An Uncertainty Structure Matrix for Models and Simulations

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Introduction

Acronyms

- **AIAA**  American Institute of Aeronautics and Astronautics
- **CAIB**  Columbia Accident Investigation Board
- **CY**  Calendar Year
- **EMB**  Engineering Management Board
- **M&S**  Modeling and Simulation
- **MER**  Mission Evaluation Room
- **MMT**  Mission Management Team
- **NASA**  National Aeronautics and Space Administration
- **OCE**  (NASA) Office of Chief Engineer
- **RTFTG**  Return to Flight Task Group
- **SME**  Subject Matter Expert
- **UA**  Uncertainty Analysis
- **UM**  Uncertainty Management
- **UP**  Uncertainty Propagation
- **UQ**  Uncertainty Quantification
Introduction
Comparison of Software Types

- Command, control, display, and support software
  - Provides a service function to its operators
    - Flight command / control within certain sets of predefined operational conditions
    - Information about the past, current, or future states of an aerospace vehicle during operations
    - Automation of a sequence of steps
      - For safety reasons (i.e., pilot cannot respond quickly enough)
      - Eliminate drudgery
    - Transforms the responses from various vehicle sensors into digital or analog displays for human interpretation
    - Enables access to information at the proper times and in the proper formats

- Modeling and Simulation (M&S) software
  - Intended to represent an actual physical, or imagined, reality
  - Involves uncertainty from various sources
  - Must be credible within a given decision-making situation
Introduction
Comparison of Software Types (2)

• Command, control, display, and support software
  – Universally expected to work correctly all the time
    • Incorrect data input flagged; incorrect answers are not permitted
    • Verification means that the software contains no errors
    • Validation means that the software commands or controls the vehicle, system, or subsystem as intended
    • Correctness can usually be demonstrated easily / without question
  – Generally developed under strict management processes
  – Requirements, policy, guidelines, and best practices generally target, and use language familiar to, the software engineering community
  – No consideration of uncertainty

• M&S software
  – Explicit consideration of uncertainty is required
    • Imperfectly modeled physics (approximation of, or unknown, physics)
    • Numerical approximations (e.g., curve fits and response surfaces)
    • Variability within the physical processes modeled
  – Natural consideration of UQ and UM practices and credibility of the M&S effort for intended application (e.g., see AIAA 2008-2156)
History and Context
Chronology of Relevant Events

Columbia Accident
Feb. 1, 2003

Columbia Accident
Investigation Board
(CAIB Report)
August 26, 2003

CAIB: Shuttle-specific Recommendations, Observations and Findings

Diaz: More generalized Recommendations, Observations, Findings and Actions
=> Action: develop NASA Standard for Models & Simulations

RTFTG: Evaluation of CAIB follow-up

A Renewed Commitment to Excellence (Diaz Report)
Feb. 9, 2004

Uncertainty Structure Matrix

Return to Flight Task Group (Stafford-Covey Report)
August 17, 2005

NAFEMS 2020 Vision of Engineering Analysis and Simulation
History and Context: Detailed Timeline

- **CY1980**
  - Challenger Accident: 1/28/1986
  - Rogers Report

- **CY1990**
  - Uncertainties: NASA budget, Shuttle lifetime, O-ring seals, and foam / ice shedding

- **CY2000**
  - Columbia Accident: 2/1/2003
  - CAIB Report
  - RTFTG Final Report

- **CY2008**
  - Here we are today

Author’s start at NASA

- Rogers Report
- Challenger Accident: 1/28/1986
- Columbia Accident: 2/1/2003
- CAIB Report
- RTFTG Final Report
- Diaz Report
- Uncertainties: NASA budget, Shuttle lifetime, O-ring seals, and foam / ice shedding
History and Context: Relevant Comments

About the Challenger Accident

- **Rogers Report (1986):** NASA should establish an STS Safety Advisory Panel reporting to the STS Program Manager ... [on] ... operational issues ... and risk management.

- **Rogers Report (1986):** NASA should establish an Office of Safety, Reliability and Quality Assurance ... [with] ... direct authority for safety, reliability, and quality assurance throughout the agency ... [including] ... reporting and documentation of problems, problem resolution and trends.

- **CAIB Report (2003):** Shuttle reliability is uncertain, but has been estimated to range between 97 and 99 percent. **If the Shuttle reliability is 98 percent, there would be a 50-50 chance of losing an Orbiter within 34 flights** [Challenger was flight 25] ... The probability of maintaining at least three Orbiters in the Shuttle fleet declines to less than 50 percent after flight 113. - The Office of Technology Assessment, 1989

- **CAIB Report (2003):** And although it is a subject that meets with reluctance to open discussion, and has therefore too often been relegated to silence, the statistical evidence indicates that we are likely to lose another Space Shuttle in the next several years ... probably before the planned Space Station is completely established on orbit. This would seem to be the weak link of the civil space program – unpleasant to recognize, involving all the uncertainties of statistics, and difficult to resolve. - The Augustine Committee, 1990

Note: Endeavor built to replace Challenger; finished in May 1991; Shuttle fleet then back up to 4 vehicles; Columbia was **flight 113**!
History and Context

Relevant Comments from the CAIB Report about the Columbia Accident

• Engineering solutions … should have included a quantifiable range of uncertainty and risk analysis

• Management … should have demanded such information ...

• The … absence of a clear and open discussion of uncertainties … should have caused management to probe further …

• The … uncertainties … were never presented or discussed in full to either the Mission Evaluation Room (MER) or the Mission Management Team (MMT) …

• The uncertainties and assumptions that signaled danger dropped out of the information chain when the MER manager condensed the Debris Assessment Team’s formal presentation to an informal verbal brief at the MMT meeting
History and Context

Relevant Comments from the RTFTG Report about the Columbia Accident

• The MMT needs to continue to improve and mature their integrated risk-versus risk identification, assessment, decision making ... this includes the certainties and uncertainties that exist in the various analytical tools and models used by the MMT

• The uncertainties in one model (or system) inherently feeds into and compounds the uncertainty in the second model (or system) ... Further compounding the modeling challenge is the fact that the models ... are deterministic, yielding point estimates, without incorporating any measure of uncertainty in the result. Methods exist to add probabilistic qualities to the deterministic results, but they require knowledge of the statistical distribution of the many variables affecting the outcome

• But, as the Columbia accident showed, in a high risk environment that involves many unknowns like human space flight, experience and instinct are poor substitutes for careful analysis of uncertainty
Early Form of Uncertainty Structure

Impact of Uncertainty Quantification (UQ) to Risk

Stage 1
No systematic effort
Inhibits the use of CFD

Stage 2
Uncertainty management

Stage 3
Reported uncertainty + confidence level for validation domain

Stage 4
Reported prediction error + confidence level

Stage 5
Certification + Protocols

All
Risk Assumed by Decision Maker
None

A question about how we know at what stage an M&S is led to current form, described subsequently, with canonical elements and levels of achievement.
Uncertainty Structure Matrix: Overview

<table>
<thead>
<tr>
<th>Canonical Elements</th>
<th>Element 1</th>
<th>Element 2</th>
<th>Element 3</th>
<th>Element 4</th>
<th>Element 5</th>
<th>Element 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td></td>
<td></td>
<td></td>
<td>M&amp;S current state</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 2</td>
<td>M&amp;S current state</td>
<td></td>
<td></td>
<td></td>
<td>M&amp;S current state</td>
<td></td>
</tr>
<tr>
<td>Level 3</td>
<td></td>
<td>M&amp;S current state</td>
<td></td>
<td>M&amp;S future state</td>
<td>M&amp;S current State</td>
<td></td>
</tr>
<tr>
<td>Level 4</td>
<td>M&amp;S future state</td>
<td>M&amp;S future state</td>
<td>M&amp;S current &amp; future States</td>
<td></td>
<td>M&amp;S current &amp; future States</td>
<td></td>
</tr>
<tr>
<td>Level 5</td>
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</tbody>
</table>

Lower level of achievement = greater potential for uncertainty under estimation and greater risk assumed by the decision maker
A. **Code verification:** The process of determining that a model implementation accurately represents the developer's conceptual description of the model and that numerically correct answers to the coded equations are obtained.

B. **Parameter calibration:** The process of optimization/adjustment of model parameters in the presence of numerical and experimental error.

C. **Model validation:** The process of determining the degree to which a model is an accurate representation of the real world.

D. **Numerical error estimation:** The process of determining an estimate of the residual numerical error based on the computed results.

E. **Model error estimation:** The process of estimating the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

F. **Outcome adjustment:** The process of adjustment/update of solutions based on either experimental data or higher-fidelity simulations.
Uncertainty Structure Matrix
General Level Definitions

1. **No process**: verification and validation are clearly inadequate; uncertainty is unknown.
2. **UM**: confidence building process that is achieved through unit problems and comparisons. SME must be used.
3. **UQ for validation**: a defined, systematic, documented process is followed to bound and quantify uncertainty for validation.
4. **UQ for prediction**: a defined, systematic, documented process is followed to bound and quantify uncertainty for prediction. The structure of the problem is understood adequately for safe prediction.
5. **Independent UQ for prediction**: an additional, independent process is carried out for high-confidence prediction error quantification.
Uncertainty Structure Matrix
Specific Level Definitions: Code Verification

1. The code has not been verified for the intended uses.
2. Verification has been performed for related problems, including unit problems and problems that are similar to the intended application. Comparisons have been made across codes for problems that are similar to the intended application. [Logically also includes formal methods]
3. A systematic, documented process (including all relevant unit problem) has been carried out to verify the code for validation.
4. A systematic, documented process (including all relevant unit problems) has been carried out to verify the code for prediction.
5. An additional systematic, documented process (including all relevant unit problems) has been independently carried out to verify the code for the intended application.
Uncertainty Structure Matrix
Specific Level Definitions: Parameter Calibration

1. The parameters have not been calibrated for the intended uses.
2. Parameters have been calibrated for unit problems and are believed to be reasonable for the intended application.
3. A systematic, documented process has been carried out to calibrate the model(s), including estimates of numerical and experimental error, for all relevant unit problems.
4. Not applicable (no additional requirement beyond Level 3).
5. An additional systematic, documented process has been independently carried out to verify the calibration of the code, including estimates of numerical and experimental error.
Uncertainty Structure Matrix
Specific Level Definitions: Model Validation

1. The model has not been validated for the intended uses.
2. Validation has been performed for related problems, including unit problems and problems that are similar to the intended application.
3. A systematic, documented process has been carried out to validate the model(s), for all relevant unit problems, to include estimates of numerical and experimental error.
4. A systematic, documented process has been carried out to validate the model structure for the intended application (including uncertainty and physics boundaries) adequately for safe prediction.
5. An additional systematic, documented model validation has been independently performed by an SME.

Note: this element really only addresses software issues; approximations introduced through execution of the software are better addressed by the NASA Standard for M&S.
Uncertainty Structure Matrix
Specific Level Definitions: Numerical Error Estimation

1. Numerical error estimation has not been performed for the intended uses.
2. Convergence residuals have been estimated for problems that are similar to the intended application.
3. A systematic, documented process has been carried out to quantify the residual numerical error for the intended application.
4. Not applicable (no additional requirement beyond Level 3).
5. An additional systematic, documented process has been independently carried out to quantify the residual numerical error for the intended application.

Note: this element readily applies to the solution of partial differential equations; the authors believe this can be easily extended to include any strict examination of the modeled temporal, spatial, or statistical behaviors.
Uncertainty Structure Matrix
Specific Level Definitions: Model Error Estimation

1. Model form error has not been estimated for the intended uses.
2. Model form error has been estimated for *unit problems*. Comparisons have been made across models for problems that are *similar to the intended application*.
3. A systematic, documented process has been carried out to *quantify the model error based* upon comparisons with available experimental data.
4. A systematic, documented process has been carried out to *quantify the prediction model error*.
5. An *additional systematic, documented process* has been independently carried out by an SME for the intended application to quantify the model error.

Note: this element really only addresses software issues; approximations introduced through execution of the software are better addressed by the NASA Standard for M&S.
Uncertainty Structure Matrix
Specific Level Definitions: Outcome Adjustment

1. The adjustment uncertainty has not been estimated for the intended uses.
2. The *uncertainty of the adjustment process*, and the *uncertainty associated with the higher fidelity source* that was used to provide input to the adjustment process, have been *captured at least at level two* across the other five canonical elements.
3. A defined, systematic, documented process has been followed to *bound and quantify uncertainty for the adjustment* with respect to validation.
4. A defined, systematic, documented process has been followed to bound and quantify uncertainty of the adjustment with respect to prediction. The structure of the problem is understood adequately for *safe prediction of the adjustment*.
5. An *additional, independent process* has been carried out for high-confidence prediction error quantification for the adjustment.

Example: an aerodynamic database developed for one configuration or flight condition that is later applied to a different configuration or flight condition through the use of defensible increments.
Conclusions

• Uncertainty structure matrix presented and described with
  – Six canonical elements common across many M&S: code verification, parameter calibration, model validation, numerical error estimation, model error estimation, outcome adjustment
  – Five rows that describe progressively more rigorous levels of UQ and UM practices for M&S applications
• Lower level of achievement = more risk assumed by the decision maker due to the potential that uncertainties have been underestimated
• Higher level of achievement = less risk assumed by the decision maker
• The matrix was intended to be inclusive of all M&S
• M&S practitioners can identify current and possible future states of their M&S application
• Estimates can be developed regarding the specific steps, cost, and schedule that would required to move an M&S to higher levels of achievement
• Supports design under uncertainty, improved products, and risk-informed decision making processes