Author Request  (To be completed by applicant) - The following author(s) request authority to disclose the following presentation in the MORSS Final Report, for inclusion on the MORSS CD and/or posting on the MORS web site.

Name of Principal Author and all other author(s):  John C. Hyland and Cheryl M. Smith

Principal Author’s Organization and address:
NSWC PC
110 Vernon Ave.  
Panama City, FL  32407

Phone:  850-234-4252  
Fax:  850-234-4141

Email:  john.hyland@navy.mil

Original title on 712 A/B:  Optimal Resource Allocation and Multi-Dimensional MCM Theory

Revised title:  Optimal Resource Allocation and Multi-Dimensional MCM Theory

Presented in (input and bold one):  (WG-13, CG___, Special Session ___, Poster, Demo, or Tutorial):

This presentation is believed to be:
UNCLASSIFIED AND APPROVED FOR PUBLIC RELEASE
**Report Documentation Page**

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

<table>
<thead>
<tr>
<th>1. REPORT DATE</th>
<th>2. REPORT TYPE</th>
<th>3. DATES COVERED</th>
</tr>
</thead>
<tbody>
<tr>
<td>01 SEP 2005</td>
<td>N/A</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4. TITLE AND SUBTITLE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optimal Resource Allocation and Multi-Dimensional MCM Theory</strong></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5a. CONTRACT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5b. GRANT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5c. PROGRAM ELEMENT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5d. PROJECT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5e. TASK NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5f. WORK UNIT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6. AUTHOR(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSWC PC 110 Vernon Ave. Panama City, FL 32407</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>8. PERFORMING ORGANIZATION REPORT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>10. SPONSOR/MONITOR’S ACRONYM(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>11. SPONSOR/MONITOR’S REPORT NUMBER(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>12. DISTRIBUTION/AVAILABILITY STATEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approved for public release, distribution unlimited</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>13. SUPPLEMENTARY NOTES</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>14. ABSTRACT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>15. SUBJECT TERMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>16. SECURITY CLASSIFICATION OF:</th>
<th>17. LIMITATION OF ABSTRACT</th>
<th>18. NUMBER OF PAGES</th>
<th>19a. NAME OF RESPONSIBLE PERSON</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. REPORT</td>
<td>UU</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>b. ABSTRACT</td>
<td>unclassified</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c. THIS PAGE</td>
<td>unclassified</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Standard Form 298 (Rev. 8-98)*

Prescribed by ANSI Std Z39-18
Traditional MCM Analysis

- Bottom Type
- A and B Values
- Clearance Level
- Nav. Error

Track Spacing - d

1960’s MCM SCENARIO (Reber)

Note: Not Drawn to Scale
Current MCM Scenario

Note: Not Drawn to Scale
Current Opportunities

Asset Allocation
- Which platforms should be assigned to the mission areas?
- Which sensors should be assigned to the platforms?

Multi-Dimensional Tactical Analysis
- What factors should the mathematical model include?
- Over what factors do we have sensor performance data?

Optimization
- What is the optimum platform trajectory?
- What are the optimum joint platform trajectories?
- What is the optimum prosecution sequence?
- When is the optimum time to reload?
- Can multi-platform performance (joint performance) be calculated?
- Should we use Monte Carlo or analytical methods?

Mine Avoidance
- What is the minimum risk of passing through a potentially mined area?
- How do we go through the minefield with minimum risk?

Minefield Planning and Analysis
- Where should we put the mines to get the best performance?
- How many mines?
- What type of mines?
Optimization Techniques For Mine Warfare Decision Making

- Dynamic Programming
- Multidimensional/Multivariate Probabilistic Modeling
- Search Tree Algorithms
- Bayesian Strategy Analysis
- Combinatorial Optimization
- Incremental Optimization
- Monte Carlo Simulations
- Markov Process Modeling
Analytical vs. Monte Carlo Analysis

Mission Factors

Uncontrollable Factors
• Environment
• Target Distribution
• Target Types
• Sensor Performance
• Intelligence Data
• Mission Constraints
• etc.

Controllable Factors
• Platform Selection
• Sensor Selection
• Asset Allocation
• Platform Trajectories
• Sensor Fusion
• Multi-Sensor Performance
• Engagement Area
• etc.

Model

Advantages:
• Computationally Fast
• Exact Solutions

Statistical Parameters
- Pd
- Pc
- Pn
- Pa
- Pi
- Risk
- Losses
- Time

Analytical Results

Monte Carlo Results

Sample Estimates

Advantages:
• Complex
• Non-Linear Models

MOEs

- Pd
- Pc
- Pn
- Pa
- Pi
- Risk
- Losses
- Time
Multi-Dimensional Tactical Analysis

PURPOSE:
- To modernize MCM theory and tactical analysis

CURRENT APPROACH:
- Approximates pd(y) curve by trapezoid of height B & width A
- Assumes Gaussian navigation error having known variance
- Implementation based upon retrieving data from tables as a function of A, B, variance, and clearance level

ADVANTAGES:
- Simple to Use
- Easily understood
- Works well when trapezoid is a good fit for the pd(y) curve

DISADVANTAGES:
- Planar Analysis Greatly Over Simplifies the Problem and Conceals Optimization Opportunities
- Analytical capability has not kept up with rapid pace of MCM sensor and platform R & D
- Not adequate for multi-sensor MCM systems
- Not adequate for multi-platform MCM systems
- Cannot determine MOP/MOE confidence intervals
- pd(y) curve modeled as a trapezoid
- Trapezoid parameters A and B not uniquely defined
- Can only accommodate Gaussian navigation error
- Can only accommodate uniform mine spatial distributions

RESULTS:
- Developed a new joint multi-dimensional MCM theory (general search theory) that accommodates:
  - Generalized pd(y) curves and nav. error distributions
  - Multiple platforms with multiple sensors on each platform
  - Multi-Dimensional sensor performance curves
  - Estimators and confidence intervals for Pd
- Increased MCM mission performance with no added cost
- Developed a preliminary Pd optimization strategy (single platform)

FUTURE RESEARCH:
- Develop new MCM MOEs
- Develop tactics for single platform mission optimization
- Develop tactics for multi-platform mission optimization
Multi-Dimensional Analysis Example

Example Problem:
• Two platforms are available
• Each platform has one sensor
• Each platform can cover the assigned mission area once
• Platforms will use traditional mow-the-lawn tracks

What coordinated track pattern will optimize mission results - parallel tracks or perpendicular tracks?
Hypothetical Target Strength vs. Aspect
Multi-Dimensional Analysis Example

Sensor 1
Pd vs. Angle

<table>
<thead>
<tr>
<th>Angle</th>
<th>Pd</th>
</tr>
</thead>
<tbody>
<tr>
<td>-180</td>
<td>0.0</td>
</tr>
<tr>
<td>-90</td>
<td>0.0</td>
</tr>
<tr>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>90</td>
<td>0.0</td>
</tr>
<tr>
<td>180</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Average Pd1 = 0.40

Sensor 2
Pd vs. Angle

<table>
<thead>
<tr>
<th>Angle</th>
<th>Pd</th>
</tr>
</thead>
<tbody>
<tr>
<td>-180</td>
<td>0.0</td>
</tr>
<tr>
<td>-90</td>
<td>0.0</td>
</tr>
<tr>
<td>0</td>
<td>0.9</td>
</tr>
<tr>
<td>90</td>
<td>0.0</td>
</tr>
<tr>
<td>180</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Average Pd2 = 0.45

-37.5 < x < 37.5
-62.5 < y < 62.5
-25.0 < z < 25

• True Pd is Typically Angle-Dependent
• Traditional Tactical Analysis Uses Average Pd

Reber: \( P(\text{At Least One}) = 1 - \left[ 1 - \int Pd1(a) p(a) \, da \right] \left[ 1 - \int Pd2(a) p(a) \, da \right] \)

Exact: \( P(\text{At Least One}) = 1 - \int \left\{ [1-Pd1(a)] [1-Pd2(a)] \right\} p(a) \, da \)

where \( p(a) = \text{pdf of target as a function of angular orientation} \)
Multi-Dimensional Analysis Example

<table>
<thead>
<tr>
<th>Scenario</th>
<th>P(none)</th>
<th>P(at least once)</th>
<th>P(twice)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel Tracks (Exact)</td>
<td>0.51</td>
<td>0.49</td>
<td>0.36</td>
</tr>
<tr>
<td>Perpendicular Tracks (Exact)</td>
<td>0.15</td>
<td>0.85</td>
<td>0.00</td>
</tr>
<tr>
<td>Reber Model (for both scenarios)</td>
<td>0.33</td>
<td>0.67</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Why the Different Results?

Theoretical Model Assumptions have been Violated! -
- Once the First “Random” Track is Chosen, All Other Tracks are No Longer Random!
- Random Target Orientation Assumption is Invalid!
Optimal Asset Allocation

Objective:
Develop Real-Time Optimal Asset Allocation Capability for Assigning Assets to Pre-partitioned Areas

Payoff:
• Optimal Mission Performance
• Dynamic Re-Allocation
• Automated
• Near Real-Time

Resource Allocation Background:
• Done Manually
• Slow (6 hours to several days)
• Limited to Small No. of Assets
• Not Optimal
• Not Dynamic

Technical Issues:
• Numerous constraints
  - Specialized Assets, Availability
  - Performance Differences
• What Objective Function to Use?
• Performances Not Known as a Function of Controllable Variables
• Minimal Effort Required
Manual Partitioning & Allocation
Minimum Risk Planning Tool

Objective:
Determine Minimum Risk Path Through a Minefield

Payoff:
• Reduced Risk
• Dynamic Path Re-Planning
• Provides Total Risk Calculation

Technical Issues:
• Mine Position Errors
• Own-Ship Navigation Errors
• Multiple Coordinate Systems
• Turn & Speed Changes
• Environment & Topography
• Different Mine Types
• Undetected Mines
• Expected Damage Functions

Approach:
• Utilize Navigation Voxels & Threat Sub-Voxels
• Map to Single Coordinate System
• Compute E{No. of Mines} for Each Threat Voxel
• Compute E{Risk} in Threat Voxels
• Use Dynamic Programming to Determine Minimum Risk Course
Minimum Risk Concept

Threat Grid

Expanded View

Local Risk Function

Navigation Grid

Minimum Risk Path
Optimal Reload Strategies

Objective:
Develop an Optimal Reload Strategy for Search and Destroy Missions

Problem Conditions:
• Given List of Potential Targets
• Each Target has Unique $p(\text{mine})$
• Assume 100% Identification
• No Navigation Error
• Reload Decisions Conditioned on Pre-defined Reacquisition Order

Results to Date:
• Developed Optimal Reload Strategy
• Added Sub-optimum Path Planner to Reload Strategy
• Demonstrated Algorithm and Path Planner in Matlab 6.1
• Identified Future Research
Target Field and Candidate Starting Points

* - Candidate Starting Points
+ - Known Targets
Sub-Optimal Path through Target Field
First Mine Encounter
Reload Decision
Overall Path
Optimal Prosecution Sequence

Objective:
Develop Algorithms for the Optimum Prosecution Sequence of Mine-Like Contacts

Payoff:
- Improved Mission Performance
- Improved Asset Allocation

Results to Date:
- Exhaustive search yields optimum for small no. of mines
- Sub-optimum solution developed for S/S/S/S and is in MEDAL
- Multi-Platform (M/S/S/S) solution partially developed

Technical Issues:
- Single vs. Multiple platforms
- prosecution devices
- sorties
- areas
- Number of contacts (N! Problem)
- Non-uniform contact weighting
Hybrid Results, 75 Nodes

Original Node Series

Node Series After Greedy Routine

Cost = 3001.3081

Cost = 721.3845
Hybrid Results, 75 Nodes

Best Node Series for Bubble Sort

Cost = 585.2038

Best Node Series for Reordering Sort

Cost = 582.8339
Hybrid Results, 75 Nodes

<table>
<thead>
<tr>
<th>Method</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>3,001.31</td>
</tr>
<tr>
<td>Greedy Routine</td>
<td>721.38</td>
</tr>
<tr>
<td>Bubble Sort</td>
<td>585.20</td>
</tr>
<tr>
<td>Re-Ordering Sort</td>
<td>582.83</td>
</tr>
<tr>
<td>Modified Re-Ordering</td>
<td>578.89</td>
</tr>
</tbody>
</table>
Joint Decision Regions

Hybrid decision region to reflect the independent nature of separate classifiers while accommodating subtle dependencies.
Common Theme - Optimized Decision-Making

• Decisions designed to maximize the probability of ‘success’ (i.e. shorter mission time, improved Pd,…)
• Small but consistent use of better choices gives easily obtainable performance boost
• Inexpensive
• Applies tried & true methods
  – playing the odds to improve performance
• Measurable performance increase with no measurable cost increase
Application to Current Navy Programs

Mission Pre-Planning – Optimize the initial setup

- Asset allocation - LCS
- Mission package selection - LCS
- Sensor selection – AUVs (BPAUV, BOSS, RMS)

Real-Time Decision Making – Adaptive re-planning

-Reloading strategies – Crawlers
-Mine avoidance – LCS, AUVs
-Asset trajectories – LCS, Crawlers, AUVs

Post Mission Data Mining – Extract more information

-Joint performance of sensors, assets, mission packages – LCS, Crawlers, AUVs
Conclusions

• Numerous tried & true techniques exist for Mine Warfare Optimal Decision Making

- Search Tree Algorithms
- Dynamic Programming
- Multidimensional/Multivariate Probabilistic Modeling
- Bayesian Strategy Analysis
- Combinatorial Optimization
- Incremental Optimization
- Markov Process Modeling
- Monte Carlo Simulations
- Optimization Techniques For Mine Warfare Decision Making
Conclusions

• The current planar analysis approach greatly over simplifies the analysis problem and eliminates optimization opportunities. This over simplification is a fundamental modeling flaw; expanding the dimensionality of the analysis provides enormous opportunity for improved performance.

• Applying these methods yields easily obtainable performance increases with no measurable cost increase.

• Much of the required sensor performance data may not currently be available.
$f(x,y | No\ Target)$

$(X_0,Y_0)$

$(X_1,Y_1)$
Conclusions

Mission Pre-Planning – Optimize the initial setup

- Asset allocation - LCS
- Mission package selection - LCS
- Sensor selection – AUVs (BPAUV, BOSS, RMS)

Real-Time Decision Making – Adaptive re-planning

- Reloading strategies – Crawlers
- Mine avoidance – LCS, AUVs
- Asset trajectories – LCS, Crawlers, AUVs

Post Mission Data Mining – Extract more information

- Joint performance of sensors, assets, mission packages – LCS, Crawlers, AUVs
Conclusions

1. Asset Allocation
2. Multi-Dimensional Tactical Analysis
3. Optimization
4. Minimum Risk Mine Avoidance
Optimization Techniques For Mission Planning

- Dynamic Programming
- Markov Process Modeling
- Monte Carlo Simulations
- Incremental Optimization
- Combinatorial Optimization
- Bayesian Strategy Analysis
- Multidimensional/Multivariate Probabilistic Modeling
- Search Tree Algorithms