Modeling Infrastructure Degradation from Visual Inspections Using Network-Scale State-Space Models

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Motivation

- Developing a deterioration model for network-scale visual inspections.
- Estimating the deterioration rate from visual inspection data.
- Quantifying the uncertainty of visual inspections.

Contributions

The main contributions of this work are:

- **Model the deterioration** behaviour based on visual inspection data taken from a network of bridges.
- **Quantify the uncertainty of the inspectors** performing visual inspections.
- **Quantify inspections uncertainty** based on the deterioration state of the structural element and the inspectors uncertainty.
- **Validate and verify** the proposed methods with real and synthetic datasets respectively.

Deterioration Behaviour Described by Kinematics:

$$\underbrace{\begin{bmatrix} x_t \\ \dot{x}_t \\ \ddot{x}_t \end{bmatrix}}_{\boldsymbol{x}_t} = \underbrace{\begin{bmatrix} 1 & \Delta t & \frac{\Delta t^2}{2} \\ 0 & 1 & \Delta t \\ 0 & 0 & 1 \end{bmatrix}}_{\boldsymbol{A}} \cdot \underbrace{\begin{bmatrix} x_{t-1} \\ \dot{x}_{t-1} \\ \ddot{x}_{t-1} \end{bmatrix}}_{\boldsymbol{x}_{t-1}} + \underbrace{\begin{bmatrix} w_t \\ \dot{w}_t \\ \ddot{w}_t \end{bmatrix}}_{\boldsymbol{w}_t}$$

Method: State-Space Models

$$\overbrace{\boldsymbol{x}_t = \boldsymbol{A}\boldsymbol{x}_{t-1} + \boldsymbol{w}_t}^{\text{transition model}}, \quad \underbrace{\boldsymbol{w}_t : \boldsymbol{W} \sim \mathcal{N}(\boldsymbol{w}; \boldsymbol{0}, \boldsymbol{Q}_t)}_{\text{process error}}$$

$$\overbrace{\boldsymbol{y}_t = \boldsymbol{C}\boldsymbol{x}_t + \boldsymbol{v}_t}^{\text{observation model}}, \quad \underbrace{\boldsymbol{v}_t : \boldsymbol{V} \sim \mathcal{N}(\boldsymbol{v}; \boldsymbol{0}, \boldsymbol{R}_t)}_{\text{observation error}}$$

Inspector-Dependent Uncertainty

$$\overbrace{\boldsymbol{y}_t = \boldsymbol{C}\boldsymbol{x}_t + \boldsymbol{v}_t}^{\text{observation model}}, \quad \underbrace{\boldsymbol{v}_t : \boldsymbol{V}(I_j) \sim \mathcal{N}(\boldsymbol{v}; \boldsymbol{0}, \boldsymbol{R}_t(I_j))}_{\text{observation error}}, \overbrace{I_i \in [I_1, I_2, \ldots, I_{\mathtt{I}}]}^{\text{inspectors}}$$

Proposed Degradation Model

State-Dependant Uncertainty

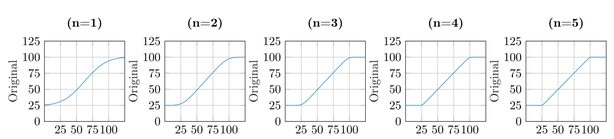


Figure 1. Transformation function $g(.)$ with different n values.

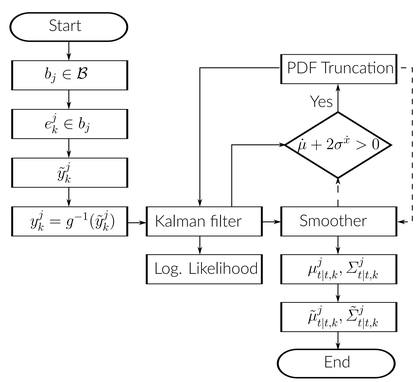
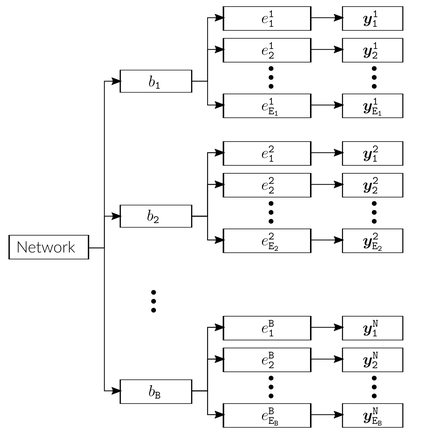


Figure 2. Flowchart of structural deterioration model

Visual Inspections Database

Information hierarchy for the data of a visual inspections system.



Level Attributes	Network Level	Bridge Level	Element Level	Inspections
	Country	Geolocation	Material	Condition
	Province	Traffic Loads	Type	Inspect. Time
	Inspcet. Code	Const. Year	Location	Inspector
	Other Att.	Other Att.	Other Att.	

Figure 3. Information Hierarchy for Visual Inspection System

Example of Inspection Data for a Structural Element:

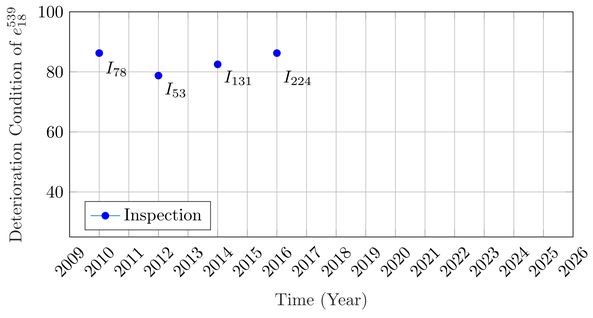


Figure 4. Inspections $\boldsymbol{y}_{18}^{539}$ of Structural Element e_{18}^{539}

Synthetic Inspection Data:

- # Structural Elements $\mathtt{E} = 10827$.
- # Inspectors $\mathtt{I} = 194$.

Results: Verification & Validation

Synthetic Data Analyses

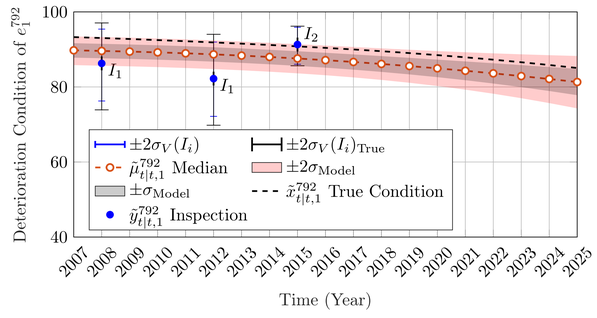


Figure 5. Condition deterioration analysis based on the observations $\tilde{\boldsymbol{y}}_1^{792}$ of the synthetic structural element e_1^{792} with error bars representing the Inspectors true (wide whiskers) & estimated (narrow whiskers) uncertainties.

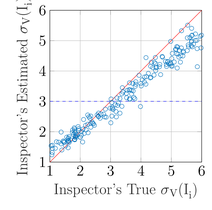


Figure 6. Scatter plot of inspectors true $\sigma_V(I_i)$ vs. estimated $\sigma_V(I_i)$ with a dashed line representing the initial value at the start of the optimization.

Real Data Analyses

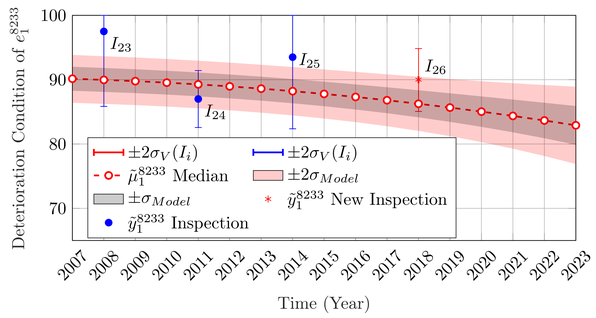
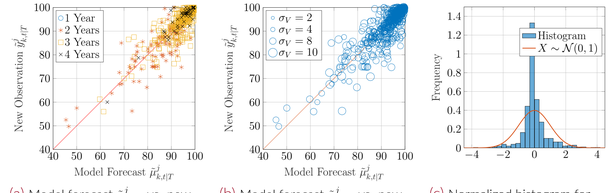


Figure 7. Condition deterioration analysis based on the observations $\tilde{\boldsymbol{y}}_1^{8233}$ of the structural element e_1^{8233}.



(a) Model forecast $\tilde{\mu}_{k,t|T}^j$ vs. new observations $\tilde{y}_{k,t}^j$.

(b) Model forecast $\tilde{\mu}_{k,t|T}^j$ vs. new observations $\tilde{y}_{k,t}^j$.

(c) Normalized histogram for $(\mu_{t|T} - y_t)/\sigma$ (Transformed Space).

Figure 8. Deterioration condition validation for real structural elements.