ISWHM: Tools and Techniques for Software and System Health Management

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Overview

- Ingredients of a GN&C System
- Selected GN&C Testbed example
- HM of major ingredients
- ISWHM testbed architecture
- Conclusions and next Steps
GN&C (Guidance, Navigation, and Control) is one of the most central software system in an aircraft/spacecraft

• Guidance: “Where do I want to go and how do I get there?”
• Navigation: “Where am I?”
• Control: “Which thrusters do I need to use to keep my attitude stable?”
Typical GN&C Architecture

- “Black box”
- run at different speeds
  - G: 2Hz
  - N: 10hz-100Hz
  - C: 100Hz
- in different processes
- use comm layer

Typical architecture:
- PowerPC 750, RAM, Flash,
- IObus: MIL 1553 or CAN bus (automotive)
- OS: Real-time: VxWorks, RTLinux, OSEK compl.,...
SW Characteristics

- Are there specific software constructs used in specific components?
- These play a major role on how SWHM models will be constructed
- Typical characteristics include
  - numerical computations?
  - branches? mode logic? state machines?
  - loops?
  - complex algorithms? (e.g., optimization)
  - communications structure
  - signals
Our GN&C Testbed Example

- “re-designed” Apollo lunar lander Autopilot
- non-trivial GN&C example
- non-ITAR Simulink and Stateflow model
- Downloadable from Mathworks
The selected GN&C architecture is typical for many aeronautics applications:

- guidance for autopilot functions (in particular for UAV)
- navigation based on sensors (e.g., inertial reference unit, GPS)
- control of actuators (mainly control surfaces)
- implemented in software (often using model-based approaches), running on an embedded processor

Examples of related architectures are NASA IFCS, Dryden Platform Precision AutoPilot,

Our demonstration example was selected because of realistic GN&C functionality, easy availability of model (non-ITAR and does not contain proprietary code) and straight-forward models of components not relevant for SWHM.
Operation

• task: from attitude (0,0,0) obtain and keep attitude (0.1,0.05,0.02)
• use the given set of control thrusters
The original example does not contain any navigational components. The “true” attitude and position is fed back to the Guidance and Controller. We are adding some “mock-up” sensors and some navigational code.
• is used for simulation only.
• dynamics are described using differential equations (given acceleration, calculate position, rates, and rate changes)
Pilot Command Handling

• extremely simple in this example
• only the final position/attitude is provided

• SW characteristics:
  – data communication
  – range issues
  – timing issues
Guidance

• The guidance component contains the actual algorithmic “meat”

• Given the current state and the target state, find an optimal trajectory using as little fuel as possible and other constraints

• This algorithm uses a fairly elaborate state machine that is modeled here as a Stateflow diagram
Guidance

• SW characteristics
  – mainly discrete logic
    • if-then-else’s,
    • state machines, ...
  – internal state variables
• (mathematical) relation between sensors and actuators
• Characteristics: arithmetic code, delays, parameters. Usually very little SW branches
Navigation

- tries to estimate state of the vehicle given (noisy) sensor readings
- SW characteristics
  - Signal flow architecture
  - Kalman filters (recursive least square)
  - coordinate conversions
  - float-point arithmetic and matrix operations
  - few but important if-then-elses (e.g., to reset a diverging Kalman filter)
Injected Failures

• This model can be “broken” at multiple parts
  – broken or noisy sensors/actuators
  – singularities in navigation (“crossing the date line”, see F22 Raptors flying to Japan)
  – logic errors in the guidance state machine
  – communication between G,N,C SW components
  – OS “problems”: timing, stack, memory, ...
Our ISWHM Testbed

- Prototype testbed architecture to run the example software with/without failures and gather information from HW and SW sensors for further processing by the ISWHM reasoner (ISWHM server, not shown)
<table>
<thead>
<tr>
<th>SW Characteristics</th>
<th>G</th>
<th>N</th>
<th>C</th>
</tr>
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<tbody>
<tr>
<td>mode logic</td>
<td>Y</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>numerical</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>coordinates</td>
<td>N</td>
<td>Y</td>
<td>N</td>
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<tr>
<td>state machine</td>
<td>Y</td>
<td>N</td>
<td>N</td>
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<td>control loop</td>
<td>N</td>
<td>N</td>
<td>Y</td>
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<tr>
<td>Kalman Filter</td>
<td>N</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Algorithm</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Comm/OS</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Update</td>
<td>slow</td>
<td>med</td>
<td>fast</td>
</tr>
</tbody>
</table>
Analysis of Feedback

- (Feedback) loops are important for all kinds of iterative update
  - feedback control
  - iterative loops (for, while)
  - Kalman filters (Navigation)
  - optimization (while converging,...)
Simple Thermostat

- Thermostat is a simplest possible feedback control loop.
  - combines arithmetic/calculation with feedback
- Easy to understand, several ways to inject failures
- Similar to a highly simplified aircraft control system, where the heater could be a control surface and the sensed temperature corresponds to, e.g., a roll-rate sensor.
Operation

- Outside temp is a sin curve (bottom curve)
- Desired temp=15deg (constant)
- Controller: with threshold
- Shown:
  - Heater command (on/off)
  - Inside temperature
  - Outside temperature
- Nominal case
Off-nominal

- controller stuck open and close at $t=15$
Off-nominal II

- door remains open at $t=20$
Observables

• observables are time-series data
  – room temperature
  – heater on/off
Modeling Approaches

- translation of loop into a Bayes Network
- naive model is not a DAG
- BN must talk and reason about time series
- we experiment with several modeling approaches also using dynamic Bayes Nets
Dynamic BN

- temporal break-up
- adding Sensor nodes
- adding Health nodes

T=t-1

Therm

Htr

House

T=t

Therm

Htr

House

H

H'

T=t-1

T=t

local CPT (Conditional Probability Table)

<table>
<thead>
<tr>
<th></th>
<th>HtrOK</th>
<th>HtrBAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMD=</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>On</td>
<td>0.01</td>
<td>0.01</td>
</tr>
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</table>

Local CPT (Conditional Probability Table)
The full BN
Nominal/Off-nominal
Conclusions/Next Steps

• SWHM has to take onto specific SW characteristics
• BN has the potential
  – suitable for different SW “ingredients”
  – monitoring on different layers (OS, middle-ware, process level, individual SW component); modularity
  – potentially: generate SWHM BN from Simulink model (NOTE: ADAPT IVHM generates BNs from wiring diagrams)
• improvement of test-bed
  – navigation component
  – failure injection
  – ARINC653 or OSEK model
  – SWHM modeling for testbed system