Model-based Autonomy for the Next Generation of Robotic Spacecraft

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Objectives

• Define "model-based autonomy"
• Describe model-based executive technology (Titan)
• Describe application to representative space mission (ST7-Autonomy concept study)

Model-based Autonomy

Creation of embedded & robotic systems that manage interactions automatically, by reasoning from models of themselves and their environment.

• Enabling technology for highly robust spacecraft.

Model-based Autonomy

Creation of embedded & robotic systems that manage interactions automatically, by reasoning from models of themselves and their environment.

• Enabling technology for highly robust spacecraft.
• Adopts notion of model-based programming.
• Automates onboard sequence execution by tightly integrating goal-driven commanding, fault detection, diagnosis and recovery.
Objectives

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Model-based Execution

- Plant model describes behavior of each component:
  - nominal and off-nominal modes
  - qualitative constraints
  - probabilistic transitions
  - costs/rewards

- RMPL Control program specifies desired state trajectories:
  - encode reactive control sequences
  - refer to hidden states as if they were directly observable & controllable
  - include constructs for expressing:
    - Concurrent Task Management
    - Contingency Handling
    - Iteration
    - Preemption

  ```
  {when (ground-command = start-playback) do
    {sequence
      {do
        {always (transmitter-mode = downlinking-data) watching (ssr-playback = complete)}
      (transmitter-mode = idle)
      (downlink-status = succeeded)
    }
  }
  ```

- Sequencer executes control program:
  - takes activity goals from system-level planner
  - each activity invokes an RMPL control program
  - conditioned on current state from deductive controller
  - issues configuration goal states to be achieved by deductive controller

- Deductive Controller maps from states to sensors/actuators:
  - Mode Estimation uses plant model and observations to deduce current state (mode tracking, fault diagnosis)
  - Mode Reconfiguration takes in configuration goals, reasons through plant model to compute commands that achieve goal (nominal, fault recovery)
Model-based Execution

- Define "model-based autonomy"
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New Millennium ST7 Autonomy Mission Concept

- 6-month concept definition phase ended January 2002
- autonomy-ready s/c design based on primarily off-the-shelf components
- mission design highlighting:
  - onboard execution of activities normally commanded from ground
  - science-driven execution
- software tested demonstrations of component technologies

Scenario One: Downlink Data Block Activity
- Demonstrate control sequencer operation
- Demonstrate interaction with deductive controller

Scenario Two: Bus Controller Failure
- Demonstrate mode estimation and mode reconfiguration on more sophisticated plant models

Downlink Data Block Plant Model Overview

Objective: downlink a block of data from onboard storage to a specified ground station
Downlink Data Block Control Program Overview

Initial State:
- omniA in view of ground station
- no ground command received
- omniA in nominal mode (remains so throughout)
- omniB in nominal mode (remains so throughout)
- transmitter in idle mode
- switch set to enable omniB

- Set switch to enable appropriate omnidirectional antenna for downlink of streaming real-time telemetry (based on omni-in-view info from ACS)
- If switch gets stuck in wrong position, fail DownlinkDataBlock activity
- Otherwise, set transmitter to start streaming real-time telemetry so that ground can establish communication link

- When start-playback command received from ground, start downlinking data from onboard storage
**Downlink Data Block Control Program Overview**

- Set switch to enable appropriate omnidirectional antenna for downlink of streaming real-time telemetry (based on omni-in-view info from ACS)
- If switch gets stuck in wrong position, fail DownlinkDataBlock activity
- Otherwise, set transmitter to start streaming real-time telemetry so that ground can establish communication link
- When start-playback command received from ground, start downlinking data from onboard storage
- When downlink finished, idle transmitter and report success of DownlinkDataBlock activity

**Scenario 2: Bus Controller Failure**

- Bus Controller maintains power to the bus, making power distribution and communications possible.
- Cascading Failure
  - Reset Bus Controller
  - Power Cycle Bus Controller
  - Switch to Redundant Backup Bus Controller

**Concept Study Results**

- Scenarios address a number of operational use cases
- Highlight desired features for autonomous spacecraft control

<table>
<thead>
<tr>
<th>Nominal operations:</th>
<th>Fault operations:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• accept high-level activity goals and decompose into sequence of configuration goal states</td>
<td>• diagnose both single and multiple faults</td>
</tr>
<tr>
<td>• accept configuration goals and generate sequence of atomic plant commands</td>
<td>• manage completely unanticipated faults</td>
</tr>
<tr>
<td>• recovery by repairing faulty components</td>
<td>• recovery by using physical or functional redundancy</td>
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</tbody>
</table>
Conclusions

- Model-based execution bridges gap between system-level planning and real-time commanding
- Robustness in sense-decide-act loop
- Cost reduction / Risk reduction / Mission enabling
- Technology maturation:

Backup Slides

The Case for Spacecraft Autonomy

COST Reduction

RISK Reduction

Mission Enabling

COST Reduction

RISK Reduction

Mission Enabling

COST Reduction

RISK Reduction

Mission Enabling

COST Reduction

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RISK Reduction

Mission Enabling
“Autonomy Rules” in Current Application

RMPL Titan

Example from MESSENGER Safing and Fault Protection Requirements Specification (Flight Software Design to Support 1290 Rules)
### Class Definition:
```lisp
(defclass comm_subsystem ()
  (public state transmitter-state transmitter-mode)
  (public state switch-state switch-mode)
  (public state goal-status downlink-status)
  (public state ground-cmd-status ground-command)
  (public state omni-view-status omni-in-view)
  (public state process-status ssr-playback))
```

### Method Definition:
```lisp
(DownlinkDataBlock()
  (do-watching (or (downlink-status = failed) (downlink-status = succeeded))
    (if-then next-else next
      (omni-in-view = omniA)
      (parallel
        (switch-mode = enable-omniA)
        (when-done next (or (switch-mode = enable-omniA) (switch-mode = stuck-at-A))
          (do-watching (ground-command = start-playback)
            (always (transmitter-mode = streaming-rt-telem))))
        (when-done next (switch-mode = stuck-at-B) (downlink-status = failed))
        (when-done next (ground-command = start-playback)
          (sequence
            (do-watching (ssr-playback = complete)
              (always (transmitter-mode = downlinking-data)))
            (downlink-status = succeeded)))
      )
    )
 );
); When playback finished, report success of DownlinkDataBlock activity.
```

### Bus Controller Failure Scenario Descriptions

#### Assumptions:
- All devices have some feedback allowing detection of anomalous behavior (e.g., report of "no-comm")
- Two bus controller devices, BC_A & B, where BC_B is the backup for BC_A.

#### Scenario A
- Initial State: BC_A = on, BC_B = off
- Diagnosis: BC_A has a resettable failure
- Recovery: Issue reset command to BC_A
- Observation: Comm-status = COMM!

#### Scenario B
- Follow on to Scenario A where last observation is:
  - Observe: Comm-status = NO-COMM!
- Diagnosis: BC_A has a power cycleable failure
- Recovery: Issue cycle-power command to BC_A
- Observation: Comm-status = COMM!

#### Scenario C
- Follow on to Scenario B where last observation is:
  - Observe: Comm-status = NO-COMM!
  - Diagnosis: BC_A is broken
  - Recovery: Switch to backup bus controller.
  - Observation: Comm-status = COMM!