National Aeronautics and Space Administration

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SPACE LAUNCH SYSTEM

Optimization of Second Fault Detection Thresholds to Maximize Mission Probability of Success

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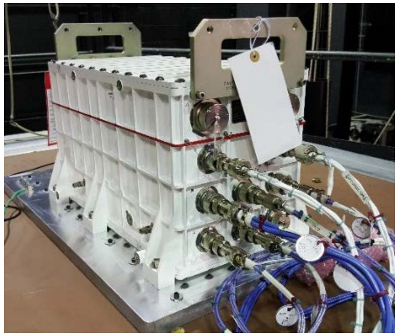
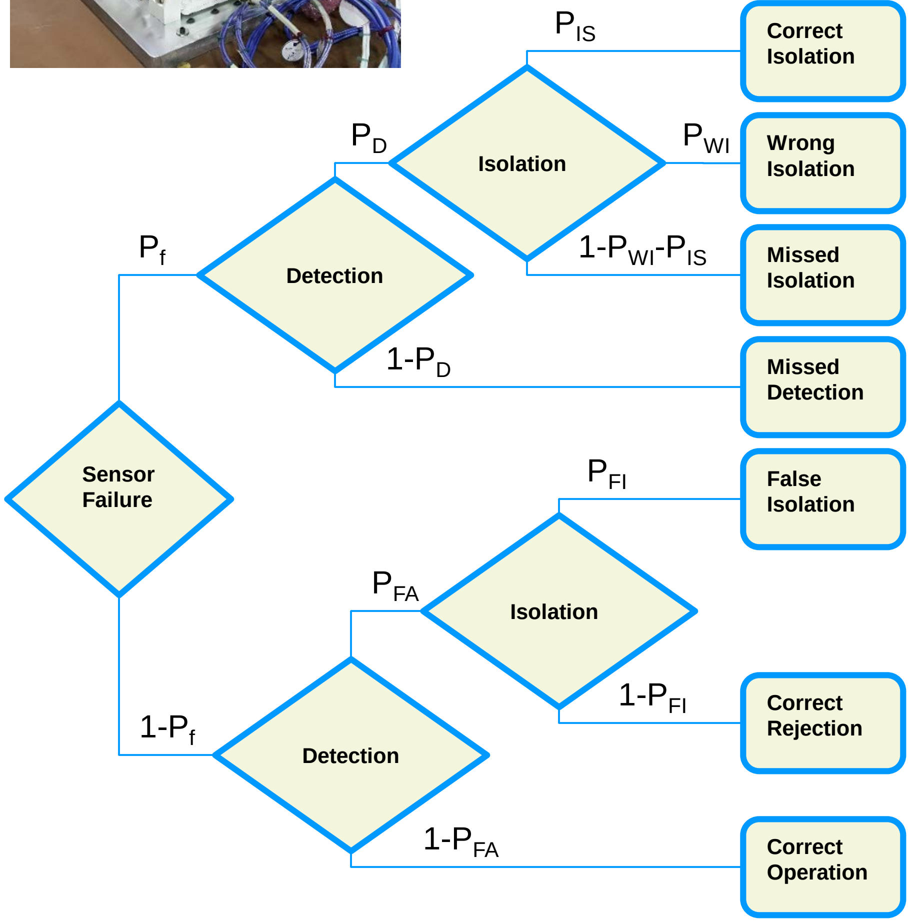
Overview

- Introduction to INS Fault Detection
- Fault Assessment Approach
- Threshold Design and Optimization
- Results and Capability
- Verification with Integrated Vehicle Simulation
- Conclusions

Fault Detection Need and Approach

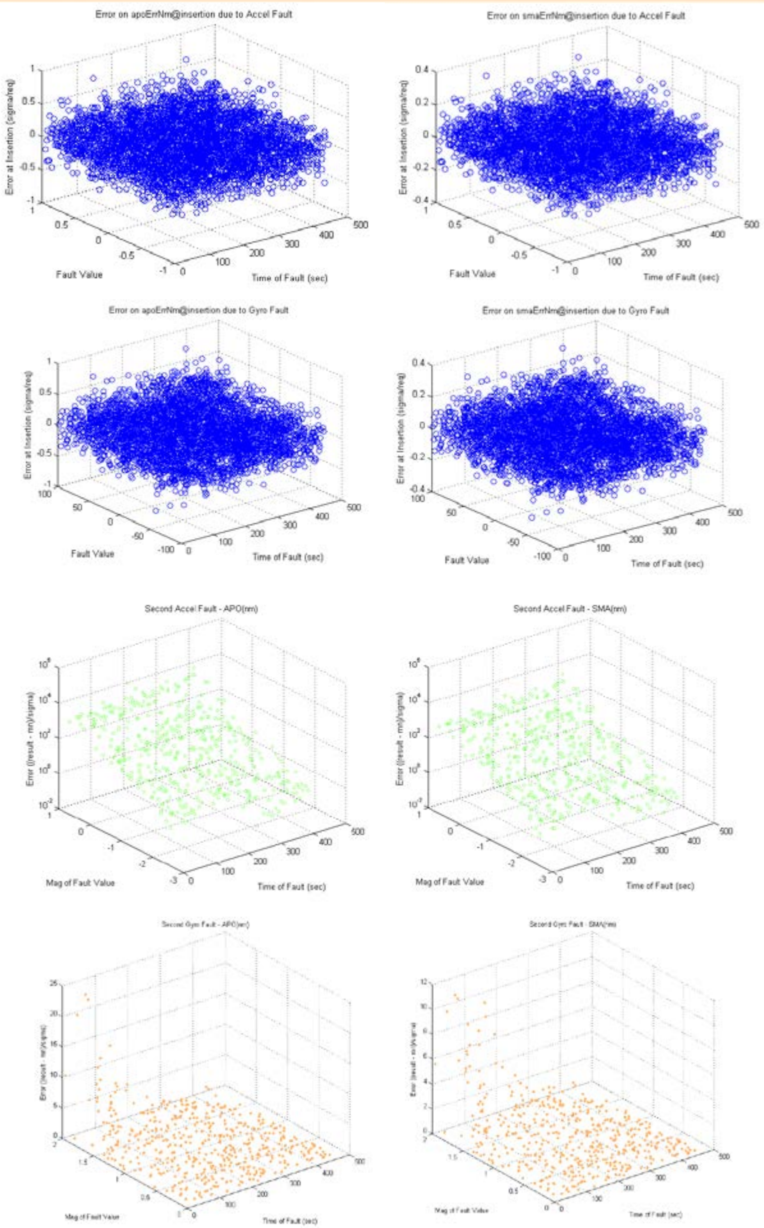
- **Goal to optimize thresholds for second fault detection to maximize probability of mission success**
- **Vehicle and Sensor Requirements**
  - Insert payload within a defined orbital envelope (SLS)
  - Navigation accuracy along a reference trajectory (INS)
  - Meet mission with single fault of each sensor type (INS)
  - Detect second sensor fault (INS)
- **Optimization enabled by simulation tools and hardware insight**
  - Detailed and verified INS model with full simulation of onboard FDIR functionality
  - Modelling fault events in sensor outputs as changes in error statistics





Fault Detection Capability

- **Detailed Modeling Approach**
  - Common INS model
  - Integration within full 6DOF model (MAVERIC)
  - Standalone analysis tools
- **First Fault**
  - Tied to insertion accuracy requirements with single fault of gyroscope and accelerometer
  - Developed by vendor (HI) with knowledge of sensor characteristics and integrated performance using heritage methodology
- **Second Fault**
  - Allows for expansion of thresholds to take advantage of vehicle-level margins
  - Minimizing chance of abort scenarios when vehicle would meet requirements
  - Assessed failures across sensor axis, fault type, and time over flight



Threshold Design and Development

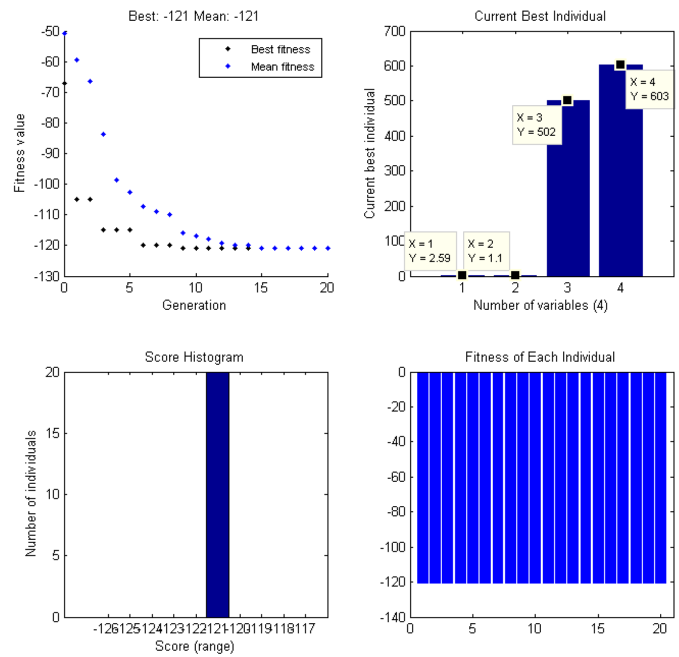
- **To maximize mission probability of success, tie thresholds to time of flight**
  - Sensitivity to failures reduces over flight
    - large failure late in flight might not be as bad as a small failure early in flight
  - Navigation sensitive to small errors integrated over time
- **Developed table capturing fault status over mission**
- **Performed sensitivity analysis to determine key design parameters**
  - Reduction in number of variables

Mode	Description
Nom	No detected sensor channel failures
AF	One accelerometer channel has faulted, but all gyroscopes are still good
GF	One Gyroscope channel has faulted, but all accelerometers are still good
AFGF	One Gyroscope and one Accelerometer have each faulted

MET Range (ms) (from, to)		NOM	AF	GF	AFGF
0	10000	2	9	16	23
10020	50000	3	10	17	24
50020	120000	4	11	18	25
120020	150000	5	12	19	26
150020	200000	6	13	20	27
200020	300000	7	14	21	28
300020	600000	8	15	22	29

Optimization via Genetic Algorithm

- **Each objective function execution consists of a Monte Carlo Assessment with random faults and dispersed sensor errors**
  - Assessed detection capability and insertion performance
- **Using MATLAB's Genetic Algorithm with Optimization and Parallel Processing Toolkits**
  - Stochastic approach to threshold optimization
- **Initial results optimized thresholds for faults in each specific phase separately**
  - Poor behavior on integrated analysis
- **Optimized all thresholds at once for faults across entire mission**
  - 7 Phases X 2 parameters/phase = 14 design variables
  - Simulated random failures across entire mission



FITNESS = -1(number of cases that meet requirement and not detected) + (number of cases that did not meet requirements and were not detected)*

Results and Verification

- **Capability of optimized thresholds**
  - Limited benefit from further expansion of accelerometer limits
  - Significant benefit from opening up gyroscope limits
- **Verification process**
  - Implementation of threshold table and schedule algorithms into 6DOF simulation tools
  - Large Monte Carlo assessment with random 2nd failures in accelerometer and gyroscope (separately) to verify performance
  - Characterized performance against null and scale factor shifts
- **Off-nominal analysis**
  - Analysis process repeated for engine out cases

		Baseline/Fixed Threshold			**Optimized Single Thresholds**			**Optimized Threshold Schedule**		
Type of Fault	Time of 2nd Fault	# Met	# Met + Not Detect	# Not Met + Not Detect	# Met	# Met + Not Detect	# Not Met + Not Detect	# Met	# Met + Not Detect	# Not Met + Not Detect
Accel.	[10, 500]	194	153	32	194	142	32	194	145	32
Gyro.	[10, 500]	2554	183	0	2529	1803	354	2564	1930	216

Conclusions and Future Applications

- **Difficulty in optimizing thresholds for complex missions for complex systems**
  - Limited data to feed forward for parameters from hardware design
  - Approach based on system-level requirements as opposed to hardware tolerance/specifications – ***enabled by program's model-based design and requirements approach***
  - Requires knowledge of sensitivities of integrated vehicle to fault events – ***enabled by detailed and verified INS model***
- **Monte Carlo probabilistic assessment increases runtimes**
  - Length of scenario, number of variables, number of cases required to generate sufficient statistics
  - Limited population size for optimization approach
- **Potential Improvements**
  - Prime candidate for further parallelization
- **Future application to in-space missions**
  - Longer mission timelines = more variability and more runtime
  - Difficulty in defining phases, times due to expanded timeline
  - With integration of GPS aiding, more complex FDIR interactions

Thank you!

Any questions?