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A Piecewise Hidden Markov Model for Degradation and Maintenance

Hidden Markov Models (HMMs) are increasingly recognized in reliability engineering as valuable tools for monitoring systems where the true operational state is not directly observable and must be inferred from certain indicators provided by a control system. Accurate estimation of these hidden health states and prediction of failures are crucial for minimizing unexpected downtime and optimizing operational costs. While recent literature has demonstrated the utility of HMMs in estimating dependability measures, such as identifying failed components and assessing system reliability, the explicit integration of maintenance actions into these models remains an evolving area of study.

Traditional HMM applications often assume time-homogeneous transition dynamics, which may not capture the discontinuous physical effects of a maintenance intervention. Specifically, a maintenance action introduces an instantaneous restorative shock and often alters the subsequent aging rate of the system, which does not agree with the homogeneous degradation assumption.

To address this gap within a structured probabilistic framework, this paper presents a piecewise, time-inhomogeneous HMM approach designed to incorporate trend changes in system degradation. We model the degradation level over a finite state space, partitioned into functional and failure states. The system's operational evolution is decomposed into distinct chronological phases.

For robust parameter estimation, we propose an adapted Expectation-Maximization (EM) algorithm. A new algorithm is discussed to decode the hidden state trajectory across these varying temporal regimes. The proposed piecewise framework allows for the modeling of systems where the transition matrix structurally changes due to external occurrences. This framework provides a practical method to isolate natural degradation from repair actions, for instance, facilitating a rigorous evaluation of maintenance effectiveness in HMM-based reliability studies to determine the optimal timing for future scheduled interventions. Furthermore, this approach can be considered for other situations where the transition matrix changes due to external events, such as the arrival of a disruptive shock.

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