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Dependability Quantification and Assurance of Mission-critical Software Systems

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Agenda

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- Problem/Approach
- Relevance to NASA
- Current Capability and Results
- Planned Capability
- Technical Solutions and Remaining Technical Challenges
- Backup Information

Problem/Approach (1)

- **Software systems continue to increase in size, complexity, and importance to the success of NASA missions. For the foreseeable future, software systems will continue to harbor residual faults.**
- **Problem is to minimize number of introduced faults and number of residual faults that manifest as significant failures.**
  - Identify potential for fault introduction during early stages of development.
  - Design and implement mechanisms for tolerating software-related defects observed during previous and currently operating missions.
  - Develop mechanisms for preventing/mitigating effects of residual faults that manifest as failures during mission operations.
    - Run-time model checking
    - Rejuvenation (controlled full or partial reset to revert to known safe state).

Problem/Approach (2)

- **Goal: develop techniques to handle the three classes of faults:**
  - Bohrbugs: consistently manifest themselves under well-defined conditions.
  - Mandelbugs: cause hard to reproduce failures.
  - Aging-related bugs: manifestation rate increases with execution time (e.g., memory leaks, improper termination of processes).
- **Plan to investigate model-checking and stochastic analytic modeling to demonstrate in a coordinated manner their applicability to and effectiveness for mission-critical software applications.**
  - Advanced model-checking to find Bohrbugs and concurrency-related Mandelbugs prior to runtime
  - On-line model-checking as a last line of defense against residual bugs.
  - Proactive failure avoidance techniques (e.g., software rejuvenation) for aging-related bugs to increase TTF
  - Reactive recovery: main mitigation for failures caused by Mandelbugs
    - Investigate analytical model-based fast recovery techniques to reduce TTR.

Problem/Approach (3)

Approach

1. Phase 1

- Analyze problem reports from current and historic JPL/NASA missions to identify most frequently encountered failure mechanisms in terms of three classes of faults
- Develop abstract models for correctness properties of collaborating system critical elements (e.g., recovery schemes)
  - Apply design-time model-checking using the Saturation algorithm and multi-way decision diagrams (MDDs).
- Develop quantitative dependability models to study and reduce the time to recover from failures.

Approach (cont'd)

2. Phase 2

- Identify and develop techniques to recover from Mandelbug-induced failures.
- Apply model checking:
  - At design time to verify abstract models of critical components to show that they satisfy correctness properties.
  - On-line when multiple applications and recovery procedures need to be verified in concert at deployment time.
- Develop and pilot training material on quantitative dependability modeling; provide guidelines, best practices of model-checking and analytic modeling.

Problem/Approach (5)

Approach (cont'd)

3. Phase 3

- Identify and develop appropriate techniques to proactively recover from aging-related bugs.
- Refine dependability models to include mitigations for aging-related bugs and reevaluate the dependability model.
- Extend abstract models to include mechanisms for recovering from aging-related bugs.
- Perform bounded run-time model-checking using linear temporal logic to verify the absence of specific faulty behavior within and across applications and to proactively steer a system towards "safer" execution scenarios.

Relevance to NASA (1)

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- **Residual software faults that manifest as failures during operations increase likelihood of adverse mission impact:**
  - Software complexity is increasing in response to increasingly complex mission goals and more complex spacecraft.
  - Software is used to control more spacecraft subsystems/components.
  - Previous work indicates:
    - Software failure intensity for spacecraft systems may be increasing.
      - A. Nikora, "Software Anomaly Trends for Space Missions", JPL internal presentation, October, 2007 (unpublished).
    - Proportions of different types of faults (Bohrbugs/Mandelbugs/Aging-related defects) have not changed significantly from mission to mission.
      - M. Grottke, A. Nikora, K. Trivedi, "An Empirical Investigation of Fault Types in Space Mission System Software," proceedings of 40th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN 2010), Chicago, IL, Jun 28 – Jul 1, 2010.
- **Techniques for identifying software faults during development are likely to be more effective if they are targeted to the most frequently occurring types of faults.**
- **Recognize that residual faults will occur in operational systems, and implement mechanisms to pro-actively avoid or mitigate their effects.**

Current Capability and Results (1)

- **Analyze problem reports from current and historic JPL/NASA missions to identify most frequently encountered failure mechanisms in terms of three classes of faults.**
  - Analyzing problem reports for same set of missions being analyzed for the task "Predicting Fault Types and Fault Links for Systems using Historical Data."
    - Also analyzing problems reported during spacecraft integration testing – dataset is somewhat larger than that for anomalies observed during mission operations.
    - A large number of new problem reports for MSL are available for analysis.
    - Approximately half-way through analyzing anomaly reports for ground software.
      - Many software-related failures classified as Bohrbugs appear to be:
        - Incorrect value for data initialization.
        - Incorrect parameter format/order when invoking a function.
        - Incorrect exception handling (unanticipated fault condition, wrong response to known fault condition). This last is consistent with earlier work by Lutz and Mikulski.

Current Capability and Results (2)

- **Develop abstract models for correctness properties of collaborating system critical elements (e.g., recovery schemes)**
  - Apply design-time model-checking using the Saturation algorithm and multi-way decision diagrams (MDDs).
  - In progress.
    - EDL for recent missions.
    - Onboard sequencing management/control:
      - Rollback/rollforward.
        - Rollback to checkpoint up to “N” times if fault encountered.
        - Noncritical mode: Suspend/terminate sequence if fault encountered more than “N” times.
        - Critical mode (e.g., orbit insertion, trajectory correction): Proceed past fault if fault encountered more than “N” times.
      - Sequence start, pause, resume, terminate.
        - Sequence starts/pauses/stops/resumes after it is commanded to do so.
        - No unexpected duplicate runs of sequence.
        - Proper pause/termination/resumption of child sequences.

Current Capability and Results (3)

- **Develop quantitative dependability model.**
  - Will use results of problem report analysis. In progress.
- **Develop training materials**
  - Classroom, on-line training.
  - Modeling guidelines.

Planned Capability (1)

- **Mechanisms for preventing and mitigating effects of specific types of faults**
  - During development
    - Identify most common types of failure mechanisms associated with Bohrbugs, Mandelbugs, and aging-related bugs. (in progress)
    - Develop correctness properties, abstract models for critical software elements. (in progress)
  - During operations
    - Proactively recover from aging-related bugs (e.g., rejuvenation)
    - Use bounded run-time model checking to verify absence of specific faulty behavior.
    - Proactively steer system towards “safer” operational scenarios.

Planned Capability (2)

- **Quantitative dependability model**
  - Dependability estimation and allocation.
  - Model dependability at system, component levels.
    - Hardware and software components.
    - Human dependability?
      - Not in original task scope, but results from earlier work indicate that up to 20% of anomalies observed for ground-based support software are related to operator error or misunderstanding.
      - Possible relation to “Command Process Modeling & Risk Analysis” task.
  - Include mitigations for Mandelbugs, aging-related bugs.

Planned Capability (3)

- **Training material for engineers.**
  - Classroom instruction.
  - On-line instruction (e.g., SATERN).
  - Guidelines.

Technical Solutions and Remaining Technical Challenges (1)

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- **Failure mechanisms**
  - Ensure representative sample of anomaly reports for analysis.
    - Preference given to “newer” missions.
    - Analyze reports for missions developed in-house as opposed to those that are contracted out.
    - Insufficient levels of detail in some problem reports prevent identification of failure mechanisms.
      - May introduce some bias into sample.
- **Correctness properties, abstract models of critical system elements.**
  - Collaboration with on-going AADL work may be possible.

Backup Information

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- Evidence for Increasing Software Failure Rates
- Trends in Fault Type Proportions for Flight Software
- Saturation Algorithm for Model Checking

Increasing SW Failure Rate?

Planetary Missions Flight Software

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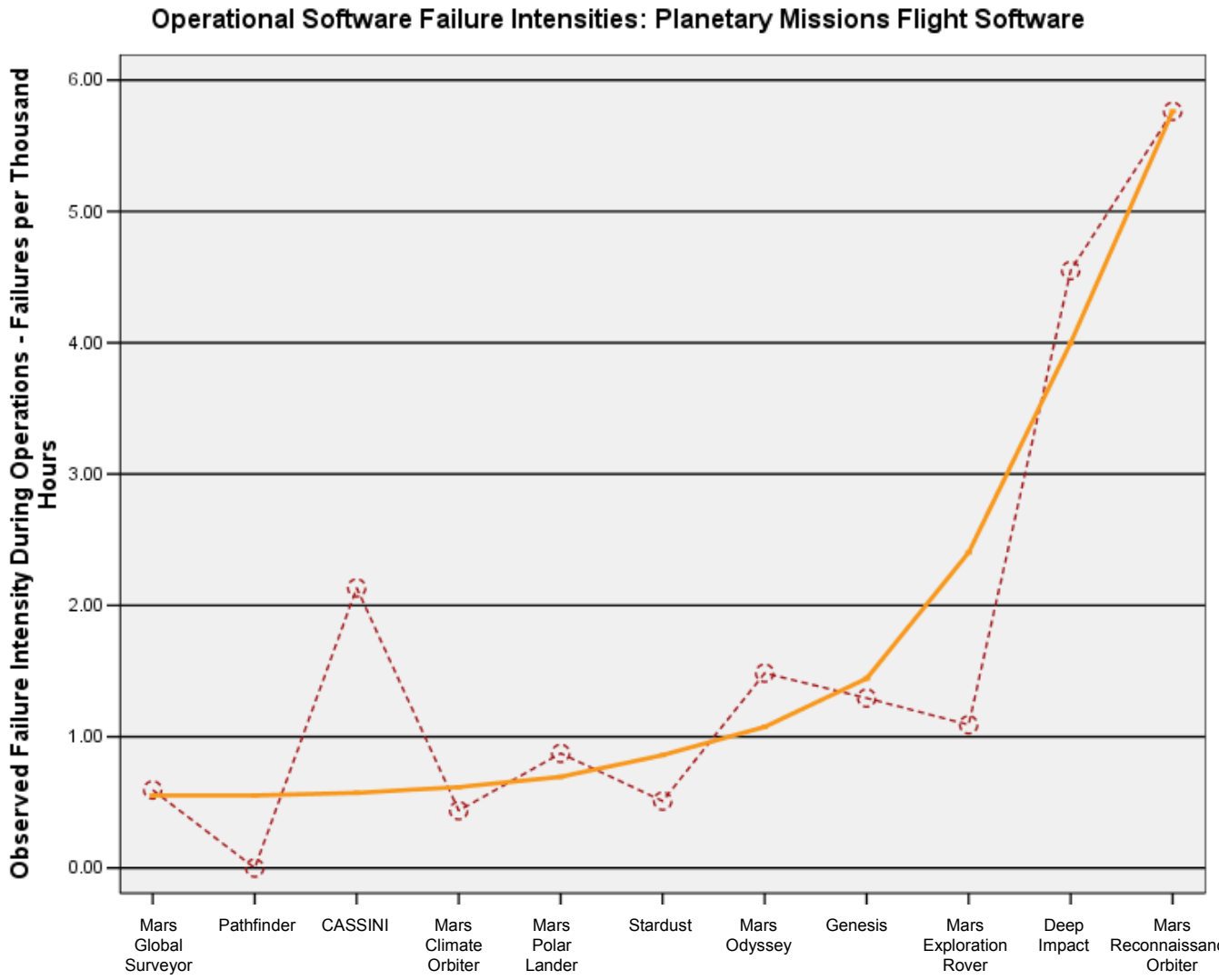

The interval between the first and last launch on this plot is 8.76 years. The interval between successive launches ranges from 23 to 790 days.

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Increasing SW Failure Rate?

Planetary Missions Ground Support Software

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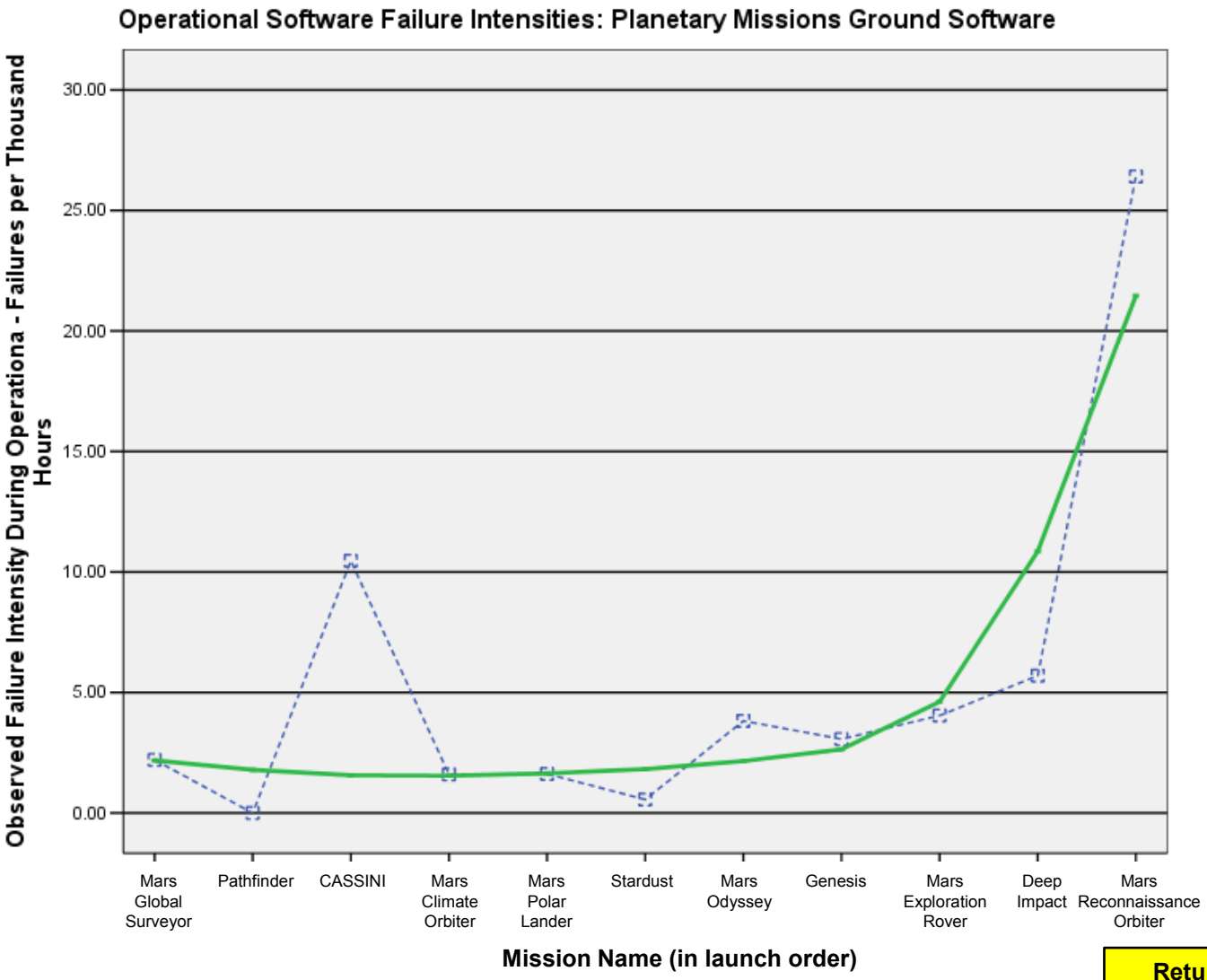

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Increasing SW Failure Rate?

Planetary Missions Ground Support Software

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- **Launch dates for missions included in failure rate analysis:**
  - Mars Global Surveyor: 07-Nov-1996
  - Mars Pathfinder: 04-Dec-1996
  - Cassini-Huygens: 15-Oct-1997
  - Mars Climate Orbiter: 11-Dec-1998
  - Mars Polar Lander: 03-Jan-1999
  - Stardust: 07-Feb-1999
  - Mars Odyssey: 07-Apr-2001
  - Genesis: 08-Aug-2001
  - Mars Exploration Rovers (Spirit): 10-Jun-2003
  - Mars Exploration Rovers (Opportunity): 07-Jul-2003
  - Deep Impact: 12-Jan-2005
  - Mars Reconnaissance Orbiter: 12-Aug-2005

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Trends in SW Fault Type Proportions

Planetary Missions Flight Software

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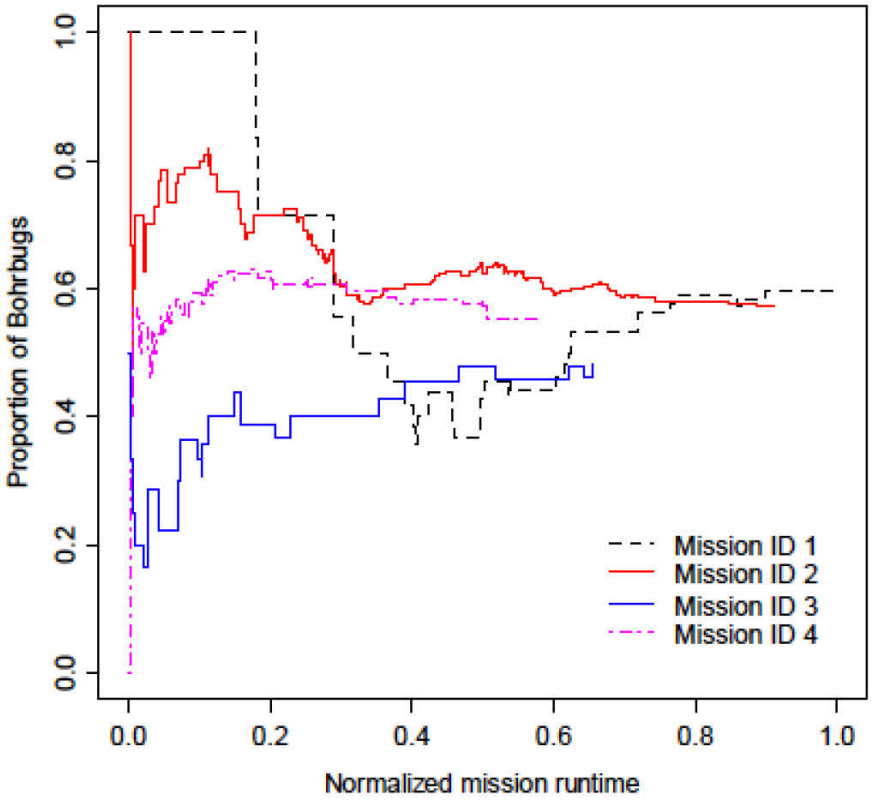

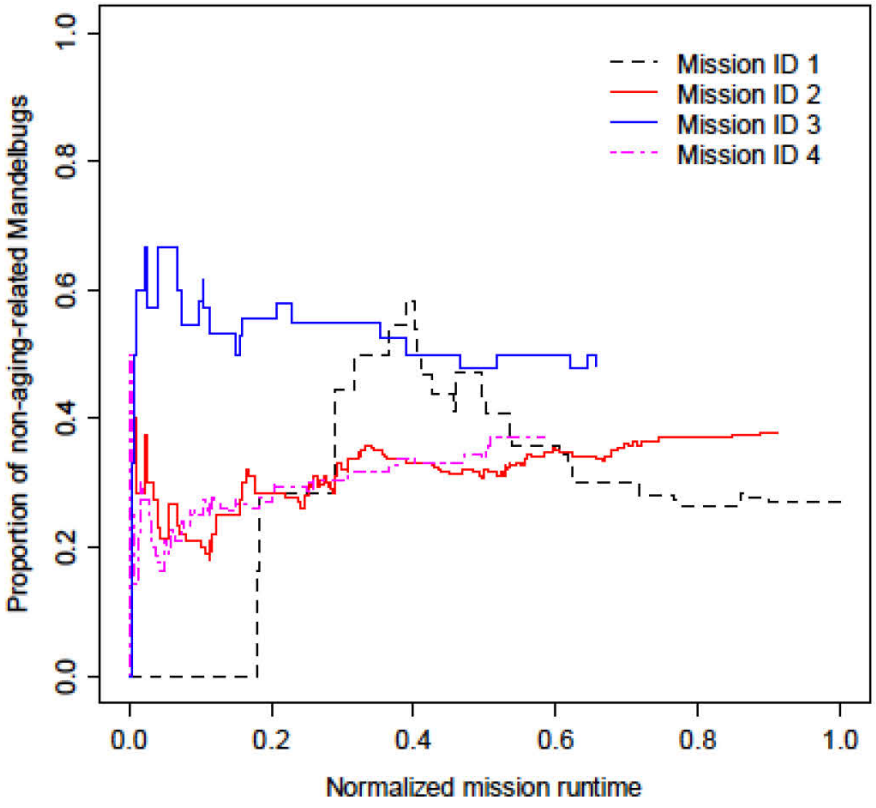

- Fault Type Proportions vs. Runtime for Four Earlier Missions (of 8 missions analyzed)
- Result: The proportion of Bohrbugs seems to settle at around the same value. Such a convergence to similar values is less obvious for the other fault types.

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Trends in SW Fault Type Proportions

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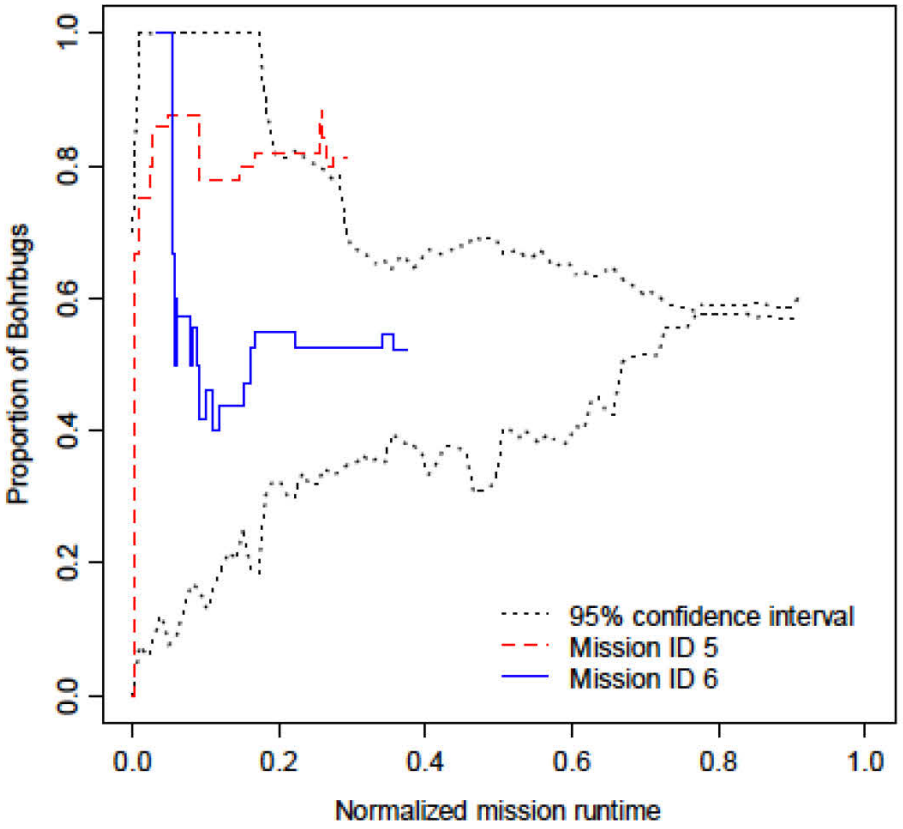

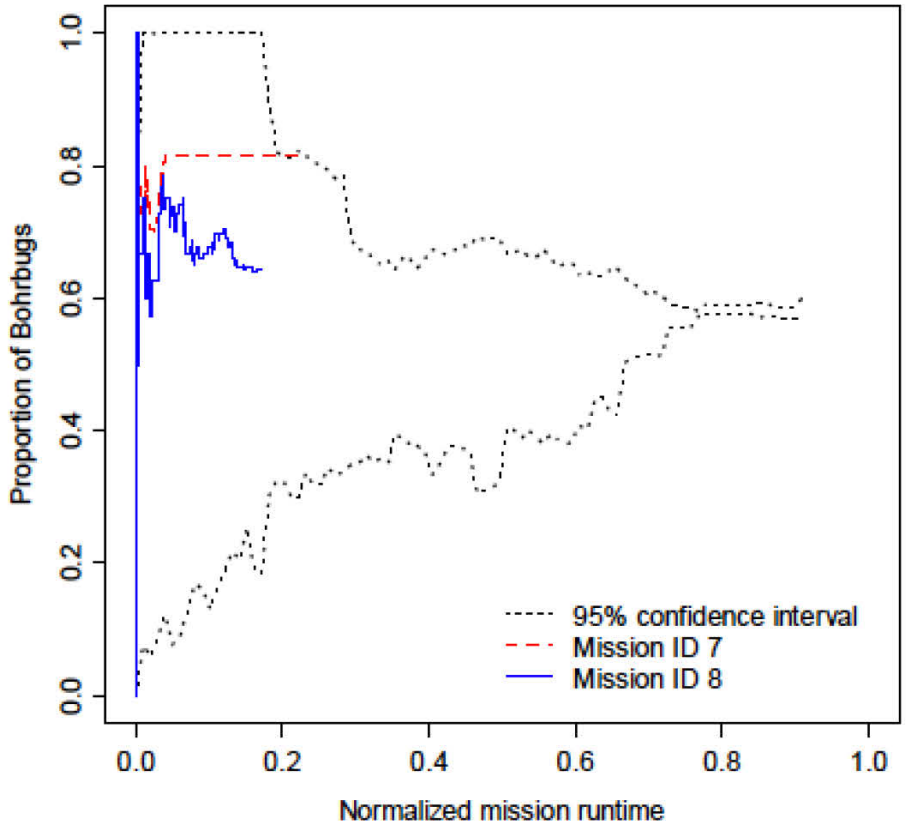

- Confidence intervals obtained for the earlier four missions, and Bohrbug proportions for the four later missions.
- Result: For two of the four later missions, the Bohrbug proportions observed are higher than expected.

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Trends in SW Fault Type Proportions

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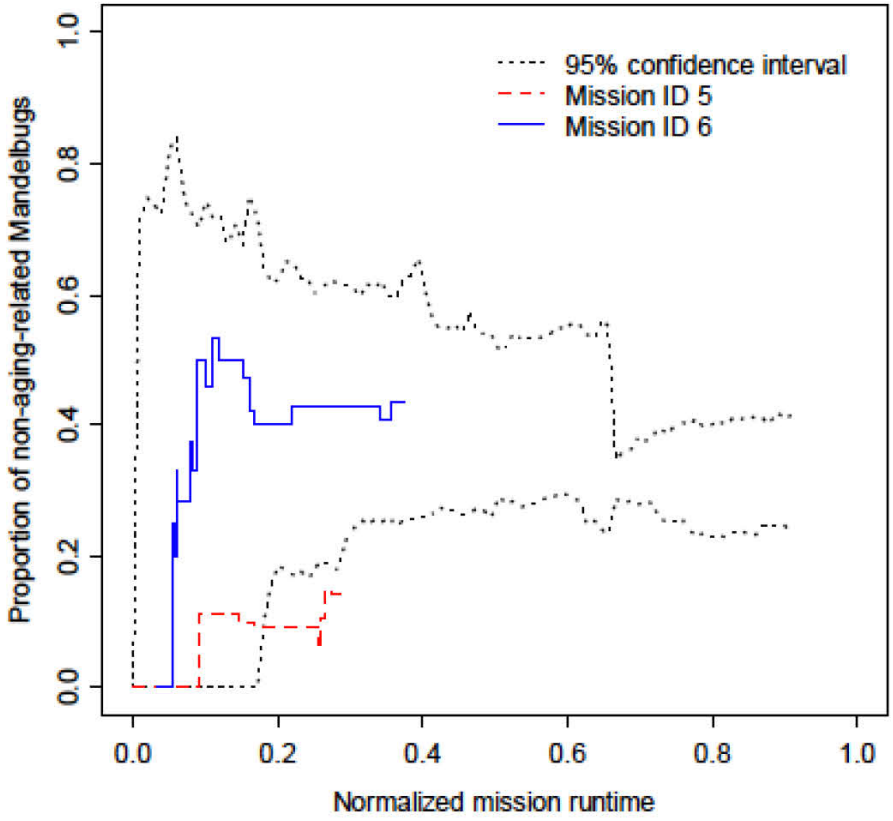

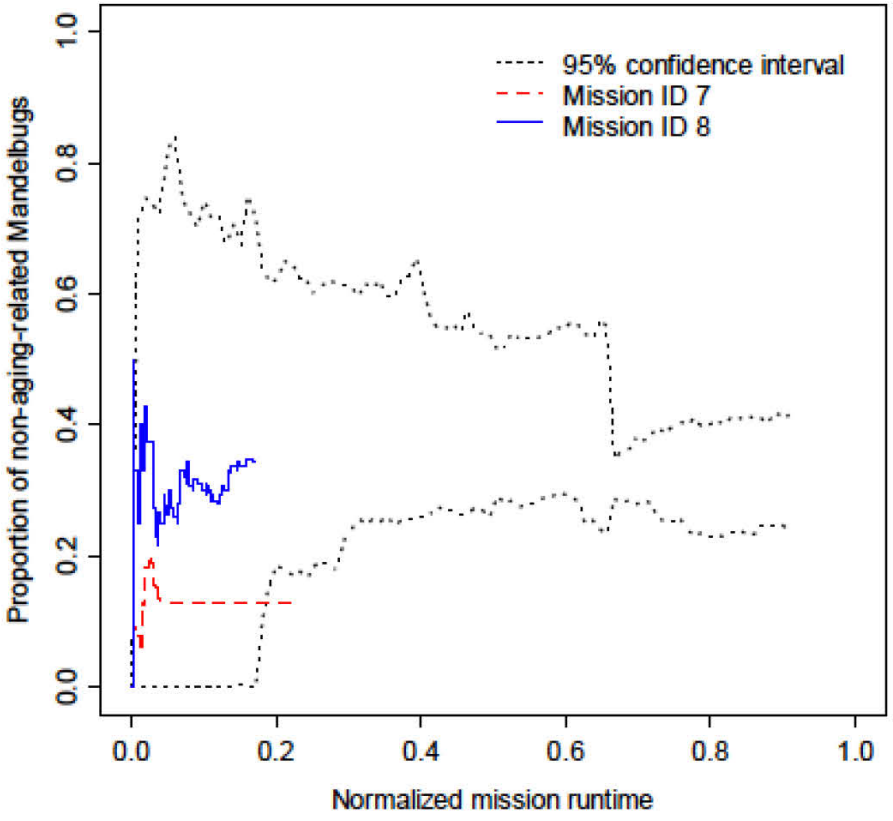

- Confidence intervals, and proportions of non-aging-related Mandelbugs for the four later missions.
- Result: The proportions of non-aging-related Mandelbugs are lower than expected for two of the four later missions.

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Saturation Algorithm for Model Checking

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- **Efficient technique to generate state spaces of asynchronous systems for model checking[1].**
  - Applicable to complex critical systems (e.g., spacecraft on-board control software) for which state space volume can be very large.
  - Based on Multi-valued Decision Diagrams (MDDs).
    - For event-based asynchronous systems, each event updates just a few components of a system's state vector.
    - Requires only the application of local next-state functions and the local manipulation of MDDs.
      - Compare to classic BDD-based techniques which construct state spaces by iteratively applying a single, global next-state function which is itself encoded as a BDD.
    - Experimental results show significant improvements in speed and memory over other state-space generators.

1. G. Ciardo, G. Luettgen, and R. Siminiceanu. Saturation: an efficient iteration strategy for symbolic state-space generation. In Proc. Tools and Algorithms for the Construction and Analysis of Systems (TACAS 2001), pages 328-342. Genova, Italy, Apr. 2001. Springer-Verlag.

Return to Current Capability (2)