Probability Driven Experimental Design for Autonomous Systems

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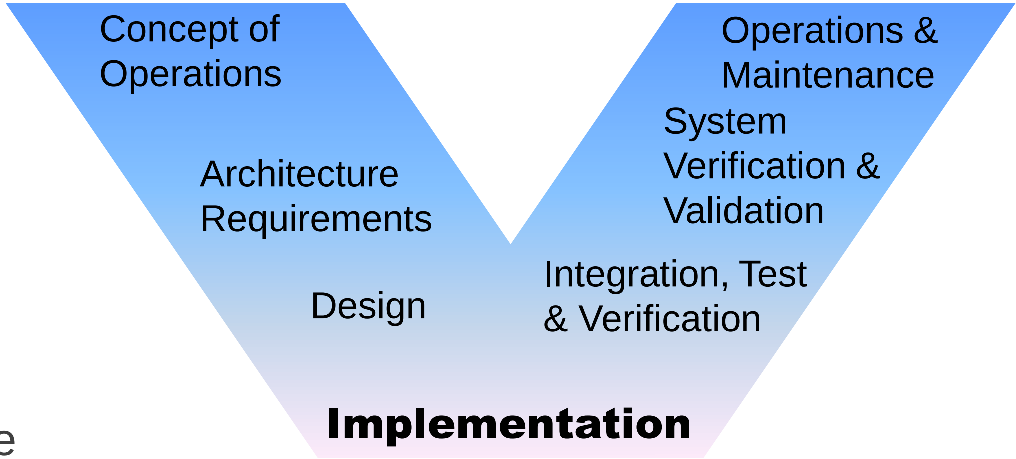
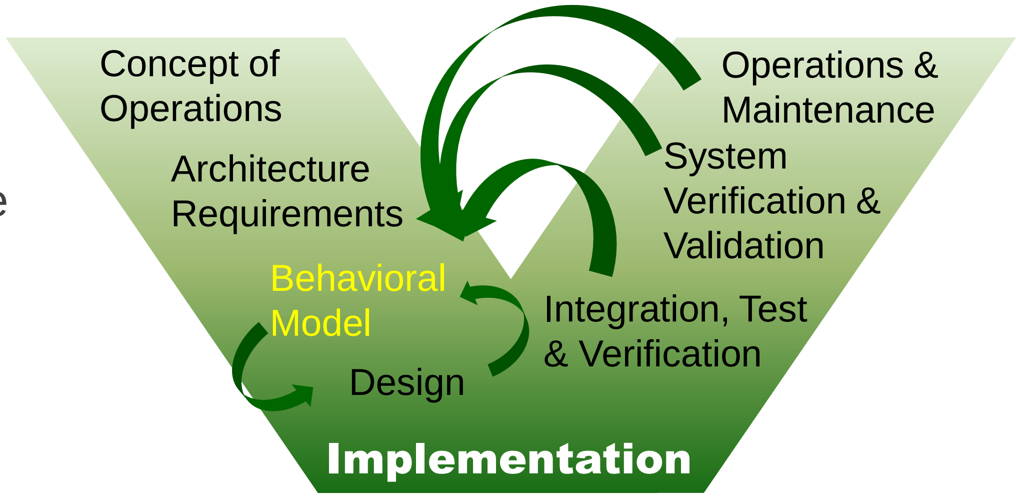
Motivation

- Across DoD, lack of common vision for how to assess performance of decision-making systems
  - Need to meet needs of commanders, acquisition, and warfighter communities who need to trust system performance when needed, safely
  - Low confidence of performance in difficult conditions
  - Intractable to physically test every possible condition
- Interesting Anecdotes
  - All deployed ground robots are tele-operated
  - Original iRobot Packbot had many autonomous driving features – they were removed
  - US Army tends to use automated Takeoff/Landing features of Predators, Air Force does not

Project Vision

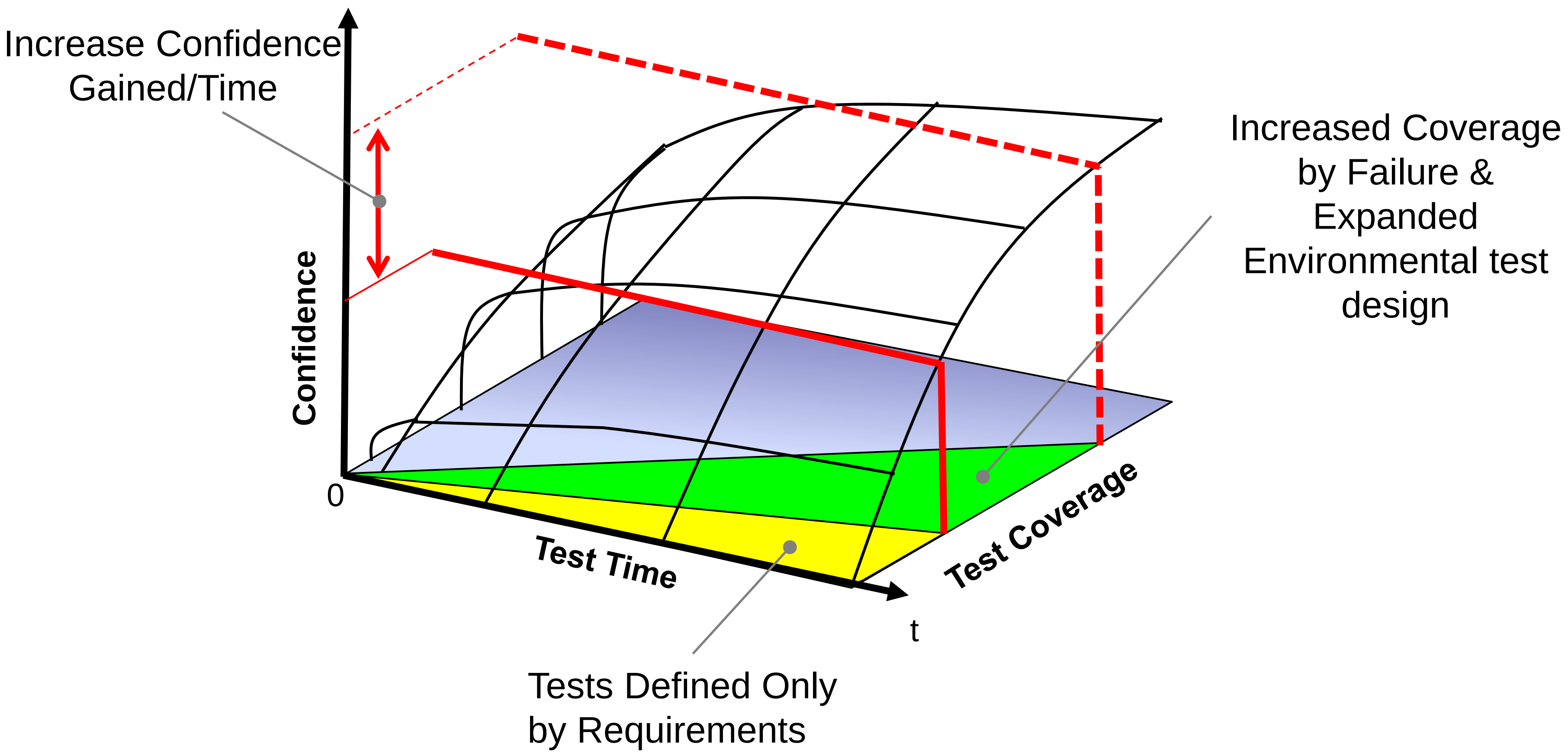
- Apply Draper experience in System Engineering, M&S, Reliability Analysis
  - Investigate use of Markov Reliability Analysis and DOE for System-Level test planning
  - Complementary with increasing emphasis on Model-Based design within DoD
  - Approach similar to human performance evaluation: Inject failure conditions during training to force off-nominal decisions
  - Feedback performance data to model over time to improve predictions of future reliability – continuous improvement
- Selected Unmanned Underwater Vehicle (UUV) for Case Study
  - Highly autonomous operations in complex environment
  - Strong interest from community in testing improvements



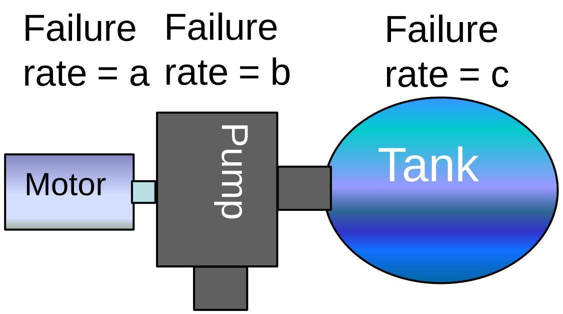


Testing Robustness to Build Confidence

Increase Test Coverage with Failure & Environmental Conditions

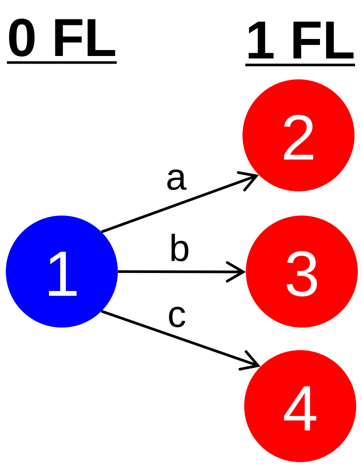


Behavioral Markov Reliability Analysis



- System Markov Model
  - System component connections & logical dependencies
  - Reliability values for each system component (MTBF)
- Model Outputs
  - Probabilities
    - Any failure condition over system life
    - System Loss
  - Reliability Metrics
    - Overall Reliability (not directly used in this project)
    - Sensitivity of Overall Reliability to failure rates of components (used to rank importance of failure modes)
- Draper developed PARADyM Tool

Operational State
System Loss State



$$\frac{dP_1}{dt} = -(a+b+c)P_1(t)$$
$$\frac{dP_2}{dt} = aP_1(t)$$
$$\frac{dP_3}{dt} = bP_1(t)$$
$$\frac{dP_4}{dt} = cP_1(t)$$

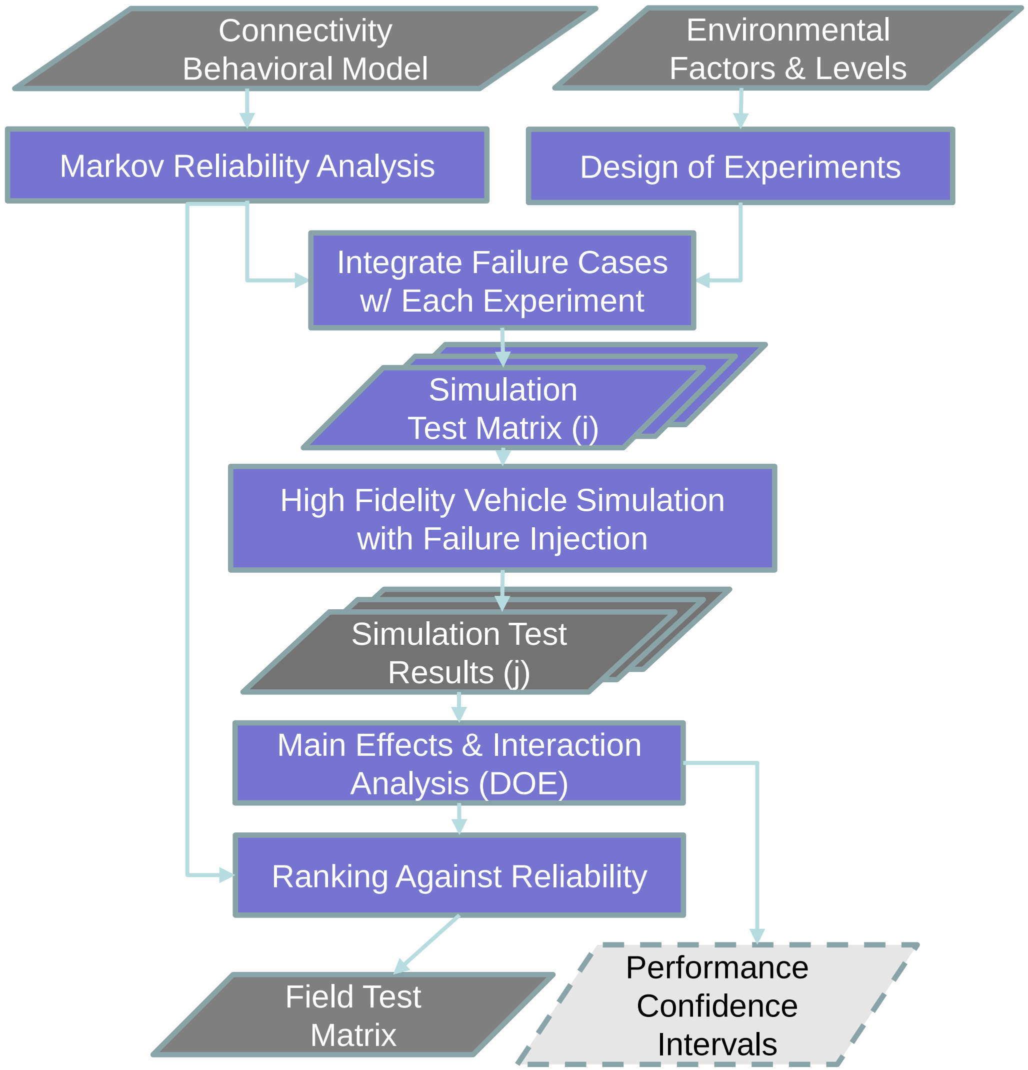
Solve

$$P_1(t) = e^{-(a+b+c)t}$$
$$P_2(t) = ae^{-(a+b+c)t}$$
$$P_3(t) = be^{-(a+b+c)t}$$
$$P_4(t) = ce^{-(a+b+c)t}$$

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

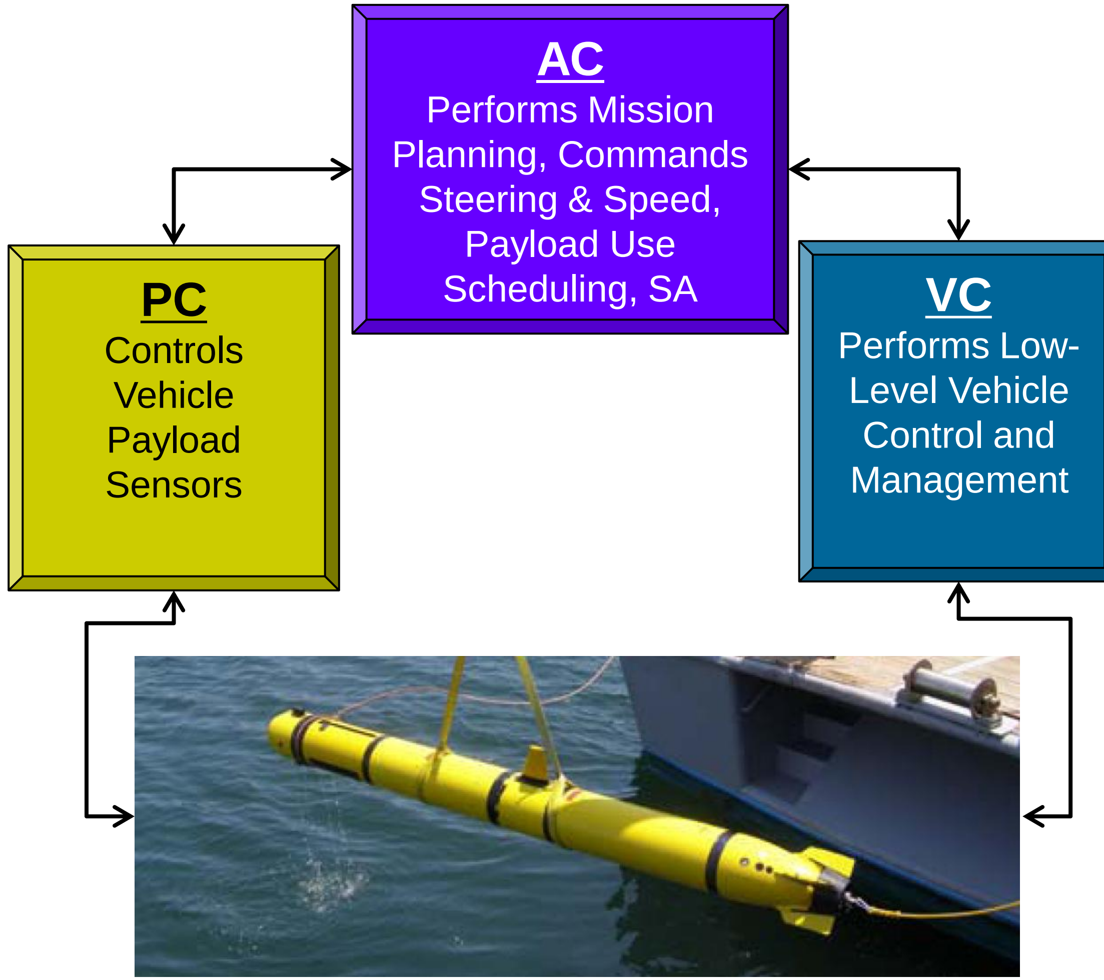
Process Summary

- Required Inputs
  - Behavioral Markov Model
  - Extreme types and ranges of environmental conditions
- Simulation Test Design
  - Perform Markov reliability sensitivity analysis
  - DOE for environmental conditions
  - Repeat all (or top subset) failure conditions for each experiment
- Simulation Execution & Analysis
  - Parallel execution of test cases
  - Analysis of Variance to find Main & Interaction Effects
  - Rank significant factors according to reliability sensitivity
- Final Results
  - Possible (not yet attempted) to extract confidence intervals for performance over bounds of operation
  - Highest significance subset of recommended tests to exercise in field

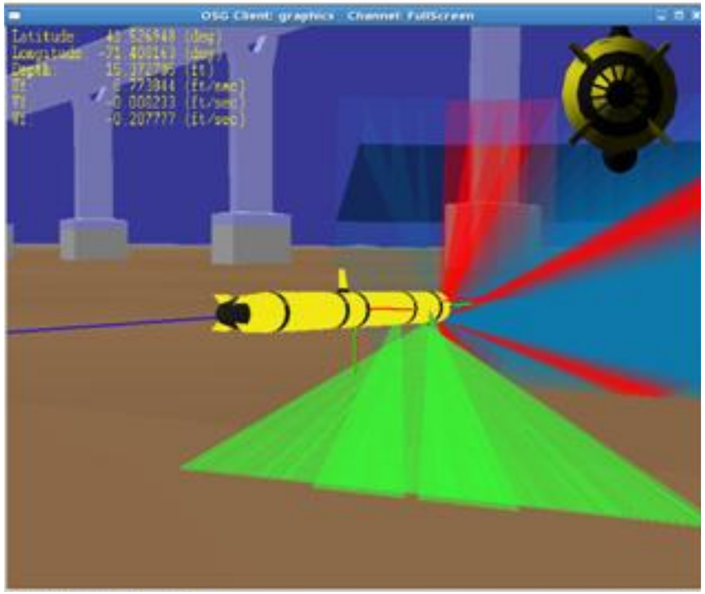


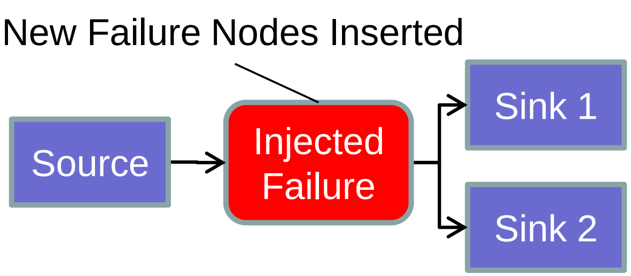
Case Study: Generic UUV

- Based on NUWC MARV UUV
  - 1’ Diameter, 12’ Long
  - Max Speed: 5 knots
  - Prop Driven with 4 Control fins
  - Forward, Left, Right, Down Looking Sonars
- ASTM F41 Software Architecture
  - Primary decision making in Autonomous Controller (AC)
  - Vehicle management by Vehicle Controller (VC)
  - Payload operations through Payload Controller (PC)
  - “Backseat Driver” Paradigm of control



UUV Simulation Based Testing





- Draper Simulation Framework (DSF)
  - Govt. Open Framework
  - Dynamics/Physics simulation
  - Soft to Hard Real-Time and faster
  - Built for Hardware-in-Loop
- MARV UUV Simulation
  - Validated vehicle dynamics
  - Simplified sensor models
  - Autonomy Controller running Software-in-Loop with simulated environment
- New Extensions to Simulation
  - Created generalized failure injection nodes for DSF
  - Failure types: Omission/Constant, Noise, Bias
  - Parallel execution of simulations & Autonomy Controllers

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UUV System Responses

Response	Description	Rationale
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
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
Vehicle Recoverable	TRUE if vehicle surfaced	Lost at sea?

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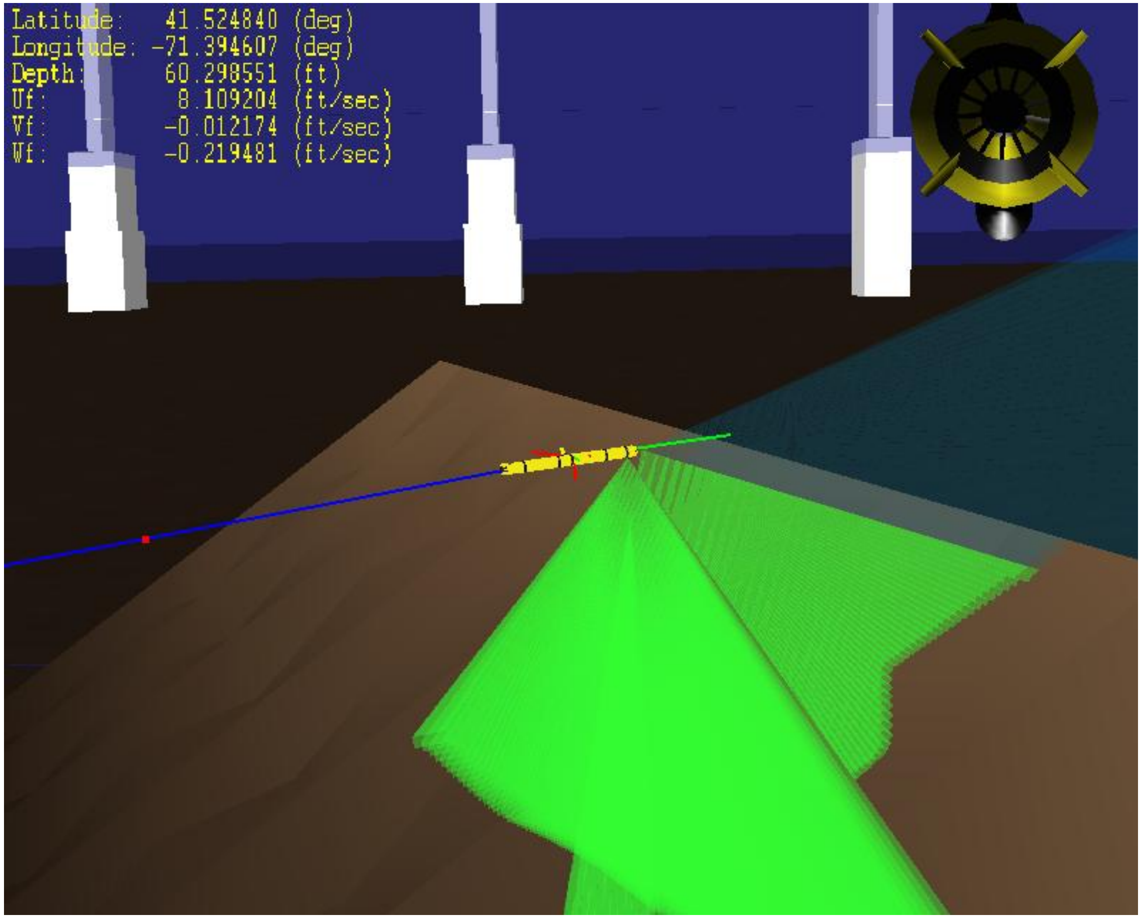
Case Study Evaluation Scenario

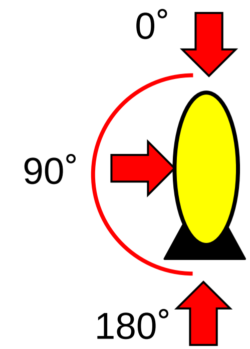
- Scenario Goals
  - Short, rapid to iterate
  - Exercises terrain avoidance
  - Exercises waypoint following
  - Varies ocean currents, map quality
- Case Study Scenario Design
  - Short mission, ~ 300 seconds
  - Approach & avoid terrain on way to waypoint
- Basis of all case study simulations
- Future Scenario Designs
  - Longer missions
  - More terrain complexity
  - Multiple time-varying objects of interest (ships, mines)



Environmental Experiment Design

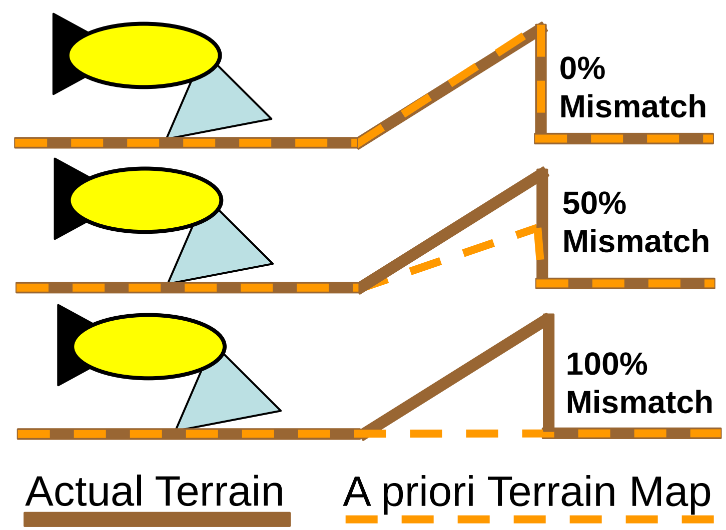
- Available Environmental Factors (3)
  - Uniform current magnitude & direction
  - Terrain under vehicle
- DOE Design
  - 2 Level, 3 Factor Full Factorial – using min/max levels, but adding median center point experiments
  - Center points show non-linearity in response, inform analysis

	Min	Median	Max*
Current Magnitude	0 Knots	**2**Knots	**4**Knots
Current Direction	0˚	90˚	180˚
Map Mismatch	0%	50%	100%



Experiment Design with Center Points

RunOrder	CenterPt	Current Magnitude (knots)	Current Direction (deg)	Map Mismatch (%)
1	1	4	0	100
2	1	4	180	100
3	1	0	0	100
4	0	2	90	50
5	0	2	90	50
6	1	0	0	0
7	1	4	180	0
8	0	2	90	50
9	1	0	180	100
10	1	4	0	0
11	0	2	90	50
12	1	0	180	0



3/8/11 – Learned 4knot 0deg current cases too strong for vehicle

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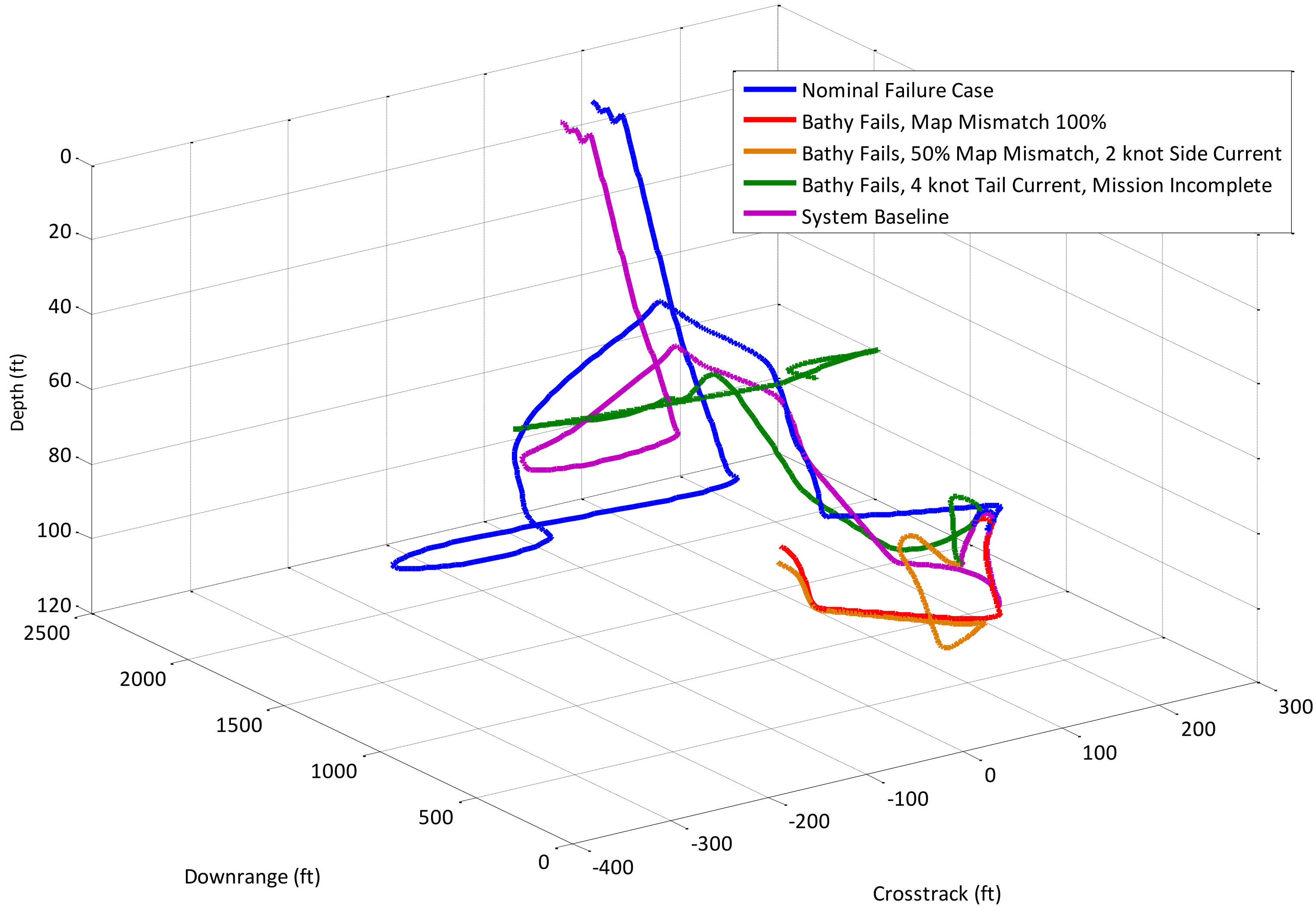
Example Results: Position Response

UUV Path During Select Bathymetric Sonar Failures



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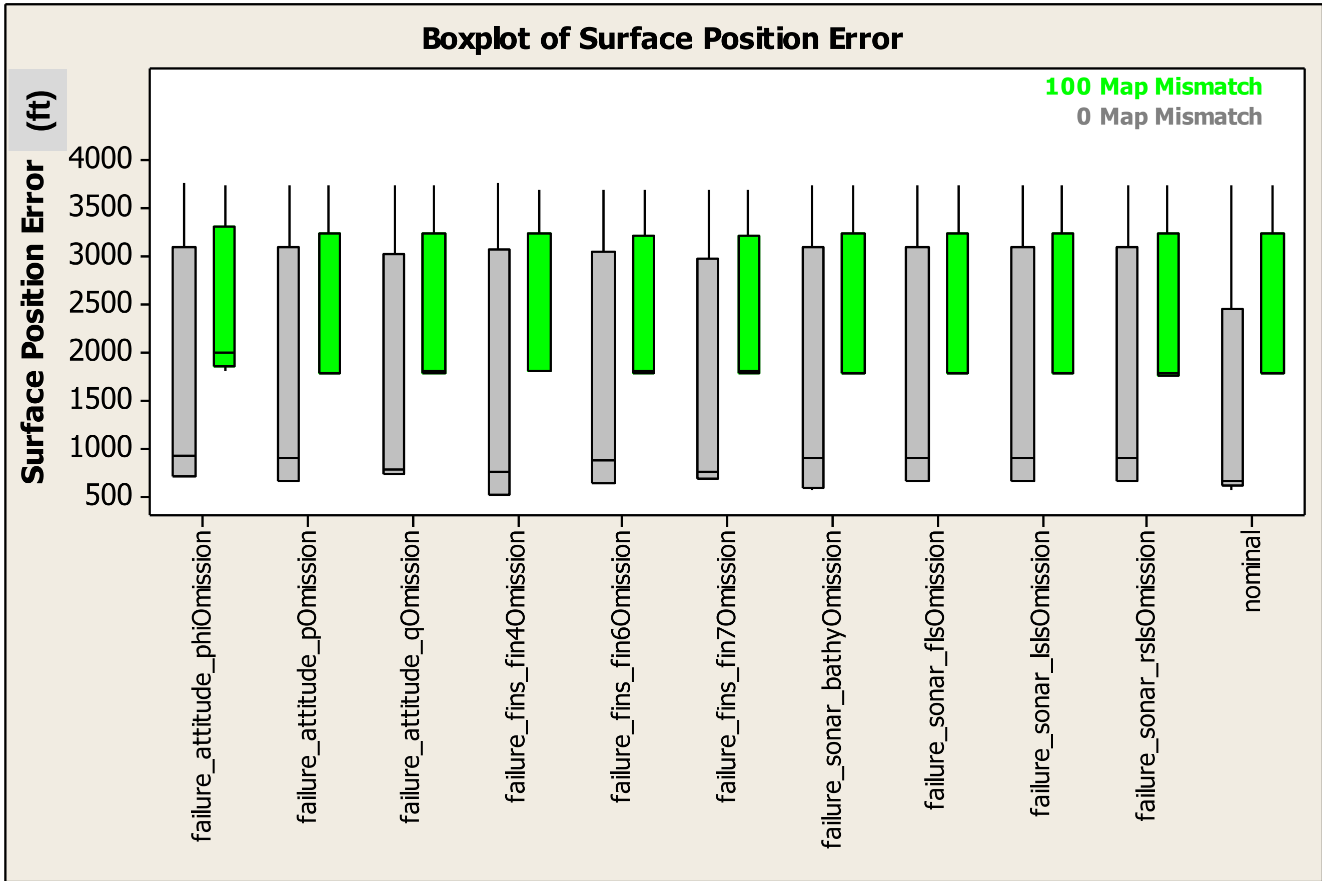
Example Results: Map Mismatch Effects

- Map Mismatch Significant Influence during Sonar Failures
  - Logical result
  - Almost 4 km Max Error in Surface Position
  - From Markov model, sonar failures drive reliability
  - Fin & attitude sensor failures much less probable
  - Failure effects same magnitude as environment only
  - *Suspect impact cases and 4knot head currents biasing results*
- Need to set bounds on responses
  - Define overall PASS/FAIL limits
  - Summarize high level results more clearly



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Summary & Future Work

- Demonstrated Reliability + DOE Test Planning method on Generic UUV case
  - Reliability analysis indicated sonars, battery monitor, VC, and AC primary drivers of system reliability
  - DOE Planning and analysis indicated Map Mismatch, Current, subset of failure modes significant
- Need to complete analysis of simulated experiments
  - Review results with engineering, end-users, and customers to get feedback on usefulness
  - Rank effects and interactions against probability of failure conditions
- Invest in method & tool improvements
  - **Simulation Environment**: Needs more fidelity in water properties, coupled with higher fidelity sensor models
  - **Simulation Environment**: Integrate reliability calculations with dynamic system model -> Avoid second model creation effort
  - **Markov Analysis:** Sources of reliability values (MTBF) for each component
  - **Simulation Environment**: Add failure mechanisms for VC and AC during simulation
  - **Simulation Environment:** Integrate autonomous controller decision logs with response data
  - **Simulation Environment**: Add time-varying failure and environmental perturbations during simulation
  - **Design of Experiments**: Also consider for integration with Simulation
  - **Design of Experiments**: Selection of best designs and analysis strategies for higher-order experiments

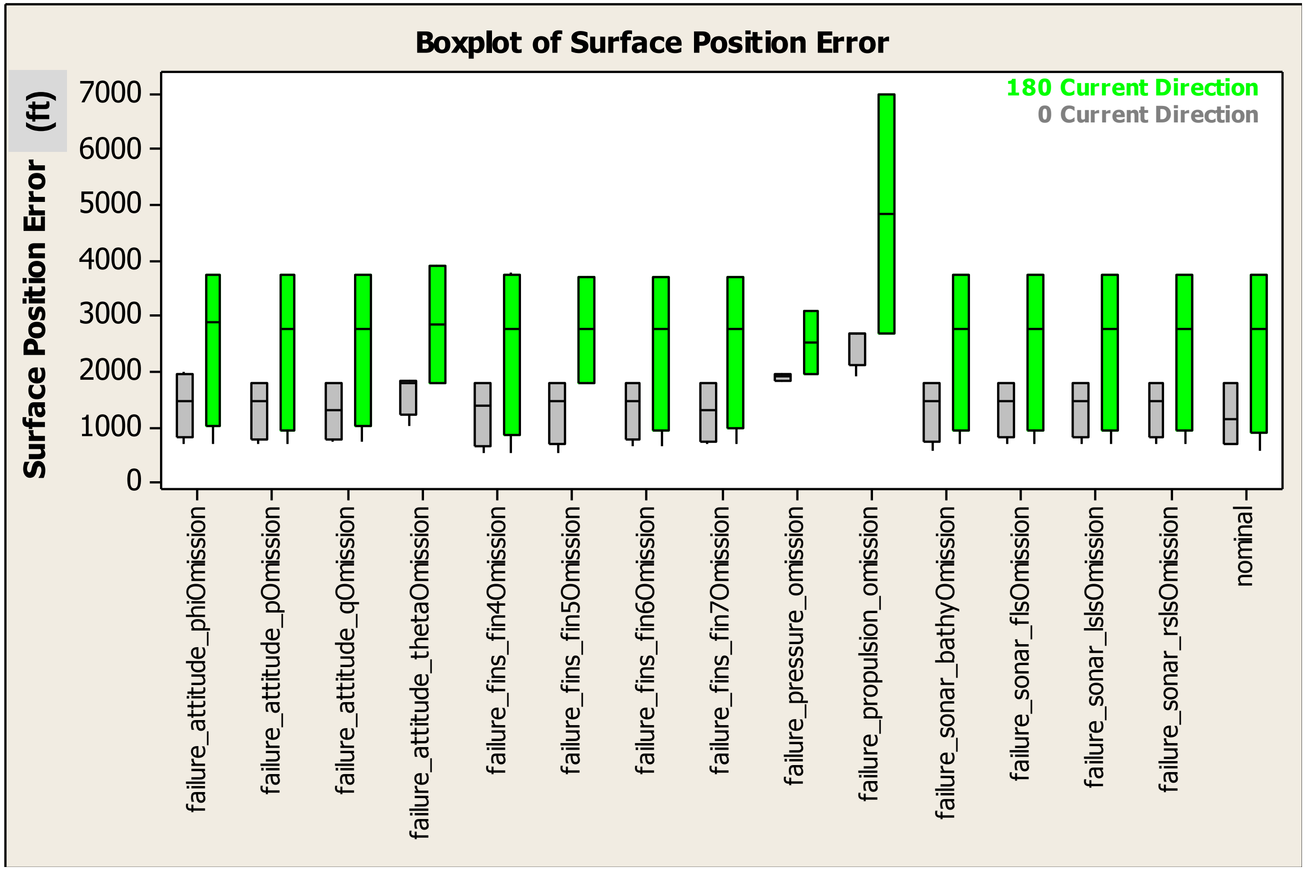
Supplemental Slides

Ongoing Testing Efforts of Note

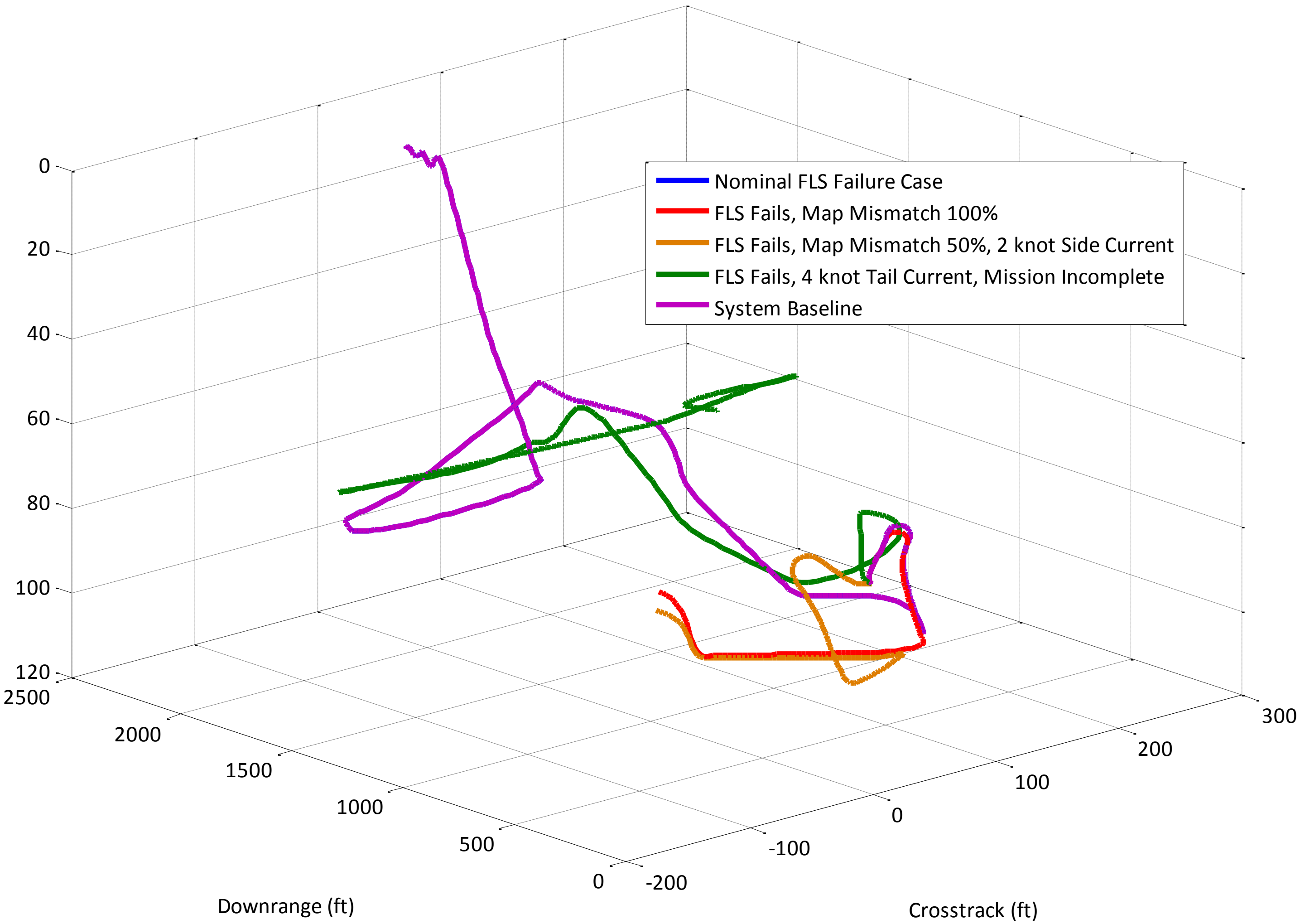
- Assistant Secretary of the Navy (ASN) Research Development and Acquisition (RDA)
  - Large scale multi-unit test scenarios with many interoperating systems
  - Amy Markowich
- Marine Corps Warfighting Lab
  - Extensive hands-on evaluation of aerial/ground robotics in relevant environments & missions
  - Jim Lasswell
- NAVSEA (Combatant Craft Division)
  - In-Water testing of USV, advocates for division of testing at key interfaces – Perception, Effectors, Planning & Control
  - Eric Hansen
- US Army Maneuver Battle Lab
  - Live/Virtual/Constructive testing with manned and unmanned systems
  - Harry Lubin
- Army Research Laboratory (ARL)
  - Autonomous ground vehicle behavior testing with NIST partnership
  - Marshal Childers
- MIT PATFrame
  - TRMC funded development of test planning framework for SoS
  - Ricardo Valerdi

Example Results: Current Direction Effects

- Current Direction Strong Effect
  - Logical result
  - Almost 4 km Max Error in Surface Position
  - From Markov model, sonar failures drive reliability
  - Fin, Prop, & attitude sensor failures much less probable
  - Failure effects same magnitude as environment
  - *Suspect impact cases and 4knot head currents biasing results*
- Need to set bounds on responses
  - Define overall PASS/FAIL limits
  - Summarize high level results more clearly



UUV Path For Select Forward-Looking Sonar Failures



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