Does Prognostics Make Maintenance Smarter?

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3. September, 2019
Prognostics

• Produces information about remaining useful life
  • Now have information that my component/system will fail in x time units
  • So, what are we going to do?
    • Repair now?
    • Repair later?
    • Change load?
    • Let it fail?
  • What we do depends on a lot of other things
  • Need to justify decision
Decisions, decisions

• Decision-making: Is it easy?
  • Yes
    • If my problem is simple
  • No
    • If my problem is not simple
    • Need to also absorb non-Prognostic information sources
Some non-prognostic information

- Fleet-level considerations
  - Needs to repair other assets

- Logistics Considerations
  - Supply Chain constraints
  - Cost of repair
  - Shop loading

- Contractual obligations
  - Uptime
  - Mission completion
  - Warranties
  - Insurance

- Policies, Laws, Regulations
  - Maintenance policies
  - Regulatory mandates
Decision Making in PHM

- HM Turns Prognostics into Action
- Take all inputs and find best answer(s)

Prognostics
Cost of repair
Shop Loading
Supply Chain Info
Operational requirements
Contractual constraints
...
Complications

- Assimilation and interpret the information sources
- Determine best course(s) of action non-trivial task.
  - large volume of information from different sources
  - partially conflicting information
    - uncertainty associated with the pieces of information
    - large possible set of actions.
  - partially conflicting goals
  - uncertainty

Decisions in Isolation
Do Not Maximize Global Utility
Repair Utility
Operations Utility
Solution
maximizes
1 axis
Solution
Maximizes
Global Utility
Solution Space
What is the Best Decision?

• There are a multitude of “best” solutions
• Choose a preferred one
• Difficult to automate
  — knowledge of prevailing conditions
  — dynamic
  — situational
• Requires further refinement
  • e.g., with human insight
Complexity

Growth of number of decision solutions

- Problem complexity growth quickly
- But also increased number of satisfiable missions, mission reliability, safety, mission success rate and part availability

With 3 Missions

<table>
<thead>
<tr>
<th>Max # of Asset Parts</th>
<th>Total # of Potential “Plans”</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>24,567</td>
</tr>
<tr>
<td>5</td>
<td>196,608</td>
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<tr>
<td>6</td>
<td>1,572,864</td>
</tr>
<tr>
<td>7</td>
<td>12,582,912</td>
</tr>
</tbody>
</table>

\[ m(m-1)2^{mp} \]

where m is number of missions to be satisfied;
p is number of parts per asset.
we assume there are as many assets available to satisfy the missions
Pareto Surface of Non-Dominated Solutions

Optimization Progress

Initial population  nth generation  n+mth generation

Efficient frontier

Mission Capability MC(x)

% Availability A(x)

Random Solutions  Improved Solutions  Near-optimal Solutions
Trade-Off Remains

- Need to achieve balance when multiple missions compete for the same resources (parts and time, man-power)
- Example: non-dominated, alternative operational plans for a group of 8 aircraft
- User indicates preferences for various tradeoffs to rank the alternatives
Needed: DSS

- Decision support system that ensures “sound” decisions
  - Overcome limited cognitive capacity in handling large quantities of information.
- Provide mechanism for discovery and evaluation of optimal decision alternatives
  - Subject to operational boundary conditions.
- Enable elicitation and application of user preferences and constraints
  - Take into account different prognostic and other information sources
  - Equipment status
  - Variables and constraints related to system logistics
  - Maintenance
  - Operations
Problem Formulation

For a time horizon $T$ at a given instant $t$,
Suppose,
$M_T(t) = \{m_1, m_2, m_3, \ldots\}$ is a set of Missions to be satisfied in time horizon $T$ where,
$m_i = (r_i, c_i, C_i)$ with,
• $r_i$ desired Mission Reliability,
• $c_i$ Mission Capability and
• $C_i$ set of constraints related to the time within which mission $m_i$ is to be met

$A = \{a_1, a_2, a_3, \ldots\}$ is a set of available assets where,
• $a_j = \{p_{1j}, p_{2j}, p_{3j}, \ldots\}$ where $p_{ij}$ is part $i$ in asset $j$

$P(t) = \{(p_1, n_1, c_1, t_1), (p_2, n_2, c_2, t_2), (p_3, n_3, c_3, t_3), \ldots\}$ is an inventory of parts available at time $t$ for use in repair where,

$(p_k, n_k, c_k, t_k)$ is the current inventory with $n_k$ units of availability of the part $p_k$ with cost of each part being $c_k$ and repair or replacement time $t_k$
Problem Formulation, contd.

What is the best set of assignments from

- $P \rightarrow A$ (we refer to this as part allocation)
- $A \rightarrow M_T(t)$ (we refer to this as asset allocation)
- such that
- $M_T(t)$ is maximally satisfied

while minimizing total cost, part usage, and total time to repair?
Optimization Algorithms

Iterative ("gradient") methods
- Walk down the mountain where the slope is the steepest
- May get stuck in local valley
- Gradient-free algorithms

Explore new area based on heuristics
- Can “jump” over a hill
- May never get to true optimal point
Iterative Algorithms (partial listing)

- Evaluate Hessian
  - Newton’s method
  - Sequential quadratic programming
  - Interior points method
- Evaluate Gradients
  - Coordinate descent methods
  - Conjugate gradient methods
  - Gradient descent
  - Subgradient methods
  - Bundle method of descent
  - Ellipsoid method
  - Conditional gradient method (Frank–Wolfe)
  - Quasi-Newton methods
  - Simultaneous perturbation stochastic approximation
Gradient-Free Algorithms (partial listing)

- Memetic algorithm
- Differential evolution
- Evolutionary algorithms
- Dynamic relaxation
- Genetic algorithms
- Hill climbing with random restart
- Nelder-Mead simplicial heuristic: A popular heuristic for approximate minimization (without calling gradients)
- Particle swarm optimization
- Cuckoo search
- Gravitational search algorithm
- Artificial bee colony optimization
- Simulated annealing
- Stochastic tunneling
- Tabu search
- Reactive Search Optimization (RSO)[8] implemented in LIONsolver
Evolutionary Optimization

start

Initialize population

Performance evaluation

Convergence/Optimality?

Keep Best

Mutate/Crossover

done
Multi-Objective Optimization

X: Design Structure & Parameters

E: Prognostics, Diagnostics

Performance Evaluation: $Y = f(X, E)$

Y: PERFORMANCE MEASURES:
Y1: Failure Avoidance
Y2: Time to Repair
Y3: Mission Readiness
Y4: Part turn-around time
Y5: Remaining Life

High Dimensional Search

Optimization Module

Decision Maker

Accept or Reject Tradeoff

Final Selection from 2-D agg. Pareto Surface

Visualization & Interaction

Analysis, Aggregation, and Decision Module
More Detail on Decision Module

Exhaustive search & evaluation of plan space

{Reliability, Fixrate, Time-to-launch, Cost} → Compute Global Pareto Optimal (GPO) Subset → Store Global Pareto Optimal Subset (GPO)

Pre-specified inventory

Select feasible P-Optimal plans

Store Feasible Global Pareto Optimal Subset (FGPO)

Ops-specific goal
{Fixrate} {Reliability} {Time-to-launch}

Apply Ops-specific constraints to FGPO

Default reasoning: search only in GPO

Satisfiable in feasible space?

Yes

Infeasible plan found?

Yes

State inventory requirements to make plan feasible

Encourage user to weaken constraints

User able to weaken constraints?

Yes

Decisioning using visual interface

NO

Report plans

NO

1,358 plans

7,858 plans

32,768 plans

1-5 plans
Interactive visualization and preference expression

- 7858 plans to begin
- All are optimal
- Only some are feasible

Each point in these plots is a plan along different 1D and 2D axes that measure some plan-variable.

Subset of feasible plans, given the part availability (inventory)

1D Range-plots of all variables of interest to user
Interactive visualization and preference expression

User-selection1: Select only feasible plans, using mouse-click

Corresponding selected points are colored in all open plots
Use Zoom option to eliminate infeasible plans

Intrinsic trade-offs in Reliabilities along different missions visible

Only feasible plans from previous selection are retained in all plots
User selects best compromise plans that satisfy both missions reasonably well from available set.
Tabular view shows only one feasible plan among the remaining ones.

Use Zoom option to retain only selected plans (we’re down to 19 plans).
User now selects plans that have high values of FixRate for Mission1 from the 1D plot using mouse (we’re down to 3 plans)
Global Plan 1:
- Asset 2 to Mission 1
- Asset 1 to Mission 2
- Repair action 56 for Asset 1
- Repair action 70 for Asset 2

Global Plan 2:
- Asset 2 to Mission 1
- Asset 1 to Mission 2
- Repair action 57 for Asset 1
- Repair action 70 for Asset 2

Global Plan 3:
- Asset 2 to Mission 1
- Asset 1 to Mission 2
- Repair action 56 for Asset 1
- Repair action 71 for Asset 2

With only 3 plans left to examine, user looks at tabular representation of the remaining plans and selects one for deployment to maintenance and operations platform.
Concluding Remarks

• Prognostics can make Maintenance smarter, if:
  • Mitigation decision is made in methodical fashion
• Decision-Making can be framed as a Multi-Objective Dynamic Problem
  - Insight necessary to make right operational decisions
  - Complexity of information that needs to be processed exceeds cognitive, information processing capacity of human decision-makers
    • potential of making suboptimal decisions
  - Allow PHM user to collaborate in decision-making process
    • drive selection and eval. of operational scenarios and plans.
    • aids in discovery and eval. of optimal decision alternatives
    • subject to operational boundary conditions and user prefs.

• Overall maturity of solutions still low
• Special needs for real-time solutions for autonomous systems
Goals and Decisions

What subset of asset-mission assignments should I make?
OR
What is the optimal set of mission plans?

MISSION Requirements: (Reliability, Capability, Safety . . .)

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Goals and Decisions:
Which parts in which asset should I replace?
OR
What is optimal set of repair plans?

Integrated Globally Optimal Decision Making

Goals and Decisions:
What quantity of each part should I order?
OR
What is the optimal set of replenishment plans?

Goals and Decisions:
What is the optimal set of mission plans?

ASSET ALLOCATION

MISSION PLANNING

SUPPLY CHAIN PLANNING

PARTS INVENTORY

<table>
<thead>
<tr>
<th>PART</th>
<th># AV</th>
<th>Cost</th>
<th>Time to replace</th>
<th>Sourcing time</th>
<th>Space</th>
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<tbody>
<tr>
<td>P1</td>
<td>n1</td>
<td>c1</td>
<td>t1</td>
<td>r1</td>
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