From Chaos to Control: Leveraging Multi-Expert Strategies for Predictive Accuracy in Autonomous Systems

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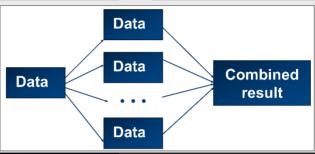[a] Center for econometrics and business analytics (CEBA), St. Petersburg State University (SPBU), Saint-Petersburg, Russia
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Introduction

Modern methods for managing complex dynamic systems rely on advanced predictive technologies and algorithms. One of the key challenges is anticipating chaotic system behavior in unstable environments, as these involve unpredictable changes represented by complex nonlinear differential equations and incomplete disturbance data. Traditional statistical methods often fall short, leading to a need for innovative computational approaches that leverage high-performance computing and AI to improve prediction accuracy for automated control.

One effective solution is the Multi-Expert System (MES) framework, which coordinates multiple independent Software Experts (SEs) to enhance predictions. Unlike decentralized multi-agent systems, MES integrates preliminary predictions from each SE through a supervisory expert, similar to ensemble learning methods. This collaborative approach boosts the reliability and robustness of predictions, making MES particularly suitable for addressing the complexities of chaotic systems and enabling more effective automated control in robotics.

Data Model

The research utilizes an additive model to represent time series data, isolating systematic trends and observational noise:

$$z_k = x_k + v_k, \quad k = 1, \ldots, N$$

where the systemic component x_k, $k = 1, \ldots, N$ represents the regular dynamics of the process being predicted, which is utilized in the formation of control decisions, and v_k, $k = 1, \ldots, N$ is the random component reflecting observational noise that needs to be filtered.

A focus on the nature of noise suggests the application of a Huber-type Gaussian model to better depict non-stationary characteristics encountered in chaotic environments:

$$v \in (1 - \varepsilon)N(0, \sigma_1^2) + \varepsilon N(0, \sigma_2^2), \quad \varepsilon \in (0, 1), \quad \sigma_2 >> \sigma_1,$$

where the contamination coefficient ε is usually significantly less than 1. For heteroscedastic non-stationary processes, the variance may change over time $\sigma = \sigma(t)$.

Evaluation Metrics

Mean Squared Error (MSE)

$$MSE = \left(\frac{1}{N_p}\sum_{k=1}^{N_p}(\tilde{x}_{k+\tau} - x_{k+\tau})^2\right)^{\frac{1}{2}}$$

Mean Absolute Deviation (MAD)

$$MAD = \frac{1}{N_p}\sum_{k=1}^{N_p}|\tilde{x}_{k+\tau} - x_{k+\tau}|.$$

These metrics help evaluate how effectively the multi-expert system enhances decision-making capabilities in dynamic settings.

Methodology

The primary object of this study is the **Multi-Expert System (MES)** framework, which utilizes a collaborative approach involving multiple **Software Experts (SEs)** to enhance predictive outcomes. Each expert serves as a weak classifier, generating preliminary predictions based on retrospective data. A supervising expert then consolidates these predictions into a cohesive final decision, akin to ensemble methods like stacking algorithms in machine learning. This methodology capitalizes on the structural redundancy of the multi-expert approach, ultimately aiming to mitigate the impact of chaotic elements within observational data.

Predictive Framework:

The MES framework is designed to adaptively analyze and predict chaotic behaviors in dynamic and unstable environments. It integrates various independent SEs, each offering unique strengths in prediction, thereby improving overall accuracy and robustness.

Challenges of Chaos:

The research addresses the difficulties associated with chaotic systems, such as their sensitivity to initial conditions and nonlinear dynamics. The MES framework is proposed as a solution that can effectively manage these challenges by enhancing adaptability and resilience.

Empirical Evaluation:

The study employs a rigorous empirical analysis to validate the efficacy of the MES approach, utilizing metrics such as Mean Squared Error (MSE) and Mean Absolute Deviation (MAD) to assess prediction accuracy across different configurations of observation window sizes and prediction horizons.

Multi-Expert Data Analysis Model:
•Software Experts (SEs)
Each SE acts as a weak classifier, generating preliminary predictions based on retrospective data.
•Supervisory Expert
Aggregates the outputs from SEs into a comprehensive prediction, mimicking ensemble decision-making strategies such as stacking algorithms.

Mathematical Framework:
•Predictive Function Transformation
Each SE's prediction can be represented as a transformation of input data utilizing polynomial approximations through a moving window, designed for rapid fluctuations, aimed at capturing momentary trends.

Bayesian Risk Analysis:
Predictions from each SE are combined using weighted averages based on confidence levels derived from performance metrics. This method accounts for varying accuracies among SEs and enhances overall prediction reliability.

Empirical Results

The MES was benchmarked against conventional linear extrapolators, demonstrating superior predictive accuracy particularly noteworthy in chaotic scenarios.

Figure 1 illustrates how varying observation window sizes (L=60, 120, 180) and prediction horizons (τ=5, 15, 30) affect prediction quality. Errors increase with larger horizons, significant in chaotic robotic systems due to sensitivity to initial conditions. While increasing the window size enhances smoothing, it does not reduce bias from chaotic behavior, posing challenges for precise real-time applications.

Table 1. Dependence of Predicting Quality Indicators on Model Parameters

τ=3, L:	60	120	180
MSE	8.99	12.61	14.56
MAD	5.80	7.41	9.17
L=120, τ:	5	15	30
MSE	8.99	12.61	14.56
MAD	5.80	7.41	9.17
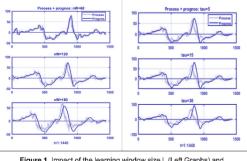
Figure 1. Impact of the learning window size L (Left Graphs) and prediction depth τ (right graphs) on predict quality
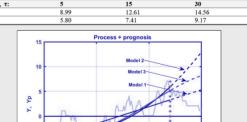
Figure 2. Illustration of the low effectiveness of SEs based on statistical extrapolation of observation series

Conclusion and Future Directions

This study presents the innovative Multi-Expert System (MES), which highlights the effectiveness of employing an ensemble of simple Software Experts for decision-making under chaotic conditions.

Future research will prioritize:

•Advancing state estimation models for unpredictable environments.
•Addressing MES limitations through theoretical frameworks that utilize entropy measures for control theory in indeterminate conditions.

Acknowledgement