Model Based Test Planning for Autonomous Systems

Merging Technology Acquisition and T&E

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Team Members

Troy Jones, George Sass, Melissa Durfee, Sean Buckley, Nick Borer, Stephen York, Eric Nelson, Mike Ricard, Glenn Ogrodnik, Scott Ingleton

Fostering Partnerships in T&E and Acquisition

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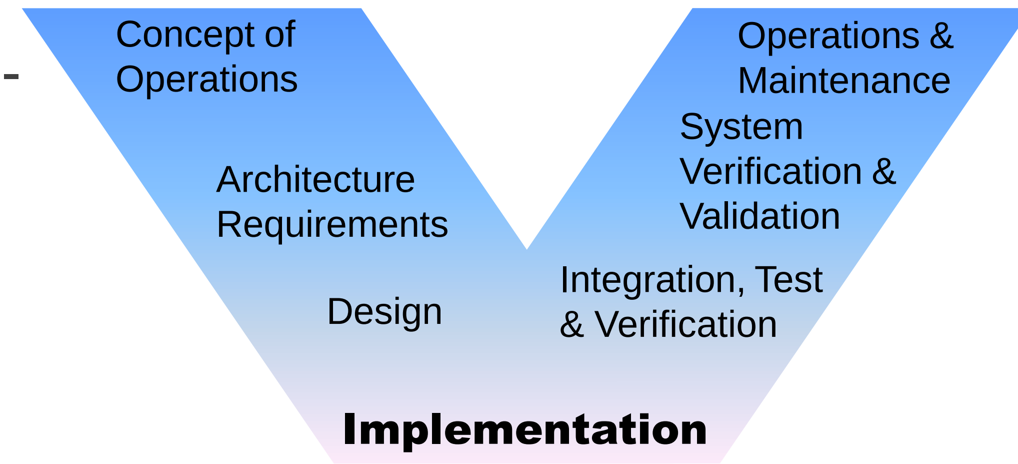
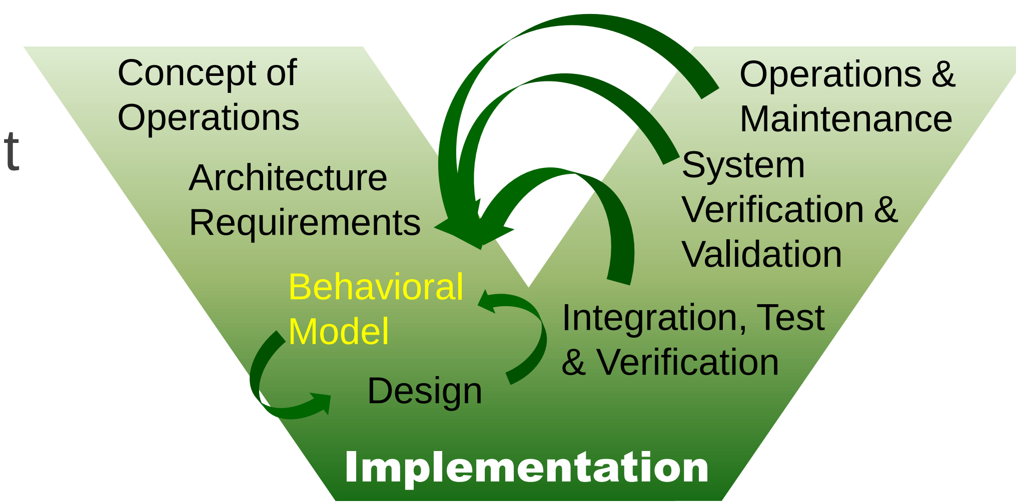
Project Vision

- Research Markov Reliability Analysis and DOE for System-Level test planning
- Complementary to Model-Based Engineering
- Performance Based Evaluation
  - Inject failure conditions
  - Force off-nominal decisions
- Continuous Model Refinement
  - Feedback performance data over time
  - Improve predictions of future reliability





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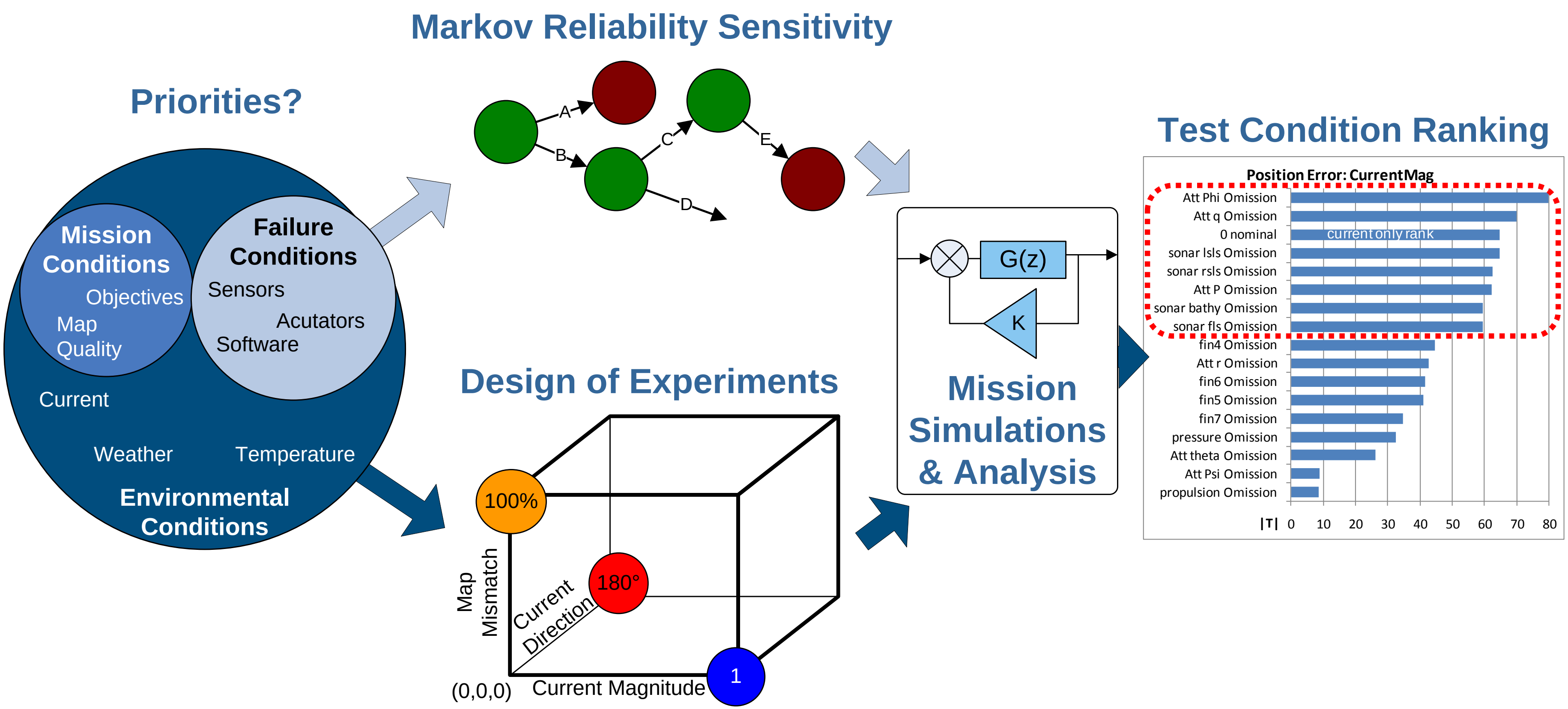
Lifecycle Autonomous System Test Design



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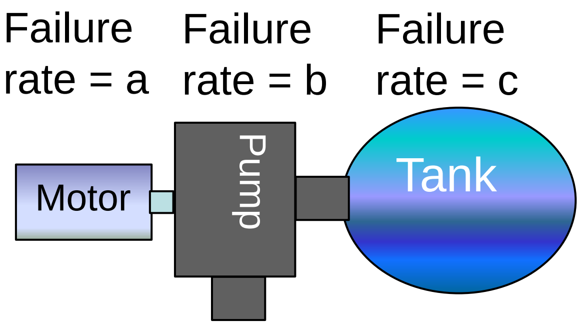
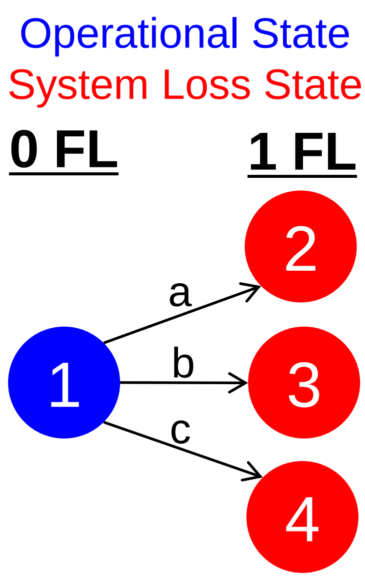
Behavioral Markov Reliability Analysis





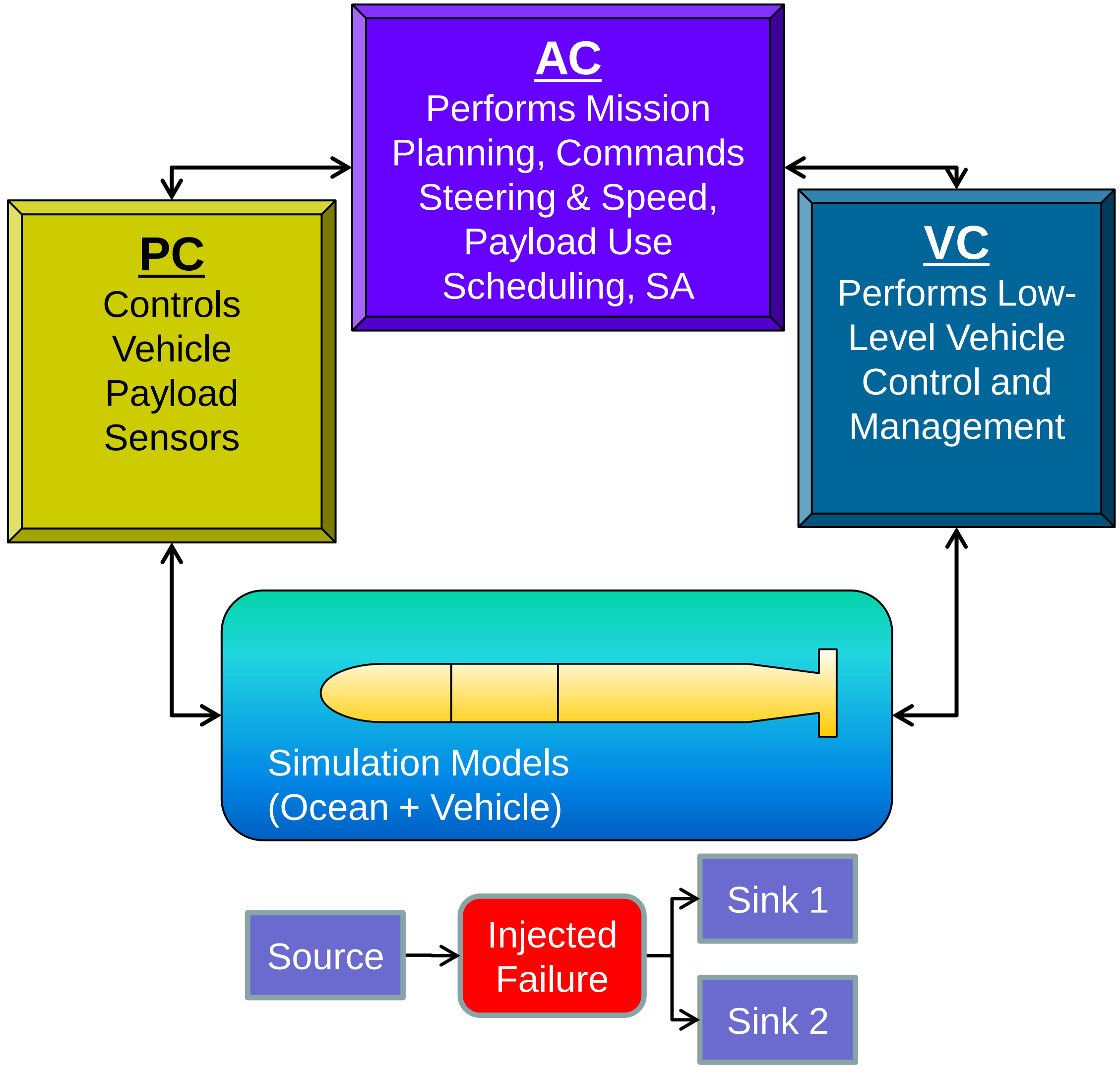
- Draper developed PARADyM Tool
- System Markov Model
  - Component connections & logical dependencies
  - Component reliability values (MTBF)
- Model Outputs
  - Probabilities
    - Any failure condition over system life
    - System Loss
  - Reliability Metrics
    - System Reliability
    - Sensitivity of Reliability to Component Failures

P(System Loss) = Σ(System Loss States)

Reliability = Σ(Operational States)

Case Study: Unmanned Underwater Vehicle (UUV)

- Based on Typical Small UUV
  - Non-redundant architecture
- ASTM F41 Software Architecture
- Component Reliability Estimates
  - Many hardware item values (motors, valves) from U.S. Army service data
  - Computer & Sonar values from vendors of similar hardware
- Simulated Failure Nodes



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Markov Reliability Analysis Results: UUV

Component	Reliability Sensitivity	Component	Reliability Sensitivity
Attitude Sensor H		Bathy Looking Sonar	
Attitude Sensor P		Forward Looking Sonar	
Attitude Sensor R		Depth Pressure Sensor	
Rate Sensor P		Propulsion Motor Controller	
Rate Sensor Q		Propulsion Motor	
Rate Sensor R		Propulsion Sensor	
Global Positioning System		Fin Actuator Motor Controller	
Doppler Velocity Sonar		Fin Actuator1	
Temperature Sensor		Fin Actuator2	
Saltwater Detector Sensor		Fin Actuator3	
Battery1		Fin Actuator4	
Battery Scanner System		Fin Sensor1	
Power Distribution System		Fin Sensor2	
Vehicle Controller		Fin Sensor3	
Autonomous Controller		Fin Sensor4	

- Predominantly equivalent sensitivities (2 Fault Level Analysis)
  - Non-fault tolerant system design
- Sonars and Battery Scanners stand out
  - Cascading failures to other components

DOE: UUV System Responses

Type	Response	Description	Rationale
Performance	Position Error (t)	Deviation from baseline mission path over time	Position errors cause data collection errors
	Attitude Error (t) [φ,θ,ψ]	Deviation from baseline attitude over time	Attitude errors cause data collection errors
	Speed Error (t)	Deviation from baseline speed over time	Speed influences execution time, stealth, energy
Recoverability	Energy Consumption	Energy consumption for mission	Must operate within available energy limits
	Mission Time	Total mission time	Establish expectations for recovery/communication
	Surface Position Error	Deviation from designated end-of-mission surface point	Large errors on surfacing impact recovery

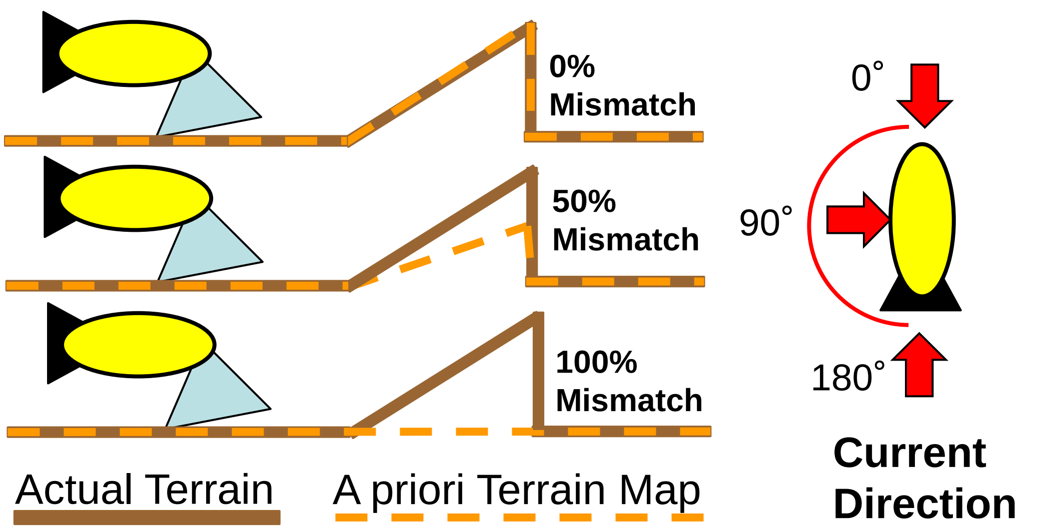
Environmental Experiment Design

- Available Environmental Factors (3)
  - Uniform Current Magnitude & Direction
  - Prior Terrain Knowledge
- DOE Design
  - 2 Level, 3 Factor Full Factorial – min/max levels with median center point
  - Center point detects curvature

	Min	Median	Max
Current Magnitude	0 Knots	1 Knots	2 Knots
Current Direction	0°	90°	180°
Map Mismatch	0%	50%	100%

Experimental Design with Center Point

RunOrder	CenterPt	Current Magnitude (knots)	Current Direction (deg)	Map Mismatch (%)
1	1	2	0	100
2	1	2	180	100
3	1	0	0	100
4	0	1	90	50
5	1	0	0	0
6	1	2	180	0
7	1	0	180	100
8	1	2	0	0
9	1	0	180	0



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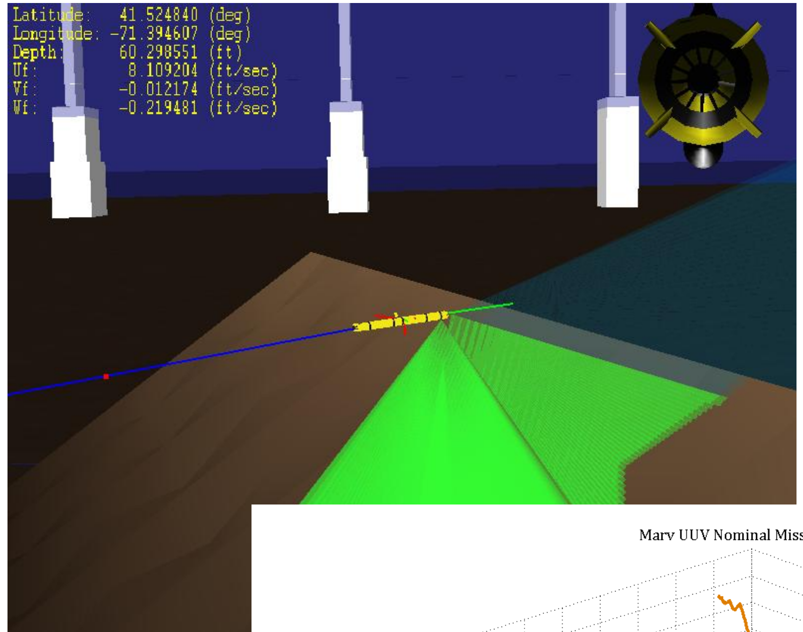
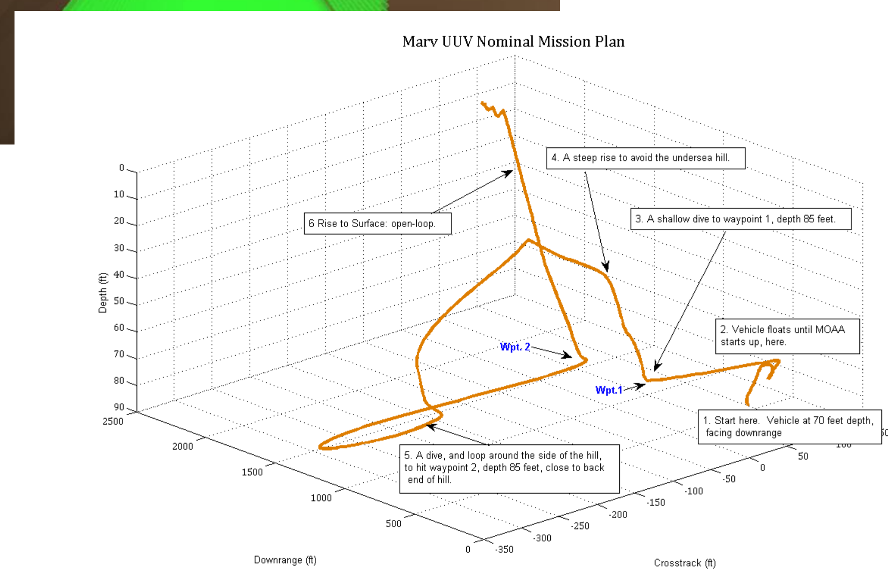
Short Mission Evaluation Scenario

- Short Mission Goals
  - Terrain avoidance
  - Waypoint following
- Case Study Scenario Design
  - Vary ocean currents, map quality
  - ~ 300 seconds
  - Approach & avoid terrain on way to waypoint
- Basis of all case study simulations



Draper Simulation Framework (DSF) Mission Visualization



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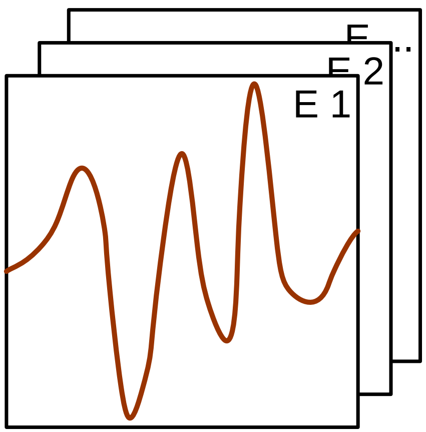
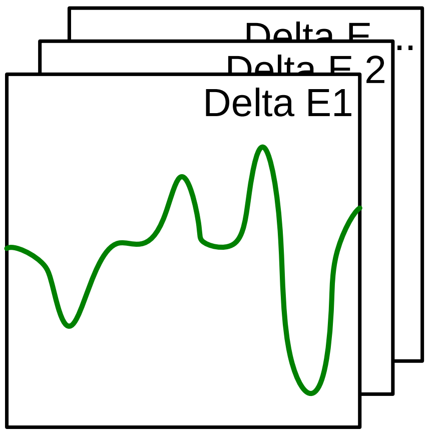
Execution & Data Analysis

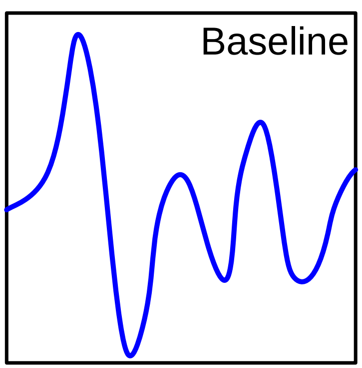
Draper Simulation + Matlab ®	Minitab ®	MS Excel ®

Execute Simulations 1..N
Parse Experiment Data Files
Identify Baseline Data Set

Delta(N)=E(N)-Baseline

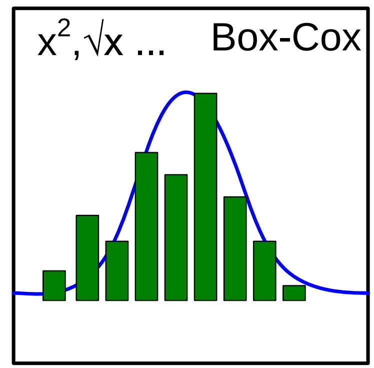


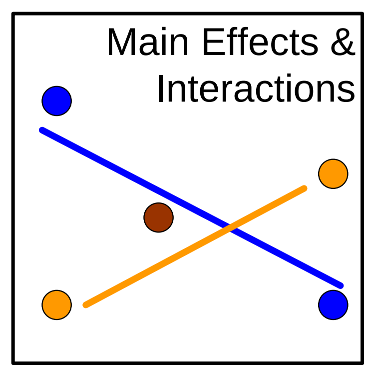




Box-Cox Transformations
General Linear Model (GLM):

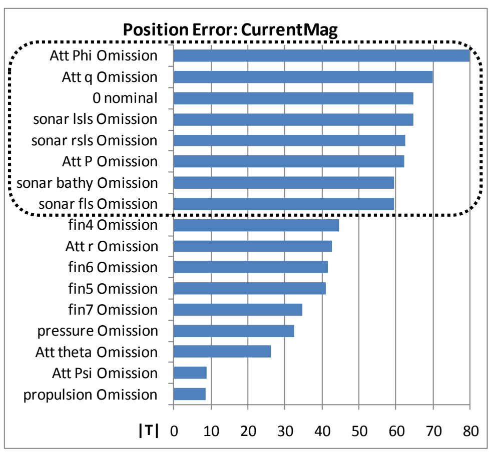
- Regression
- Main Effects & Interactions
- T-Test Values





T-Test Ranking
(Pivot Tables)
Graphing

Max of |T-value| / Row Labels	Column Labels: MapMismatch
Energy2**	
pressure_omission	
Mission Time	**143.44**
attitude_rOmission	143.44
pressure_omission	
fins_fin4Omission	116.2
Surface Position Error-2**	
pressure_omission	



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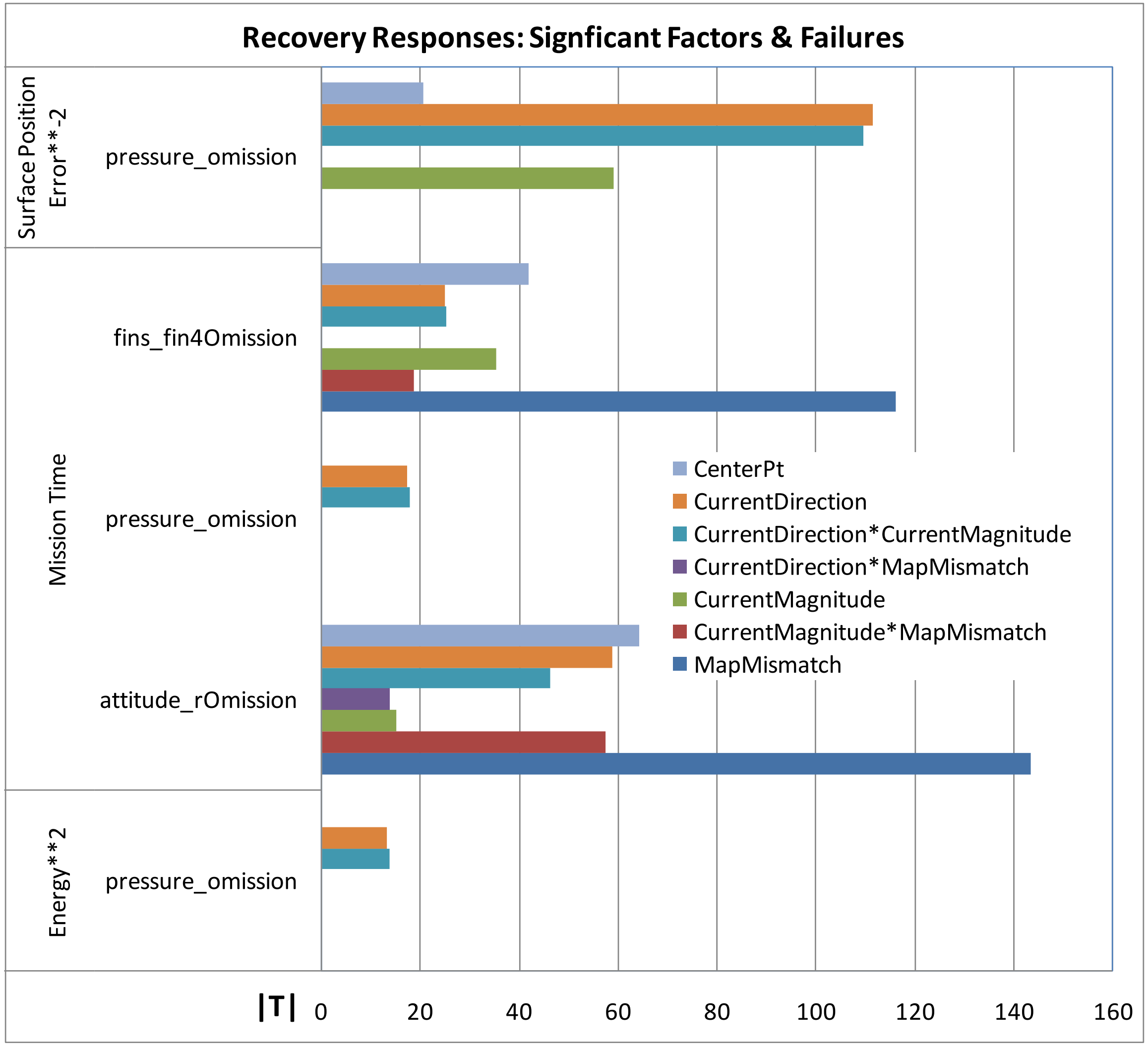
Results – Recoverability Responses

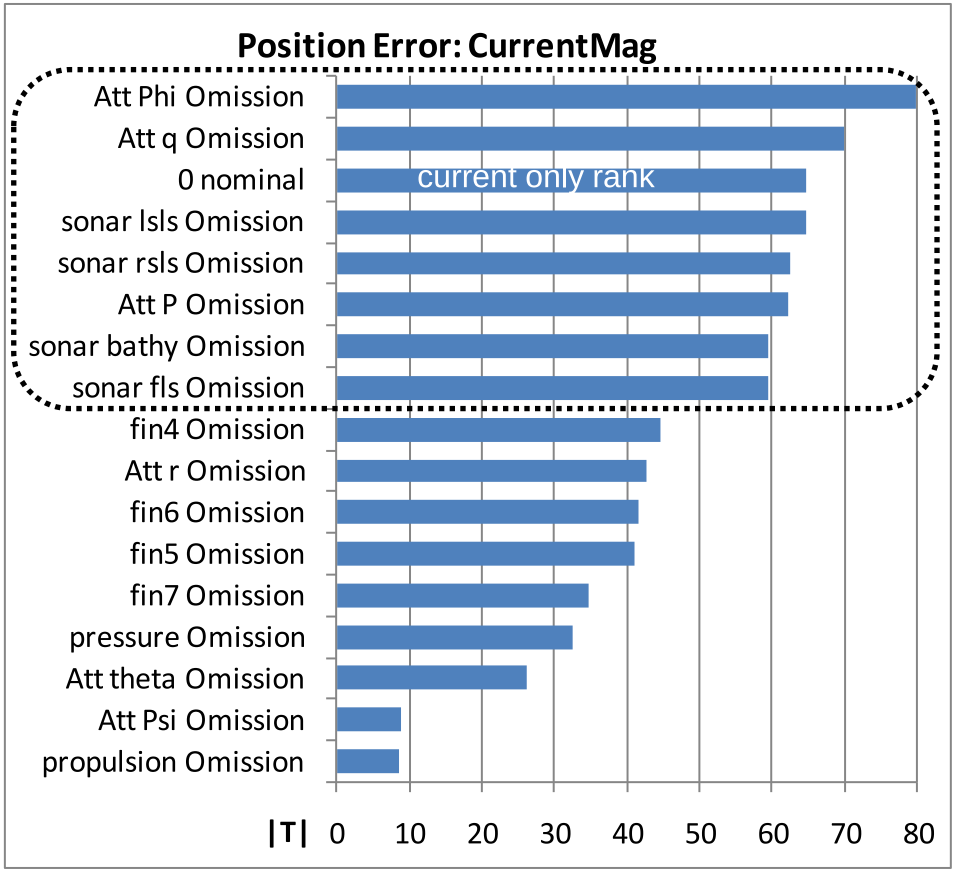


- Many Failures Not Significant
  - Encouraging robust behavior
  - Vehicle recoverable from ~12 other failures
- Candidates for Higher Fidelity Tests:
  - Map Mismatch (navigation error) with attitude sensor & fin failures
  - Pressure sensor failures in strong currents
- Caveats
  - Propulsion failures not registered as “significant”
  - Scenario setup/duration and simulation boundaries mask effects

Results – Mission Performance Responses

Position Control

- Key Failures to Test Further
  - Certain attitude & rate Sensors (Phi, p, q)
  - All Sonars (agrees with Markov)
- Observations
  - Sensor failures more important than fin failures
  - Similar sensor failure rankings in other responses
  - Propulsion rank likely incorrect for longer scenarios



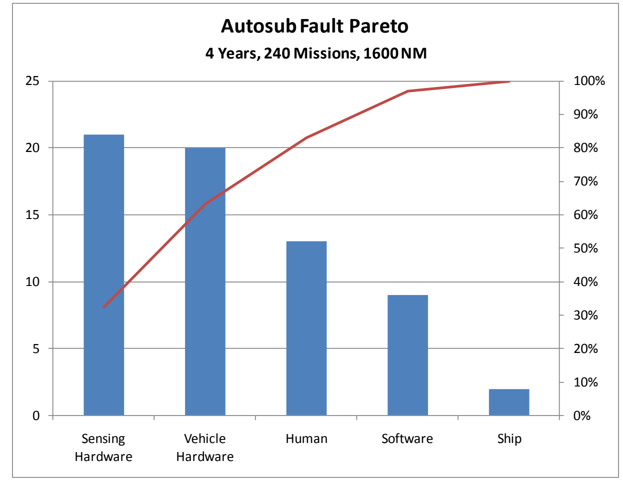
Conclusions

- Lifecycle Autonomous System Test design process developed & evaluated
- Unmanned Underwater Vehicle (UUV) Case Study
  - Markov Reliability Analysis – shows utility, needs better integration
  - Design of Experiments – valuable insights to prove relationships and focus subsequent tests
- Future Work
  - Integration of Markov Analysis with Draper Simulation
  - Fault injection into software layers of the system

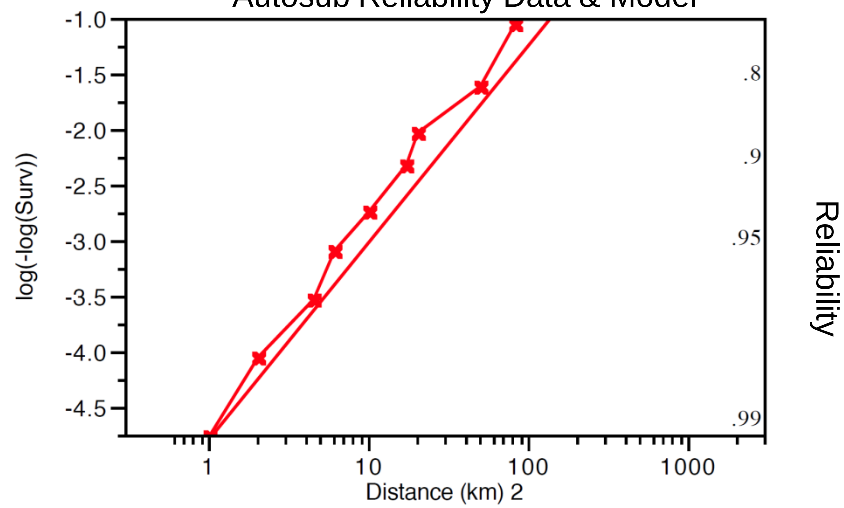
Supplemental Slides

UUV Reliability Studies

- Little Published Reliability Data
  - Many University projects
  - Inconsistent record keeping
- Multi-Year Reliability Studies on Autosub
  - UK Oceanographic Survey UUV
  - Extreme deep diving
  - Terrain following
  - Science data collection
- The Ocean is a Harsh Mistress
  - Majority of failures in [sensor] hardware (leaks, shorts)
  - Humans caused more faults than software
  - Estimated 63% Survival Probability for long Under-Ice mission
- Lessons
  - Need Test & Evaluation rigor in development (happening now)
  - Don’t always assume software is the long-pole



Autosub Reliability Data & Model



Data from Griffiths, G. et al., “On the Reliability of the Autosub Autonomous Underwater Vehicle”, Underwater Technology, 2002

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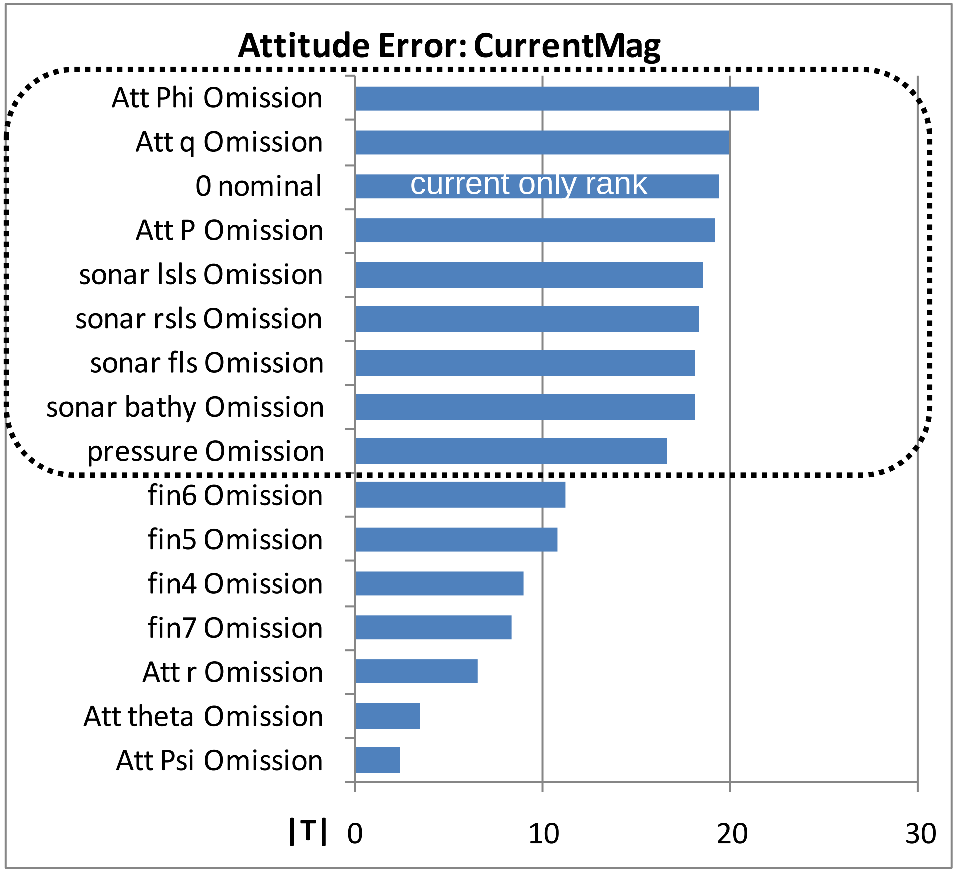
Results – Mission Performance Responses

Attitude Control

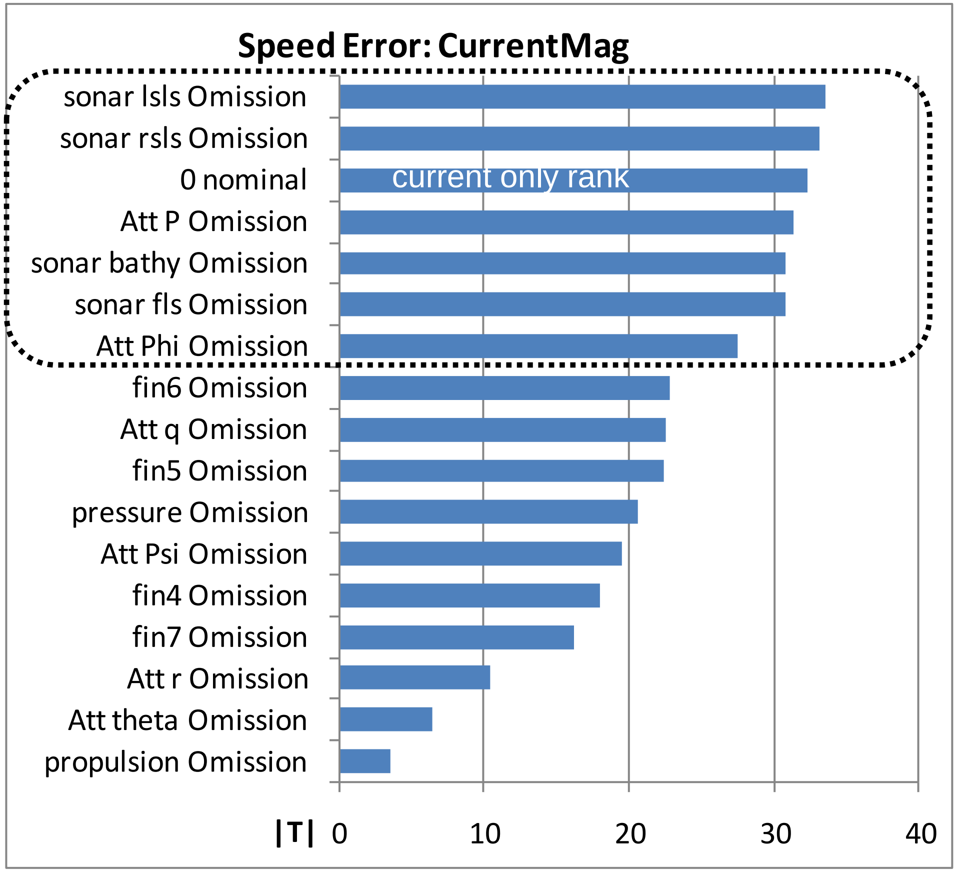
- Key Failures to Test Further
  - Certain attitude & rate Sensors (Phi, p, q)
  - All Sonars (agrees with Markov)
- Observations
  - Equivalent to Position Control, plus pressure sensor failures
  - Repeat of Phi & q as top ranking failures (not predicted by Markov)



Results – Mission Performance Responses

Speed Control

- Key Failures to Test Further
  - Certain attitude & rate Sensors (Phi, p)
  - All Sonars (agrees with Markov)
- Observations
  - Repeat of Phi as high ranking failure
  - All performance responses highly dependant on current
  - Consistent high rankings of similar failures



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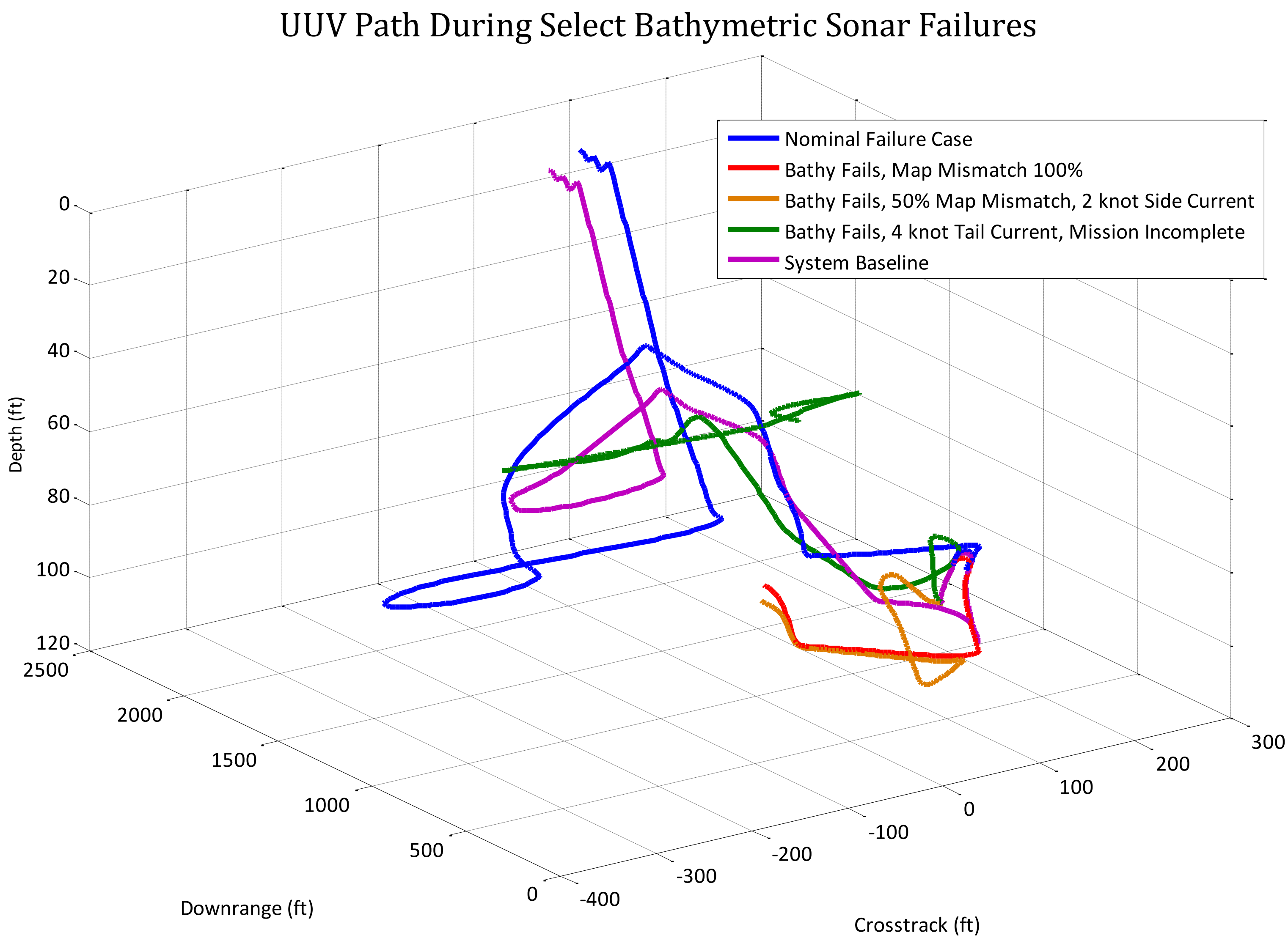
Example Results: Position Response



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