system of equations, where the temperature change, humidity change, and their lags are used as predictors:

$$\begin{aligned} \Delta T_{t+1} &= \beta_0 + \beta_1 \cdot T_t + \beta_2 \cdot H_t + \cdots + \epsilon_t \\ \Delta H_{t+1} &= \gamma_0 + \gamma_1 \cdot T_t + \gamma_2 \cdot H_t + \cdots + \epsilon_t \end{aligned} \tag{1}$$

Where:

- ΔT_{t+1} is the change in temperature at time $t + 1$,
- ΔH_{t+1} is the change in humidity at time $t + 1$,
- T_t and H_t are the current temperature and humidity,
- The ellipsis ($\cdots$) represents the lagged variables (e.g., previous time steps for temperature and humidity).

3.5.2 Model Results

The VAR regression results for temperature and humidity changes are summarized in Table 2. The results include the coefficients, standard errors, t-statistics, and p-values for each variable and lag, as well as the model's overall fit statistics.

Table 2: VAR Regression Results (N=12,429)

Statistic	**Value**
R-squared (Temperature)	0.021
R-squared (Humidity)	0.019
F-statistic (Temperature)	131.1
F-statistic (Humidity)	119.8
Prob (F-statistic)	4.38e-57
Coefficients (Temperature)	0.0161
Coefficients (Humidity)	-0.0331
Condition Number	821

3.5.3 Diagnostic Analysis

Three primary issues were identified: (1) Multicollinearity between predictors, as indicated by some NaN values in the standard errors of lagged coefficients, particularly for temperature and humidity, suggesting that these variables may be highly correlated, (2) Inherent nonlinear dynamics suggested by the system's residuals and the potential instability of some lagged coefficients, which may require further investigation using nonlinear modeling techniques, and (3) the large sample size (N=12,429), which may have contributed to amplifying these computational challenges.

4 Discussion

4.1 Bee Colony Environmental Regulation Mechanisms

The analysis results reveal the efficient environmental regulation capabilities of the bee colony. The presence of the primary attractor (32-33 °C, 60-62% humidity) indicates that the colony actively maintains these specific environmental conditions, which align with the optimal temperature range for brood development (33-36 °C)(Mucci et al., 2021). The strong tendency of the system toward the primary attractor suggests that collective colony behavior effectively resists external environmental fluctuations. The existence of a secondary attractor may reflect alternative stable states under different physiological demands or external conditions.

4.2 Dynamical Characteristics and Biological Significance

The state space reconstruction (Image 4) reveals the fundamental temperature-humidity relationship throughout the beehive's operational range, showing both the broad thermodynamic constraints and the regions where active regulation occurs. The dual attractor structure suggests the colony may have two operational "modes," with the primary mode focused on brood environment maintenance and the secondary mode potentially related to other functions (such as honey storage, ventilation). The temperature-humidity inverse correlation likely reflects the behavioral strategy of increasing ventilation to reduce humidity under high-temperature conditions(Rodríguez-Vásquez et al., 2024). The consistency of the vector field indicates strong buffering capacity against environmental disturbances, which is crucial for maintaining colony stability.

4.3 Methodological Limitations

The current analysis has several limitations. Only temperature and humidity variables were considered, while the actual system may be influenced by multiple factors. The analysis does not fully account for the impact of daily cycles and seasonal variations on the system. Linear regression cannot capture the complex nonlinear dynamic characteristics of the system. Additionally, observational data cannot determine the causal direction of temperature-humidity changes (whether bee colony behavior causes or responds to environmental changes) (Yuan and Shou, 2022).

5 Conclusion

The beehive system exhibits clear attractor dynamics characteristics, forming stable states primarily in the region of 32-33 °C and 60-62% humidity. The system contains a secondary attractor (33-34 °C, 45-47% humidity), suggesting the colony may have multiple operational modes. Vector field and phase space analysis indicate that the bee colony possesses strong environmental regulation capabilities, actively pulling the system back to stable states. The complex relationship between temperature and humidity suggests that the colony's environmental regulation is a highly coordinated process(Stabentheiner et al., 2010).

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