Distributed, hierarchical sensor network enabling park wide control of O&M on demand: a strategic research agenda

Deepwind 2012

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Trondheim, Norway

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ERA NET - AERTOs

Nature
- ERA NET project: Associated European Research and Technology Organisations
- Partners: European RTOs
- Duration: April 2008 - March 2012

Objectives
- Construction of a new, integrated pan-European RTO infrastructure
- Intended result is the alignments of the European Research Area by increasing coordination between national research programmes of a horizontal nature

Activities
- Systematically compare the activity profiles of the participating RTOs
- Identify those activities of common interest (full or variable geometry) which promise added value from greater cooperation
- **Implement first joint activities**
- Identify and develop joint governance mechanisms and structures
Motivation for OMO

Contradicting/competing goals

- Maximize energy production
- Maximize availability
- Maximize lifetime
- Minimize maintenance

Complexity

- Individual wind turbine ➔ wind turbine park
- Onshore ➔ offshore installations

Unifying measure of success

- Costs, costs, costs…
OMO’s Vision

Utilization of hierarchical, smart sensor and control networks to reduce the overall life-cycle costs of off-shore wind farms

- **Level 1**: sensor network in single wind energy plant

- **Level 2**: Plant to plant interaction between the local sensor networks in the wind farm

Outside the scope of the project

- **Level 3**: Farm to farm interaction to optimize grid performance
OMO‘s Objectives

Objective

Definition of a strategic research agenda (SRA) for the development of a distributed, hierarchical sensor network

- for the control of the wind park operation
- for enabling (remote) maintenance-on-demand of offshore wind parks
- and to enable Predictive Health Monitoring (PHM) and Condition Based Maintenance (CBM) strategies

Approach

- Review of the state of the art (presented at the 1st OMO Workshop in 2010)
- Get views from the end users
- Identification of future research needs and gaps and definition of a joint research agenda
- Studies on representative problems
Topics considered within OMO

Level 1: Distributed sensor network in single wind energy plants
- Wireless communication
- Sensor / electronics development and sensor integration
- Smart structures for load control / fluid-structure interaction
- Load and condition monitoring
- Predictive health models
- Control and optimization concepts

Level 2: Plant to Plant interaction between local sensor networks
- Wireless communication
- Distributed monitoring and control architectures
- Distributed optimization and decision making
End-User’s Point of View – Extract from the 1\textsuperscript{st} OMO Workshop

- Although only one maintenance visit per year is planned, seven or more unplanned maintenance visits per year are quite common
  - offshore wind turbines are typically not accessible by boat about 150 days/year and by helicopter about 20 days/year
  - a team of at least three mechanics is needed per visit
  - large spare parts require a vessel

- Monitoring systems are already used e.g. in the drive train or the rotor blades
  - about 150 sensors are currently applied
  - detection of large damages at the rotor blade, of unbalanced masses, of icing or lightning strikes
  - the applied systems are too complex with too much redundancy
  - only about 2\% of the registered failures requires maintenance
  - a typical failure is loss of electrical contact
## Research trajectories & milestones

<table>
<thead>
<tr>
<th>Trajectory 1: Optimisation of control &amp; operation</th>
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</thead>
<tbody>
<tr>
<td><strong>2015</strong></td>
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<td><strong>2020</strong></td>
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<thead>
<tr>
<th>Trajectory 2: Optimisation of maintenance</th>
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<tr>
<td><strong>2015</strong></td>
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<tr>
<th>Trajectory 3: Integral approach</th>
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<tr>
<td><strong>2020</strong></td>
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<td><strong>2025</strong></td>
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Optimisation & Control: Challenges

Diagram showing interactions between maintainer, wind turbine, environment, owner/producer, grid operator, other energy sources, consumer, contract, use, demand action, maintain, context, interaction.
Optimisation & Control: Challenges

› Scaling up – turbine level
  › Non-uniform wind load
  › Sub-rotor size turbulence
  › Novel designs (structures, blades, turbines, inverters, etc.)

› Scaling up – wind parks
  › Aero-dynamical interactions among turbines
  › Wind flow dynamics

› Competitiveness, costs
  › Production uncertainties
  › Maintenance
Optimisation & Control: research needs

- Wind flow dynamics
  - Validated models for sub-rotor turbulent structures
  - Modeling for control

- Aerodynamic interaction
  - Validated interaction models, models for control
  - Cooperative control

- MIMO control (production, vibration, wear)
  - Robust model-based design
  - Multi-objective optimization

- Operation & maintenance joint optimization
  - Input from PHM!

- Business model formalization

- Implementation, information infrastructure
  - Distributed/parallel algorithms, inherently fault tolerant algorithms
## Optimisation & Control: Roadmap

### Advanced technologies on single wind turbine

#### Trajectory 1: Optimisation of control & Operation

<table>
<thead>
<tr>
<th>Year</th>
<th>2015</th>
<th>2017</th>
<th>2020</th>
<th>2022</th>
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**Control & Optimisation**

<table>
<thead>
<tr>
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<th>2030</th>
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<tbody>
<tr>
<td>Wind flow dynamics (level 1)</td>
<td>wind-rotor interaction modeling, spatially varying load, sub-rotor turbulent structures (SRTS)</td>
<td>measurement system for model validation, calibrated model</td>
<td>modeling for control</td>
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<tr>
<td>Scaling up - MIMO control (production, vibration, wear) (level 1)</td>
<td>robust model-based control</td>
<td>MIMO for production &amp; advanced controllers for optimized</td>
<td>control in presence of component</td>
<td>multi-objective MIMO controllers</td>
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<tr>
<td>Aerodynamic interaction (level 2)</td>
<td>aerodynamic interaction modeling</td>
<td>modeling for control</td>
<td>measurement system for model validation and calibration</td>
<td>calibrated models</td>
<td>cooperative production controllers</td>
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</tr>
<tr>
<td>Operation &amp; maintenance joint optimization (level 2)</td>
<td>business models: formalization</td>
<td>case studies</td>
<td>distributed, multi-criteria constrained optimization (dedicated)</td>
<td>optimization for production</td>
<td>optimization for business</td>
<td>advanced operator support systems for park-level optimization</td>
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**Implementation, information infrastructure (level 1&2)**

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<tr>
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<tbody>
<tr>
<td>Distributed model-based controllers</td>
<td>distributed model-based controllers for</td>
<td>parallel algorithms for MPC</td>
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<td>High-dependability distributed computation</td>
<td>high-dependability distributed computation</td>
<td>new generation grid</td>
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**Joint optimisation of operation & maintenance**

**The results are enabling the products indicated above**

[Image: AERTOs logo]
Optimisation & Control: expected progress
Load and Condition Monitoring – research needs → roadmaps

Automation of global damage detection using an **intelligent sensor network**

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<tbody>
<tr>
<td>Adaptation of hardware</td>
<td>sensor nodes available on market</td>
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<tr>
<td>Optimization of communication</td>
<td>adaptation to product requirements</td>
<td>introduction into product development</td>
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<tr>
<td>Development of automated data acquisition</td>
<td>enhancement of reliability</td>
<td>market introduction of whole sensor network</td>
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![Diagram of sensor network](image)
Wireless sensor networks & remote presence: research needs

Wireless sensor networks

- Interoperability amongst different systems locally
- Interoperability amongst different systems plant wide
- Energy supply for sensors and other networked equipment
- Capacity and range
- Temporal properties (response time)
- Integration/mounting of physical sensors

Remote presence

- Remote inspections
- Remote controlled maintenance
- User interface / Human factors
- Integration with surveillance and condition monitoring systems
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<tr>
<td>Marketing and dissemination to the wind power industry</td>
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<tr>
<td>Ensuring interoperability amongst different systems locally</td>
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**Trajectory 1: Optimisation of control & Operation**

- **2015**: Marketing and dissemination to the wind power industry
- **2017**: Ensuring interoperability amongst different systems locally
- **2020**: Ensuring interoperability amongst different systems plant wide

**Advanced technologies on single wind turbine**

- **2015**: Marketing and dissemination to the wind power industry
- **2017**: Ensuring interoperability amongst different systems locally
- **2020**: Ensuring interoperability amongst different systems plant wide

**Joint optimisation of operation & maintenance**

- **2022**: Marketing and dissemination of results
- **2025**: ISO/IEC standards on access and interpretation
- **2027**: Market-wide implementation

**Wireless Sensor Networks**

- **2015**: Energy scavenging inside the nacelle
- **2017**: Energy generation within structures
- **2020**: Reducing size and energy needs while improving guaranteed response times
- **2022**: IEEE standards
- **2025**: IEEE standards development, e.g. additions
- **2027**: IEEE standards
- **2030**: IEEE standards

**Energy supply for sensors and other networked equipment**

- **2015**: Lab testing
- **2017**: Lab testing
- **2020**: Lab testing
- **2022**: Lab testing
- **2025**: Lab testing
- **2027**: Lab testing
- **2030**: Lab testing

**Temporal properties (response time)**

- **2015**: Improve guaranteed response times
- **2017**: Improve guaranteed response time long-range, e.g. WIMAX/GSM
- **2020**: Improve guaranteed response time long-range, e.g. WIMAX/GSM
- **2022**: Improve guaranteed response time long-range, e.g. WIMAX/GSM
- **2025**: Improve guaranteed response time long-range, e.g. WIMAX/GSM
- **2027**: Improve guaranteed response time long-range, e.g. WIMAX/GSM
- **2030**: Improve guaranteed response time long-range, e.g. WIMAX/GSM

**Integration/mounting of physical sensors**

- **2015**: Lab testing
- **2017**: Lab testing
- **2020**: Lab testing
- **2022**: Lab testing
- **2025**: Lab testing
- **2027**: Lab testing
- **2030**: Lab testing
Wireless sensor networks: expected progress
Remote presence: expected progress
Sensor technologies: research demands

Fibre optic sensor are one of the most promising sensor technologies for application in maintenance and control

- Packaging/mounting
  - Sensor should be part of system,
  - Embedding of optical fiber is crucial

- Detection system
  - Currently far too expensive, heavy/big, not always applicable for high sampling rates, high number of sensors.
  - Detection system needs attention

- Multi parameter sensing

- Standardisation

- Reliability
  - Self calibration/self assessment increase confidence
  - Repair strategies have to be developed
  - Reliable temperature compensation has to be available

- Nanophotonic sensing
Sensor technologies: expected progress
# Impact of OMO technologies by 2030 compared to 2010

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Measures / Indicators</th>
</tr>
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<tbody>
<tr>
<td><strong>Power generation</strong></td>
<td></td>
</tr>
<tr>
<td>cost of energy production: - 40%</td>
<td>availability &gt;&gt; 2010</td>
</tr>
<tr>
<td>power generation: +30%</td>
<td>operational hours: + 20%</td>
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<tr>
<td></td>
<td>park wide efficiency: +20%</td>
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<tr>
<td><strong>Life-Cycle-Costs</strong></td>
<td></td>
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<tr>
<td>life-cycle-costs: - 30%</td>
<td>life-time: + 50%</td>
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<tr>
<td></td>
<td># of spare parts: - 50%</td>
</tr>
<tr>
<td><strong>Maintenance Costs</strong></td>
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<tr>
<td>maintenance costs: - 70%</td>
<td>maintenance interval: &lt; 1/year</td>
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<td>failures and false positive &lt;&lt; 2010</td>
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<td>zero overloading</td>
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<td></td>
<td>prediction of failures / prognosis of wear</td>
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<tr>
<td><strong>Lightweight Design</strong></td>
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<tr>
<td>weight: - 20%</td>
<td>improved design</td>
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<tr>
<td></td>
<td>operational loads: - 10%</td>
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</tbody>
</table>
Conclusion

- The presented SRA provides research gaps and needs harmonised between independent research providers.
- New concepts are needed for wind parks and wind turbine operations for minimum energy cost over the lifetime while maintaining predefined level of availability, reliability and safety.
- Optimized maintenance strategies rely on Predictive Health Monitoring (PHM) and Condition Based Maintenance (CBM).
- Distributed sensor networks will play a critical role providing real-time information on operational conditions and the structural integrity of the asset.
- In 2030, offshore wind parks will possess a very high level of control authority on park level being controlled in any desired way such as:
  - to highest efficiency,
  - to minimal costs,
  - longest life time,
  - needs of the electricity grid.
- Research and development is needed in areas such as:
  - control and optimisation,
  - predictive health monitoring,
  - load and condition monitoring,
  - wireless communication,
  - sensor technologies (particular fibre optic sensors) and
  - smart structures including self healing.
Thank you very much for your attention!