Multi-Objective approach to sensor placement in IGCC power plants

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MOTIVATION & BACKGROUND
Motivation

- The U.S. Energy Information Administration (EIA) predicts global demand of energy will rise by 56% from the year 2010 to 2040.
- Renewable energy and nuclear power are fastest growing energy sources.
- Yet, 80% of the world’s power is still generated from conventional sources.
- Conventional fossil fuel based power plants have low efficiency, high environmental impact.
- IGCC plants are better on both fronts.
- Hence, it makes sense to invest in research for improving performance of IGCC plants.
IGCC Power Plant

- More than 80 unit operations
- Over 200 streams

VIRTUAL SENSING IN IGCC PLANTS

- The process of estimating value of a variable through mathematical modeling.
  - Eliminates need of placing direct physical means of measurement such as a sensor.
  - Two types - analytical and empirical

- Advantage - Economical and less invasive.
  - Appropriate choice for IGCC plant due to harsh operating conditions and hundreds of process variables.

- Disadvantage - lower measurement accuracy than actual sensing
  - High measurement error gives rise to uncertainty in the system.
  - Only variables that are expensive or difficult to measure directly are measured virtually.
SENSOR NETWORK – WHY DO WE NEED IT?

 OBSERVABILITY
  ▪ Monitoring and controlling the process variables in real time.
  ▪ To maintain all process variables within a safe range of operation at all times.
  ▪ Ensures smooth, safe and reliable operation.

 EFFICIENCY
  ▪ Certain variables that directly impact efficiency should be close to target value.
    o Gasifier temperature
    o Steam to air ratio in gasifier
    o Air to fuel ratio in gas turbine.
  ▪ If these variables are above or below their optimal values, the plant will run at a sub-optimal level.
OBJECTIVES & PROBLEM STATEMENT
OBJECTIVES

- METHODOLOGY
  - Develop sensor deployment methodologies applicable to IGCC power plant systems.
  - Incorporate measurement error (uncertainty) and non-linear nature of the system in the formulation and solution of the optimal sensor deployment problem.

- ALGORITHM
  - Develop a new algorithmic framework that can improve the computational efficiency significantly.

- MULTI-OBJECTIVE APPROACH
  - Develop multi-objective optimal sensor deployment algorithms to provide trade-off designs between various objectives – maximizing observability & maximizing efficiency.
**Problem Statement**

- **Decision variables** - number & location of sensors in the plant and the type of sensors.
- **Objective functions** - maximizing observability (using FI), maximizing efficiency, minimizing cost.
- **Constraint** - budget, mass & energy balances.

**Multi-objective**
- Simultaneous achievement of multiple objectives

**Stochastic**
- Uncertainty in process variables due to system and measurement noise.

**Non-linear**
- Equations governing the physical processes in the IGCC power plant are non-linear.

**Mixed Integer**
- Presence of integer and binary integer decision variables.
Variables & Control

- 24 intermediate variables selected
  - They have effect on output variables and plant performance.
  - Sensors are to be installed in these locations
  - Selected based upon experience
  - Placing actual sensors reduce measurement error.
  - Place sensors strategically to gain as accurate information as possible for all these process variables.

- Without sensor – measurement error is $\pm \ 20\%$
- With sensor
  - Low cost sensors, error $= \pm \ 5\%$
  - Medium cost sensors, error $= \pm \ 2.5\%$
  - High cost sensors, error $= \pm \ 1\%$
Table 2
Intermediate and output process variables.

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\(^a\) Stream notation refers to DOE/NETL model [11].
- Specify uncertainties in key input parameters in terms of probability distributions.
- Sample the distribution of the specified parameter in an iterative fashion.
- The model is evaluated for each of these sample points to determine the probabilistic value of objective function & constraints.
- Derivative estimation through perturbation analysis

ALGORITHMIC FRAMEWORK BASED ON BONUS

B- Better
O- Optimization for
N- Non-Linear
U- Uncertain
S- Systems
STOCHASTIC PROGRAMMING FRAMEWORK

Optimizer (outer approx. of MINLP using GAMS)

Reweighting (using MATLAB)

Computational time for 800 samples reduced from 18 hours (ASPEN) to less than a minute (BONUS).

• Initial uniform distributions (lower & upper bound) assumed for decision variables.
• PDFs of Decision & uncertain variables form base distributions.
• BONUS samples solution space of objective function using base distributions.
• As decision variables change, the distributions for the objective function & constraints also change.
• BONUS algorithm estimates objective function & constraints based on ratios of the probabilities for the current and the base distributions.
• Thus, BONUS avoids sample model runs in subsequent iterations.
MULTI-OBJECTIVE OPTIMIZATION
Multi-objective approach

- Objectives: maximize fisher information, efficiency, minimize cost

- Constraint method, a posterior method for generating pareto set where
  - The multi-objective problem is transformed into a series of single objective problems.
  - Any single objective is optimized while the rest are converted into constraints with lower & upper bounds.

- Lower bound to cost corresponds to using no sensors, i.e., zero (0).
- Upper bound to cost corresponds to using high accuracy sensors for all 24 locations.
STEPS IN OUR SOLUTION

- 2-tier constraint method

- To derive only feasible solutions, Divide cost values into 10 bins between upper and lower bound.

- For each cost, solve single optimization problem to maximize efficiency and calculate the corresponding FI.

- Similarly, for each cost, solve single optimization problem to maximize FI and calculate the corresponding efficiency.
**STEPS (contd..)**

- Derive upper & lower bounds of efficiency & FI & generate pay-off tables for each cost,
- For each pay-off table, select feasible values of efficiency in small increments and solve single optimization problems to find maximum FI for each of these values.
- Generate the complete pareto surface (trade-offs) by solving multiple single objective problems.
- Plot the complete pareto surface and analyze.
MAXIMIZING FISHER INFORMATION

\[
\begin{align*}
\max_{w \in \mathcal{W}} & \quad \sum_{\tau=1}^{3} \sum_{j=1}^{S_{\text{out}}} f_j(w, Y) w_j, \tau \\
\text{Subject to} & \quad \sum_{\tau=1}^{3} \sum_{j=1}^{S_{\text{out}}} c_j(w_j, \tau) \leq B \quad j = 1, 2, \ldots, S_{\text{out}} \\
& \quad \sum_{\tau=1}^{3} w_j, \tau \leq 1,
\end{align*}
\]

Mass & Energy Balances

\[f_j^A(w, Y) = 1 - I_{Y_j}^{\text{ns}}(\theta_{y_j})/I_{Y_j}^s(\theta_{y_j} | w_j = 1),\]

- Fisher information: a probabilistic nonlinear function
- Constraint on cost
- Stochastic Mixed integer nonlinear programming problem
MAXIMIZING EFFICIENCY

- Second Objective – maximize expected value of plant thermal Efficiency
- Constraint – budget
- Efficiency depends upon only certain variables - coal feed rate, gas turbine electric power, steam turbine electric power etc.

\[ E = \frac{P_{\text{net}}}{F_{\text{coal}} * F_{\text{mf}} * HOC} \]

Mass & Energy Balances
Mass & Energy balance equations:

The mass balance equation is given by:
\[
\frac{dM_i}{dt} = \sum Y_{i,in}M_{in} - \sum Y_{i,out}M_{out} + \sum R_i
\]

Where
- \(Y_{i,in}\) = mass concentration of content \(i\) in inlet flow
- \(M_{in}\) = inlet mass flow rate
- \(Y_{i,out}\) = mass concentration of content \(i\) in outlet flow
- \(M_{out}\) = outlet mass flow rate
- \(R_i\) = net production rate of \(i\) by chemical reactions.

The energy balance equation is given by:
\[
\frac{dU}{dt} = \sum H_{i,in} - \sum H_{j,out} + \sum Q_k + \sum P_m
\]

Where
- \(U\) = internal energy in block
- \(H_{i,in}\) = enthalpy flow rate of content \(i\) in the inlet flow
- \(H_{j,out}\) = enthalpy flow rate of content \(j\) in the outlet flow
- \(Q_k\) = heat flow
- \(P_m\) = mechanical power.
Pareto set using only High Accuracy Sensors
Pareto set using Low, Medium & High Accuracy Sensors
Low Cost - High efficiency
Low Cost - High efficiency
Low Cost - Low FI - High Efficiency

Pareto Set only LMH & H [Red-LMH, Blue-H]
High Cost - High Efficiency - low FI
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Pareto Set only LMH & H [Red-LMH, Blue-H]
Moderate Cost - High efficiency - High FI
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### Sensor Locations - L, M, H sensors

Cost: $5275000, FI: 154.81, Efficiency: 0.4377  
L: 10, M: 3, H: 8, Nil: 3

### Sensor Locations - only H sensors

Cost: $5275000, FI: 144.04, Efficiency: 0.4456  
H: 13, Nil: 11
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High Cost - High efficiency - High FI
Moderate Cost - High efficiency - High FI
INFERENCES

- Maximizing efficiency is cheaper than maximizing FI.
- Even if we are trying to maximize efficiency, a budget of $5.27 million is sufficient.
- Even if we are trying to maximize both, a budget of $7.38 million is sufficient.
SUMMARY

- Initial sample generated from ASPEN
- Off-line APSEN simulations for the fixed number of samples
- Algorithmic framework based on BONUS for single objective optimization
- Feasible solutions by fixing cost bins apriori
- 2-tier constraint method for solving multi-objective optimization.
- Pareto surface generation for decision makers
- Analysis of pareto surface can help determine the solution for desired trade-off.
KEY CONTRIBUTIONS

Objectives satisfied

- Developed sensor deployment methodology which incorporates non-linearity and uncertainty - a framework for virtual sensing and hybrid hardware and virtual sensing in power plants.
- Developed computationally efficient algorithm - significant reduction in the number of model runs to be solved for optimization and the number of samples for the uncertainty analysis.
- Obtained tradeoffs between multiple objectives.
FUTURE WORK

- Comparison of stochastic approach to SND with dynamic simulation approach to determine which is more computationally efficient.

- Include other objective functions, e.g., CO2 capture efficiency.

- Application of this methodology to dynamic sensor problems.

- Extension of this methodology to other systems which have a black box model.
Thank You