POMDP based Maintenance Optimization of Offshore Wind Substructures including Monitoring

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Introduction – Offshore wind substructures

Sequential decision making under uncertainty

Deterioration
Fatigue & corrosion

RISK

Information available

….Inspections
Monitoring...

Waves

Source: http://windpowerneikata.blogspot.com/2017/05/wind_power.gif.html

Source: https://www.researchgate.net/figure/Optical-strain-gauges-as-installed-at-a-Belwind-and-b-Northwind


Wind
Maintenance decision problem

‘Pre-posterior decision analysis’...

12²⁰ = 3.8e21 branches
1 second per branch = 1.24e14 years
Maintenance decision problem

‘Pre-posterior decision analysis’…

$12^{20} = 3.8 \times 10^{21}$ branches
1 second per branch = $1.24 \times 10^{14}$ years

Monitoring system?

Computational Requirements!
Proposed POMDP methodology

Partially Observable Markov Decision Process (POMDP)
Proposed POMDP methodology

(1) Able to solve large state problems
(2) Evaluation of the Value of Monitoring
(3) Easy to model/evaluate: Dynamic Bayesian Net

‘Grid-based’ technique
- Finite set of belief points
- Extrapolation/interpolation

‘Point-based’ technique
- ‘Optimally’ reachable beliefs
- Large state space (Robotics)
Proposed POMDP methodology

Methodology (Inspection + Monitoring)

RBI

- Deterioration model
- Repair model
- Inspection model
- Cost model

POMDP

- Dynamic Bayesian Network
- Transition matrix
- Emission matrix
- Monitoring model
- Rewards
- Expected maintenance costs (insp. & monitoring)

POMDP model

[INS+ MON]

POMDP policy
Proposed POMDP methodology

(1) Able to solve large state problems
(2) Evaluation of the Value of Monitoring
(3) Easy to model/evaluate: Dynamic Bayesian Net
Proposed POMDP methodology

1. Able to solve large state problems
2. Evaluation of the Value of Monitoring
3. Easy to model/evaluate: Dynamic Bayesian Net

\[ a_0 \rightarrow a_1 \rightarrow a_2 \rightarrow \ldots \rightarrow a_T \rightarrow E_1 \rightarrow Z_1 \rightarrow Z_2 \rightarrow Z_T \]

\[ \text{Failure prob. (\%) } \]

\[ \text{Time (months)} \]

- MCS
- DBN 30-states
- DBN 200-states
Application: Fatigue deterioration

Fracture mechanics - Paris’ Law

\[ g_{FM}(t) = a_c - \left[ \left( 1 - \frac{m}{2} \right) C \pi^2 \frac{m}{2} \Delta S^m \Delta n + a^{\left(1-\frac{m}{2}\right)}_{t-1} \right]^{2-m} \]
given \( a_0 \)

(1) States: 200

(2) Combined actions

- **Do-nothing** + No inspection
- **Do-nothing** + Inspection
- **Do-nothing** + Monitoring
- **Repair** + No inspection

(3) Transitions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Distribution</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_0 )</td>
<td>EXP</td>
<td>0.2</td>
<td>-</td>
</tr>
<tr>
<td>( a_c )</td>
<td>Determ.</td>
<td>9</td>
<td>-</td>
</tr>
<tr>
<td>( \ln(C) )</td>
<td>Determ.</td>
<td>-33.5</td>
<td>-</td>
</tr>
<tr>
<td>( m )</td>
<td>Determ.</td>
<td>3.5</td>
<td>-</td>
</tr>
<tr>
<td>( \Delta S )</td>
<td>NORMAL</td>
<td>60</td>
<td>10</td>
</tr>
<tr>
<td>( \Delta n )</td>
<td>Determ.</td>
<td>(10^6)</td>
<td>-</td>
</tr>
</tbody>
</table>

Transition matrix:

- Do-nothing
Application: Setting up the model

(4) Observations

**Inspections**

- Mild damage
- Some damage
- Significant damage
- Several damage
- Failure

**Monitoring**

- Low alarm
- High alarm
- Failure

No inspection?
Application: Setting up the model

(5) Rewards / costs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>State 1</th>
<th>...</th>
<th>State 200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do nothing + No inspection</td>
<td>0</td>
<td>0</td>
<td>-500</td>
</tr>
<tr>
<td>Do nothing + Inspection</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>Repair + No inspection</td>
<td>-50</td>
<td>-50</td>
<td>-50</td>
</tr>
</tbody>
</table>

Failure state

*Discount factor: \( \gamma = 0.95 \)

Infinite horizon POMDP - SARSOP

Solving .................
Application: Results

'SARSOP Algorithm': POMDP 200 states

\[ NVoI = Vol - C_{mon} = E(C_0) - E(C_1) - C_{mon} \]
Application: Policy evaluation

‘SARSOP Algorithm’: POMDP 200 states

- No detection
- Mild damage
- Severe damage

Diagram:
- Initial state: $a_0$
- Transitions: $a_1 \rightarrow a_2 \rightarrow \ldots \rightarrow a_T$
- Events: $E_1, E_2, \ldots, E_T$
- States: $Z_1, Z_2, \ldots, Z_T$

Graph:
- Nodes: $a_0, a_1, a_2, \ldots, a_T, E_1, E_2, \ldots, E_T, Z_1, Z_2, \ldots, Z_T$
- Edges: $a_0 \rightarrow a_1, a_1 \rightarrow a_2, \ldots, a_{T-1} \rightarrow a_T, E_1 \rightarrow E_2, E_2 \rightarrow E_T, Z_1 \rightarrow Z_2, Z_2 \rightarrow Z_T$
Discussion & Conclusions

• Estimation of the Value of Monitoring

• Large state space - Reasonable CPU Time

• Only time-variant parameters

• Future:
  ▪ Include time-invariant parameters
  ▪ Compare with finite horizon POMDPs
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Questions?

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