The Instrumented Oil Field
Towards Dynamic Data-Driven Management of the Ruby Gulch Waste Repository

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Supported by:
Knowledge-based Data-driven Management of Subsurface Geosystems: The Instrumented Oil Field (ITR/DDDAS)

Detect and track changes in data during production.
Invert data for reservoir properties.
Detect and track reservoir changes.

Assimilate data & reservoir properties into the evolving reservoir model.
Use simulation and optimization to guide future production.
A New Approach: Dynamic, Data Driven Reservoir Management

Dynamic Decision System
- Optimize
  - Economic revenue
  - Environmental hazard
  - …
  - Based on the present **subsurface knowledge** and **numerical model**
- Update knowledge of model
- Improve numerical model

Dynamic Data-Driven Assimilation
- Improve knowledge of subsurface to reduce uncertainty
- Acquire remote sensing data
- Plan optimal data acquisition
- Subsurface characterization

Management decision

START

Processing Middleware

Grid Data Management

Autonomic Grid Middleware

Experimental design
Vision: Diverse Geosystems – Similar Solutions

- Landfills
- Oilfields
- Underground Pollution
- Undersea Reservoirs

Models, Simulation, Control, Data
Dynamic Data Driven Simulation Framework: Models, Methods

• Integrated Parallel Accurate Reservoir Simulation: IPARS
  – Multiple individual physical models and algorithms for multiphase flow and transport.
    • Provides linear solvers with state of the art preconditioners.
    • Couplings with geomechanics and chemistry
  – Multiblock approach (subdomain can treat unstructured grids)
  – Multi-physics, multi-numeric, multi-scale capabilities

• Seismic Data Simulation: FDPSV
  – Simulation of seismic data gathering
  – Simulates sound traces shot from sound sources and captured by receivers
    • Can scale up to thousands of sources and receivers

• Optimization Tools
  – Very Fast Simulated Annealing (VFSA)
  – Finite Difference Stochastic Optimization (FDSA)
  – Simultaneous Perturbation Stochastic Optimization (SPSA)
Dynamic Data Driven Simulation Framework: Data Management

• Data Virtualization: STORM
  – Large data querying capabilities
  – Distributed data virtualization
  – Indexing, data cluster/decluster, parallel data transfer

• Metadata Service: Mobius
  – XML metadata definition
  – XML database creation and federation

• Data Analysis/Processing Workflows: DataCutter
  – Filter-stream based framework for combined task/data parallelism
  – On demand data product generation
Dynamic Data Driven Simulation Framework: Autonomic Middleware Substrate (AutoMate)

• Grid Computational Engine: Seine/MACE/Armada
  – Enable scalable, dynamically adaptive parallel applications
  – Enable complex (dynamic) application/multiblock coupling and parallel data redistribution
  – Adaptive, application and system sensitive runtime management

• Programming system for self-management: Accord
  – Specify application components/services that can adapt their behavior and interactions/compositions at runtime using high-level rules
  – Runtime engine for efficient, scalable, correct and consistent rule enforcement

• Content-based middleware service: Meteor/Squid
  – Content based service discovery and composition
  – Scalable associative messaging and coordination

• Grid Computational Collaboratory: Discover
  – Seamless and secure (collaborative) access to and interactions between users, applications, and services
Effective Oil Reservoir Management: Well Placement/Configuration

• Why is it important
  – Better utilization/cost-effectiveness of existing reservoirs
  – Minimizing adverse effects to the environment

Bad Management

Better Management

Much Bypassed Oil

Less Bypassed Oil
Effective Oil Reservoir Management: Well Placement/Configuration

• **What needs to be done**
  – *Exploration of possible well placements and configurations for optimized production strategies*
  – *Understanding field properties and interactions between and across subdomains*
  – *Tracking and understanding long term changes in field characteristics*

• **Challenges**
  – *Geologic uncertainty: Key engineering properties unattainable*
  – *Large search space: Infinitely many production strategies possible*
  – *Complex physical properties and interactions.*
  – *Complex numerical models*
An Autonomic Well Placement/Configuration Workflow

Generate Guesses
- SPSA
- VFSA
- Exhaustive Search

Send Guesses
- Optimization Service
- IPARS Factory
- MySQL Database

Start Parallel IPARS Instances
- Instance connects to DISCOVER
  - DISCOVER Notifies Clients
    - Clients interact with IPARS

If guess not in DB:
- Instantiate IPARS
  - with guess as parameter

If guess in DB:
- Send response to Clients
- and get new guess from Optimizer

AutoMate Programming System/Grid Middleware

History/Archived Data

Sensor Data
Autonomic Oil Well Placement/Configuration (VFSA)


Autonomic Oil Well Placement/Configuration

Permeability

Pressure contours
3 wells, 2D profile

Contours of \( \text{NEval}(y,z,500)(10) \)

Requires \( NY \times NZ \) (450) evaluations. Minimum appears here.

VFSA solution: “walk”: found after 20 (81) evaluations
Autonomic Oil Well Placement/Configuration (SPSA)

Solution for 7 different initial guesses

Convergence history
## Optimal Well Placement

### Comparison of optimization approaches

<table>
<thead>
<tr>
<th>Method Metric</th>
<th>Nelder-Mead</th>
<th>GA</th>
<th>VFSA</th>
<th>FDSA</th>
<th>SPSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best solution</td>
<td>-1.018e8</td>
<td>-1.073e8</td>
<td><strong>-1.083e8</strong></td>
<td>-1.062e8</td>
<td>-1.075e8</td>
</tr>
<tr>
<td>Average number of function evaluations</td>
<td>99.95</td>
<td>104.02</td>
<td>75.5</td>
<td>57.0</td>
<td><strong>37.8</strong></td>
</tr>
</tbody>
</table>

Optimal solution: $F^* = -1.098E8$

**Learned lessons:**

- Robust stochastic algorithms increase the chances to find (near) optimal solutions (VFSA)
- Several trials of a fast algorithm pay off against sophisticated algorithms (SPSA)
- Need to develop hybrid strategies
Gilt Edge Mine Superfund Site


- Divided in 3 Operable Units. OU3 is the Ruby Gulch Waste Rock Repository: a valley with about 20 million cubic yard of waste rock. The waste rock generated AMD (acid mine drainage) which impacted drinking water supplies.

- Water captured at toe of repository for treatment in water treatment plant. Treatment costs are substantial over repository lifetime based on observed outflows in 1997-1999.

- Cost driven solution: cap 70 acre waste rock repository to reduce AMD production.
Monitoring system hardware

- Multi electrode resistivity system (523)
  - *One data point every 2.4 seconds from any four 4 electrodes*
- Temperature & Moisture sensors in four wells
- Flowmeter at bottom of dump
- Weather-station
- Manually sampled chemical/air ports in wells

- Current state: data is automatically collected and transmitted from data acquisition systems to web accessible relational database – data is accessible to user within hours of being collected
  - *Approx 40K measurements/day*
- Design lifetime: 30 years
Gilt Edge Site

Ruby Gulch Waste Rock Repository System Status
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Ruby Repository Outflow Meter
MAY 11 2005 - MAY 18 2005

Ruby Repository Total Daily Flow

Pressure
Wall 1
Depth (m)
Temperature

Wall 2
Depth (m)

Wall 3
Depth (m)

Pressure
Water Level

Pressure
Water Level

Pressure
Water Level

Pressure
Water Level

Pressure
Water Level

Pressure
Water Level

Pressure
Water Level

Pressure
Water Level

Pressure
Water Level

Dynamic Data-Driven Waste Management

Observations

Sensors

AutoMate

STORM/Datacutter

Ruby Gulch
Waste Repository

Data Assimilation

Surrogate/Reduced model

IPARS

Control
algorithms

Controllable input

Optimization
Many Challenges and Opportunities

- **Applications and algorithms**
  - *model development and calibration*
  - *uncertainty estimation*
  - *parameter selection and optimization*

- **Measurement and actuation systems**
  - *“real-time” data collection and transport*
    - *in-network aggregation, assimilation*
  - *data selection and application integration, data quality management*
  - *actuation*

- **Systems software**
  - *programming systems/models for data integration and runtime self-management*
  - *data management mechanisms for real time, space and data quality constraints,*
  - *runtime execution services that guarantee reliable execution with predictable and controllable response time*
First steps …

• Coupled air-water models
  – Model diurnal/seasonal variations in the outflow measurements observed

• Wide-area model/simulations coupling
  – Abstractions, parallel data redistribution, node-to-node data transport

• In-network data aggregation mechanisms
  – Evaluated using the Orbit 400 node sensor testbed

• Runtime data steaming middleware using model-based control/optimization strategies
  – Minimize impact on simulations, eliminate data loss

• Reservoir and seismic data archives
  – 30TB of seismic dataset, relatively small volume of oil reservoir data
Conclusion

- **DDDAS**: Enabling the next generation knowledge-based, data-driven, dynamically adaptive applications on the Grid
  - can enable accurate solutions to complex applications; provide dramatic insights into complex phenomena
- The Instrumented Oil Field: DDDAS for the management and control of subsurface geosystems
  - Models, algorithms, numerics – IPARS/Mace/Seine
  - Programming system, middleware – Accord/Meteor/Rudder/Squid
  - Data management, assimilation – Storm/Mobius/DataCutter
  - Collaborative monitoring, interaction, control - Discover
- Dynamic data-driven waste management
  - Many challenges and opportunities
- More Information, publications, software
  - [www.caip.rutgers.edu/~parashar/](http://www.caip.rutgers.edu/~parashar/)
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