Contingency Software in Autonomous Systems

NASA OSMA Software Assurance Symposium
July 18-20 , 2006
Technical Briefing

Robyn Lutz, JPL/Caltech & ISU
Ann Patterson-Hine, NASA Ames

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and at NASA Ames Research Center, under a contract with the National Aeronautics and Space Administration. The work was sponsored by the NASA Office of Safety and Mission Assurance under the Software Assurance Research Program led by the NASA Software IV&V Facility. This activity is managed locally at JPL through the Assurance and Technology Program Office.

Contingency Software in Autonomous Systems

Problem

PROBLEM STATEMENT

Autonomous vehicles currently have a limited capacity to diagnose and mitigate failures.
We need to be able to handle a *broader* range of contingencies (anomalous situations).

A contingency is an event or condition (as an emergency) that may but is not certain to occur [Merriam-Webster]

Contingency Software in Autonomous Systems

Goals

1. Speed up diagnosis and mitigation of anomalous situations.
2. Automatically handle contingencies, not just failures.
3. Enable projects to select a degree of autonomy consistent with their needs and to incrementally introduce more autonomy.
4. Augment on-board fault protection with verified contingency scripts

Contingency Software in Autonomous Systems

Overview of this year's accomplishments (1)

- Completed Autonomous Rotorcraft Project (UAV) case study
  - Documented process & results (1 published & 2 submitted papers)
  - Performed hardware-in-loop testing of diagnostic tree
  - Project applied results, modifying camera controller to enable autonomous switching between color and video cameras
- Modeled MER Critical Pointing software to be reused on MSL
  - Called if commandability lost & before trajectory-correction maneuvers
  - Auto-generated diagnostic tree from TEAMS model of what is known when a "quit-failed" signal occurs
  - Supplemented available project documentation before reuse

Contingency Software in Autonomous Systems

Overview of this year's accomplishments (2)

- New case study
  - ADAPT emulates a typical spacecraft power system with redundant power buses, a solar panel, and battery storage
  - The approach for developing contingencies resulted in critical function identification and preliminary identification of required contingency plans
- Described work to date at the Mini-SAS at JPL
- Data availability potentially high (needs packaging, sanitizing of models)
- Technology Readiness Level:
  - FY05: 3 ("Experimental demonstration of critical function &/or proof of concept")
  - FY06: 4 ("Validation in a lab environment") on grounded rotorcraft

What is a contingency?

- Contingencies are obstacles to the fulfillment of a system's high-level requirements that can arise during real-time operations
  - Failures: camera fails due to hardware or software problem
  - Operational situations of concern: lens cap left on means that all images are black, so can't land unassisted
  - Environmental situations of concern: strong crosswind interferes with imaging, thus with finding landing site
- Contingency-handling involves requirements for detecting, identifying and responding to contingencies.
- Contingency handling includes, but extends, traditional fault protection

Contingency Software in Autonomous Systems

Autonomy

- Something previously not done automatically is now done by the software
  - Previously done manually, or
  - Previously could not be done
- Example of incremental autonomy:
  - Collision avoidance (not hitting buildings)
  1. Remote control by pilot steering from ground
  2. Path calculated on ground, loaded into system, path-plan executed in flight
  3. Path calculated in flight based on real-time imaging
- Autonomy allows system to detect and respond to a broader class of anomalies in many more ways

Contingency Software in Autonomous Systems

Safety-Critical

- The rotorcraft software is safety-critical:
  - Requires collision-avoidance
  - Requires autonomous take-off & landing in populated areas
  - Used for critical missions: finding lost hikers, downed pilots; detecting highway accidents; imaging (early warning) forest fires

Contingency Software in Autonomous Systems

Approach

1. *Identify contingencies* that risk mission-critical functions in a power system testbed (using S-FTA, S-FMECA, Obstacle Analysis)
2. *Model contingencies* & autonomous recovery actions using TEAMS (Testability And Engineering Maintenance System, QSI)
3. *Analyze contingencies*: TEAMS produces diagnostic tree of checks needed to detect & isolate contingency, identifies missing checks and recovery actions
4. *Code contingencies*' diagnosis & recovery behavior in the project's planner scripting language (auto-translation from TEAM's XML output)
5. *Verify contingency scripts* with hardware-in-loop simulation

Using the above steps:

- Verify contingency plans used by NASA projects
- Investigate issues in coverage of contingencies
- Test results on power system testbed

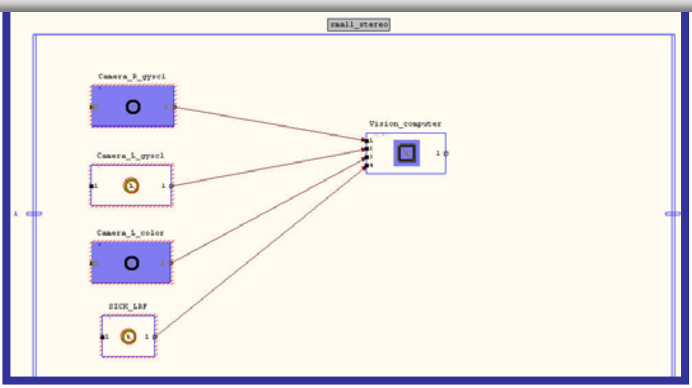
Contingency Software in Autonomous Systems

Contingency analysis

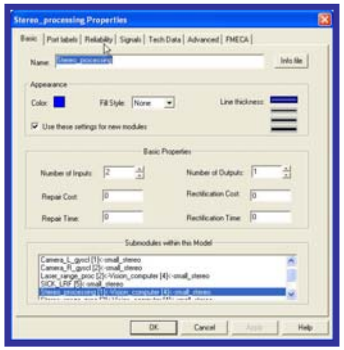
- Used Bi-Directional Safety Analysis to find contingencies
  - Forward analysis from potential failures to their effects (Software Failure Modes, Effects & Criticality Analysis)
  - Backward analysis from failures to contributing causes (Software Fault Tree Analysis)
- Guided thinking about possible ways to handle contingencies:
  - Use “Mitigation” column in SFMECA
  - Remove leaf nodes from SFTA graphs
  - Use obstacle resolution patterns [van Lamsweerde & Letier, 2000]
- TEAMS produces a diagnostic tree of checks needed to detect & isolate contingencies; identifies missing checks and recovery action
  - “Testability Engineering and Maintenance System”
  - Modeling & analysis toolset
  - Won NASA Space Act Award
  - Used successfully on 2nd generation RLV IVHM risk reduction program

Contingency Software in Autonomous Systems

Approach



1. TEAMS Model


Stereo_processing Properties
Basic | Port labels | Reliability | Signals | Tech Data | Advanced | FMECA
Info file
OK
Cancel
Apply
Help

Name: Stereo_processing

Appearance

Color: 🟦 Fill Style: None Line thickness:

☑ Use these settings for new modules

Basic Properties

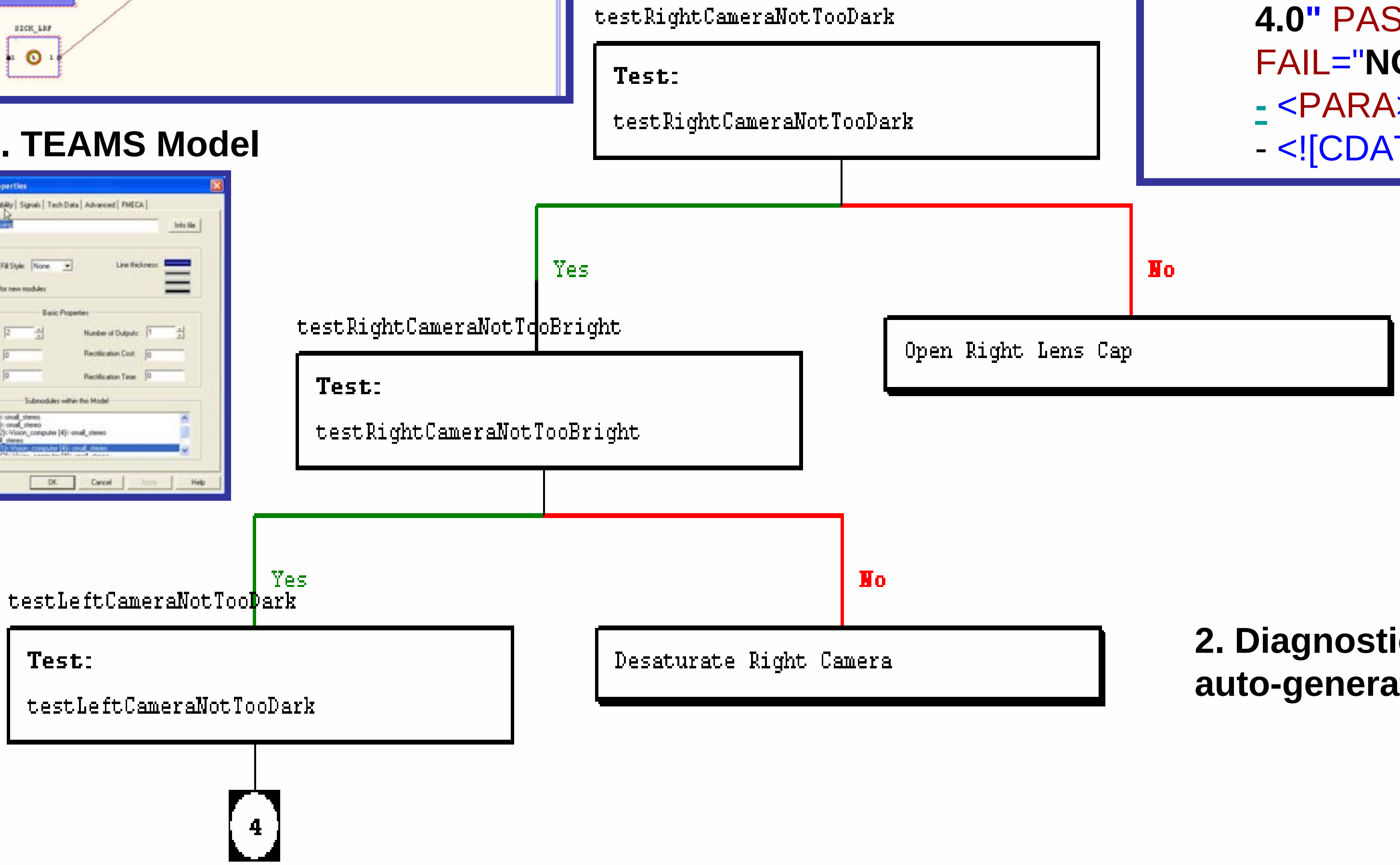
Number of Inputs	2	Number of Outputs	1
Repair Cost	0	Rectification Cost	0
Repair Time	0	Rectification Time	0

Submodules within this Model

```
Camera_L_gyscl (1)<-small_stereo
Camera_R_gyscl (2)<-small_stereo
Laser_range_proc (2)<-Vision_computer (4)<-small_stereo
SICK_LRF (5)<-small_stereo
Stereo_processing (1)<-Vision_computer (4)<-small_stereo
```

3. XML auto-translated to verify contingency handling on platform

```
</LABEL>
  <SYMPTOM />
- <NODE LABEL="1"
TYPE="TEST"
ID="T.small_stereo_0.1.2.
4.0" PASS="YES"
FAIL="NO">
- <PARA>
- <![CDATA[
```



2. Diagnostic Tree auto-generated

Obstacle analysis approach

- KAOS framework for goal-oriented obstacle analysis [van Lamsweerde & Letier, 2000]
  - Goal is a set of desired behaviors
  - Obstacle is a set of undesirable behaviors that impede a goal
- Relevance to application:
  - Contingencies are
    - Obstacles to achieving goals, or
    - Indications that goals are unrealizable with available agents
- Advantages
  - Structured approach early-on (anticipatory planning)
  - Supports more formal analysis, as needed

Contingency Software in Autonomous Systems

Identifying contingencies & contingency-handling software actions

- Step 1. Identify the goals
- Step 2. Identify the agents
- Step 3. Identify the obstacles to the goals (these are the contingencies)
- Step 4. Identify alternative resolutions to the obstacles (the contingency-handling that can be done autonomously)
- Step 5. Select a resolution among the alternatives

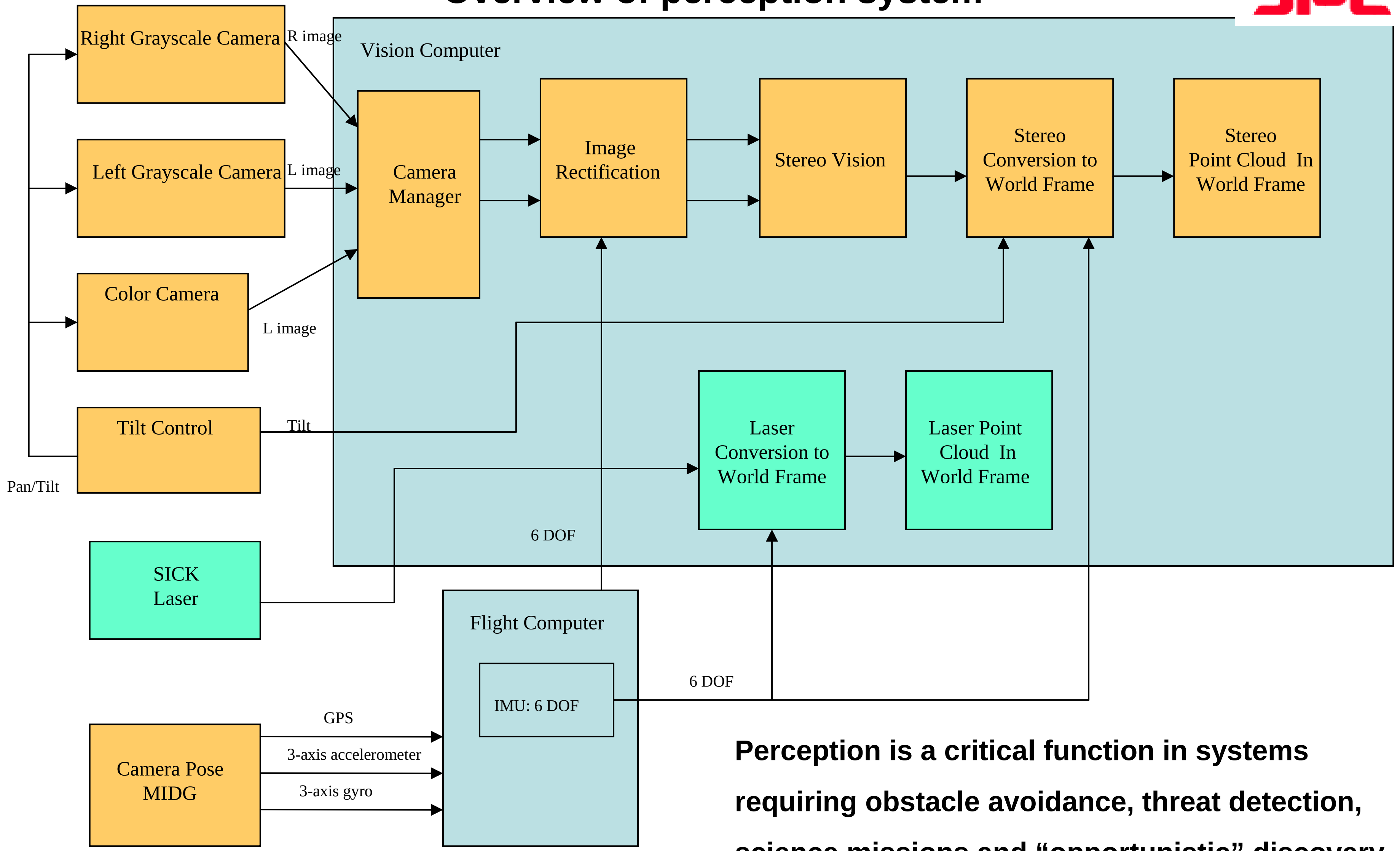
Contingency Software in Autonomous Systems

Other related work

- Requirements evolution
  - Use goal & obstacle analysis to refine requirements in a developing system [Anton & Potts]
- Maintenance
  - Focus on management of requirements changes [Bennett & Rajlich]
  - Evaluate in terms of traceability or change-impact [Cleland-Huang]
- Dynamic monitoring
  - Monitor operational systems for mismatch assumptions/ environment & perform remedial evolutions [Fickas & Feather]
- Autonomous fault handling with AI planners [Brat et al., Chien et al.]
- Safety in autonomous systems [Fox & Das, ESA ESTEC]
- Vehicle health management [Patterson-Hine et al.]

Contingency Software in Autonomous Systems

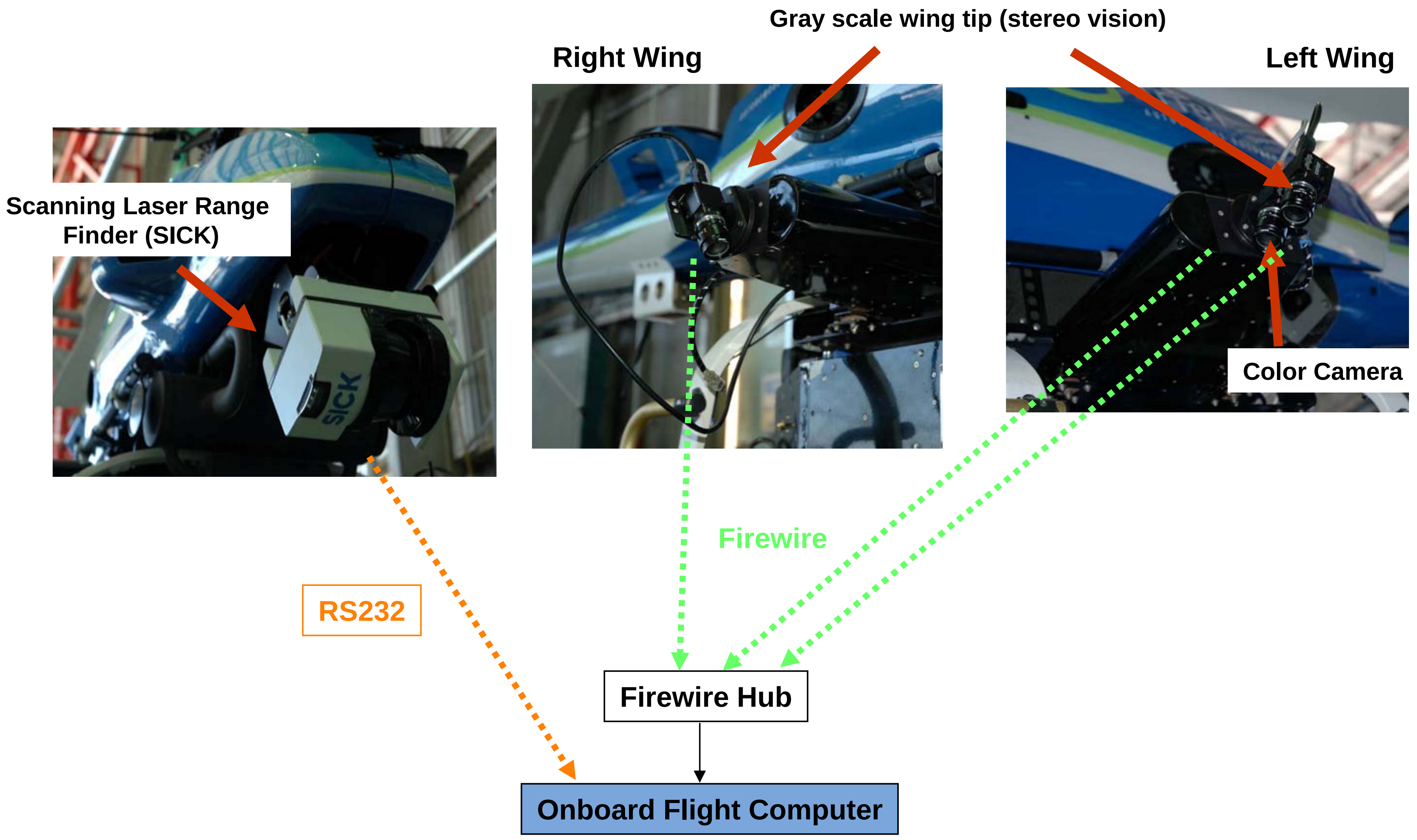
Overview of perception system



Perception is a critical function in systems requiring obstacle avoidance, threat detection, science missions and "opportunistic" discovery.

Contingency Software in Autonomous Systems

Perception instrumentation onboard rotorcraft



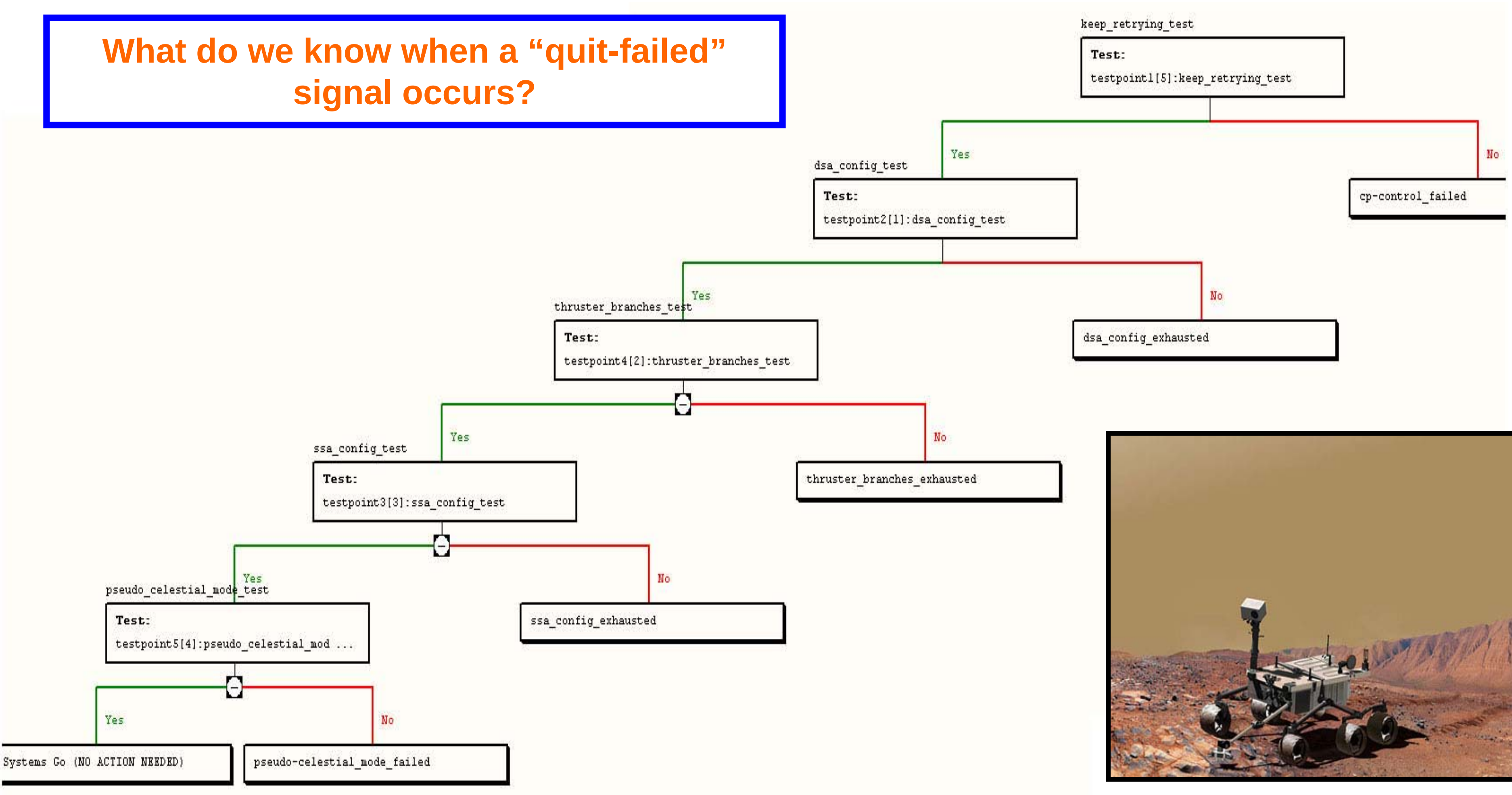
Contingency Software in Autonomous Systems
Camera criticality

- Cases in which the cameras are a critical system:
  - Cameras assigned responsibility during nominal ops
    - No line of sight -> Camera provides position info
  - Cameras are backup when other subsystems fail
    - Failed/degraded GPS -> Camera provides position info
    - Failed/degraded ARP -> Camera provides landing-site data
  - Images as mission objective (surveillance)
    - Failure of cameras can jeopardize success
- Thanks to Matt Whalley, Autonomous Rotorcraft Project Manager, & to Rob Harris, Chad Frost, Doron Tal, Stacy Nelson, Anupa Bajwa

Contingency Software in Autonomous Systems

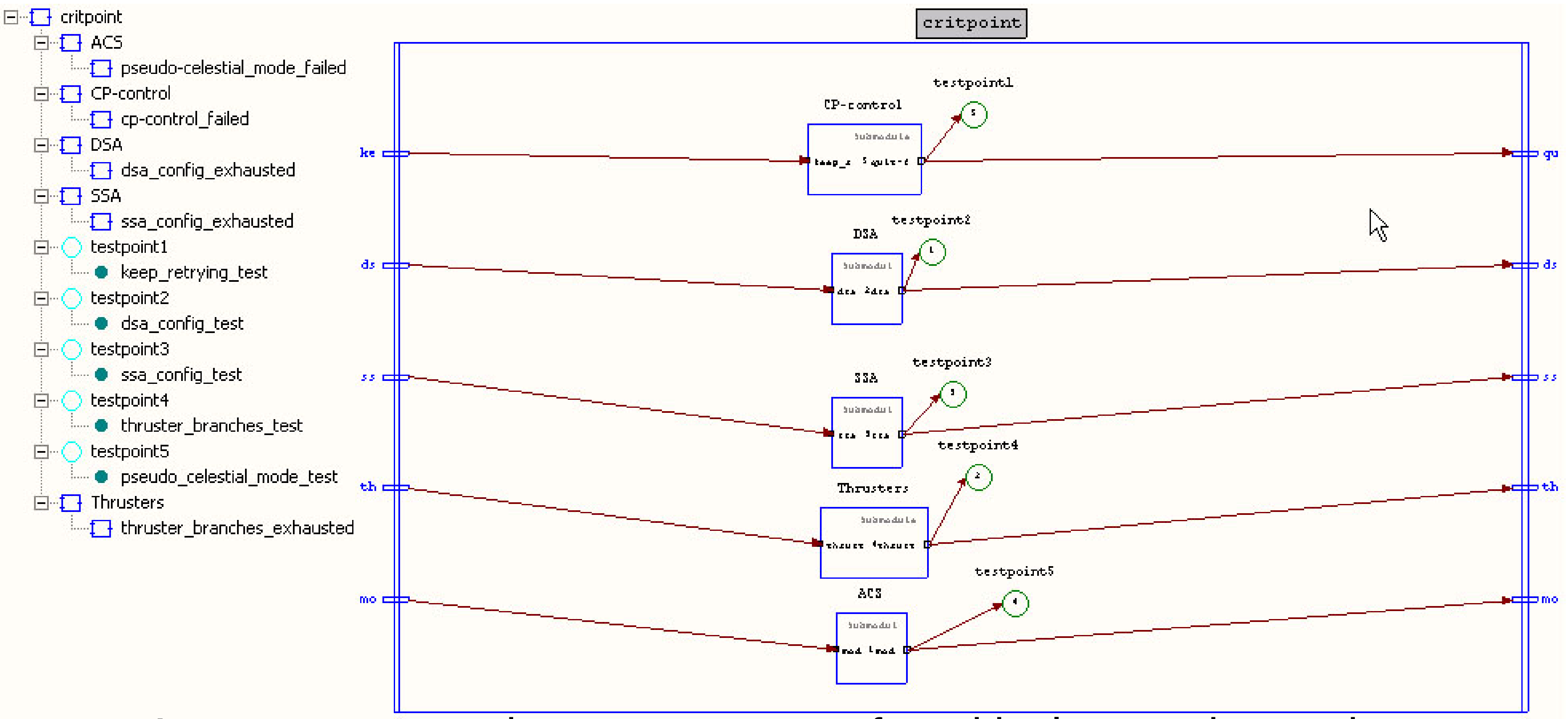
Critical pointing for Mars spacecraft

What do we know when a "quit-failed" signal occurs?


keep_retrying_test
Test:
testpoint1[5]:keep_retrying_test
Yes
No
dsa_config_test
Test:
testpoint2[1]:dsa_config_test
cp-control_failed
Yes
No
thruster_branches_test
Test:
testpoint4[2]:thruster_branches_test
dsa_config_exhausted
Yes
No
ssa_config_test
Test:
testpoint3[3]:ssa_config_test
thruster_branches_exhausted
Yes
No
pseudo_celestial_mode_test
Test:
testpoint5[4]:pseudo_celestial_mod ...
ssa_config_exhausted
Yes
No
Systems Go (NO ACTION NEEDED)
pseudo-celestial_mode_failed

Contingency Software in Autonomous Systems

Critical pointing for Mars spacecraft



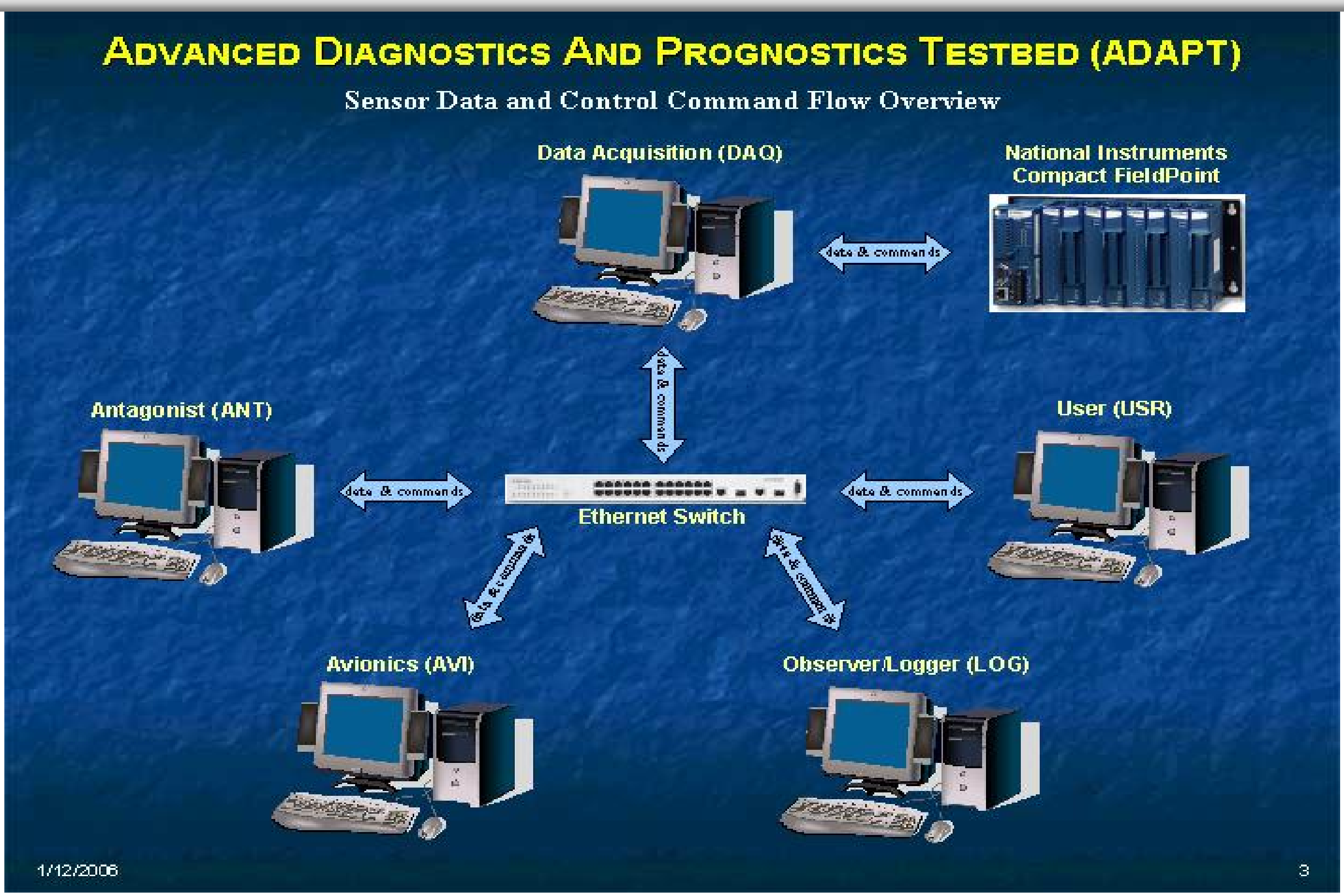
```
critpoint
    ACS
        pseudo-celestial_mode_failed
    CP-control
        cp-control_failed
    DSA
        dsa_config_exhausted
    SSA
        ssa_config_exhausted
    testpoint1
        keep_retrying_test
    testpoint2
        dsa_config_test
    testpoint3
        ssa_config_test
    testpoint4
        thruster_branches_test
    testpoint5
        pseudo_celestial_mode_test
    Thrusters
        thruster_branches_exhausted
```

•Autonomous, contingency response for critical scenarios such as commandability loss, & before critical trajectory-correction maneuvers

•Thanks to Tracy Neilson, MER/MSL

Contingency Software in Autonomous Systems

Emulates a typical spacecraft power system

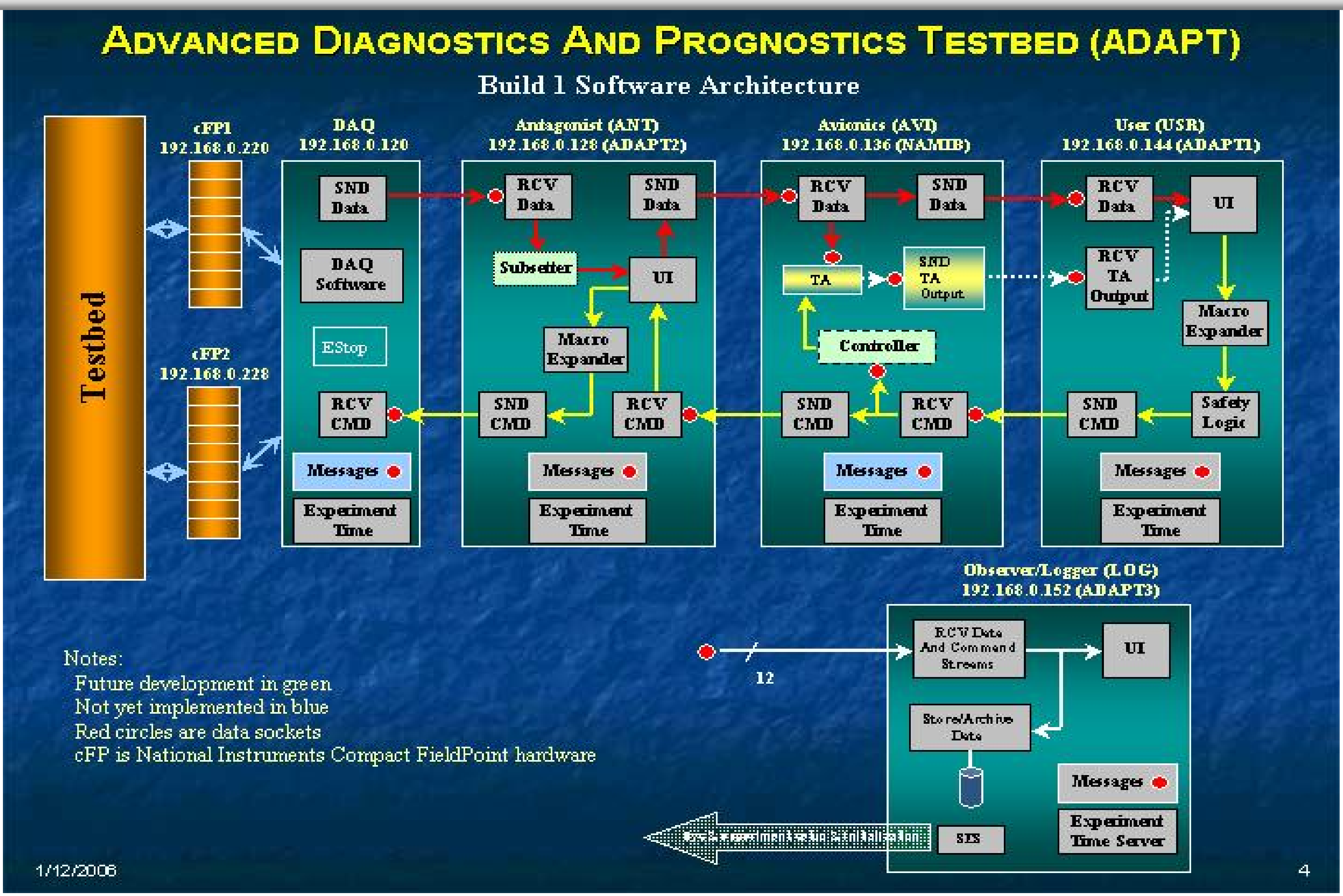


ADVANCED DIAGNOSTICS AND PROGNOSTICS TESTBED (ADAPT)
Sensor Data and Control Command Flow Overview
Data Acquisition (DAQ)
National Instruments Compact FieldPoint
data & commands
Antagonist (ANT)
User (USR)
Ethernet Switch
Avionics (AVI)
Observer/Logger (LOG)
1/12/2006
3

- Thanks to Scott Poll, ADAPT manager

Contingency Software in Autonomous Systems

Preliminary identification of some required contingency plans



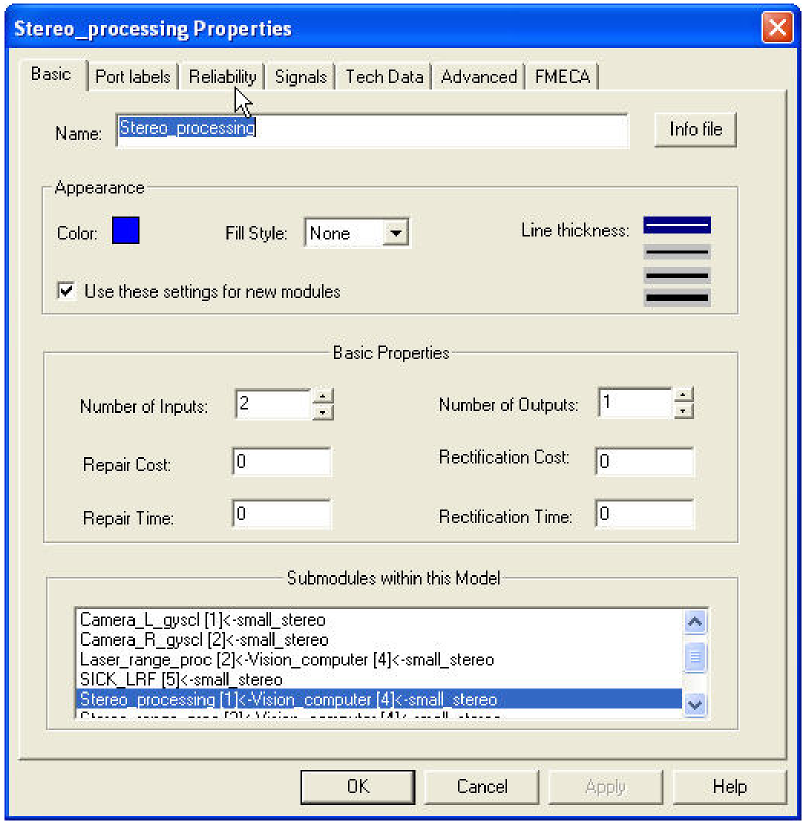
ADVANCED DIAGNOSTICS AND PROGNOSTICS TESTBED (ADAPT)

Build 1 Software Architecture

Notes:
Future development in green
Not yet implemented in blue
Red circles are data sockets
cFP is National Instruments Compact FieldPoint hardware

Contingency Software in Autonomous Systems

Results



Stereo_processing Properties

Basic | Port labels | Reliability | Signals | Tech Data | Advanced | FMECA

Name: Stereo_processing

Appearance

Color: 🟦 Fill Style: None Line thickness:

☑ Use these settings for new modules

Basic Properties

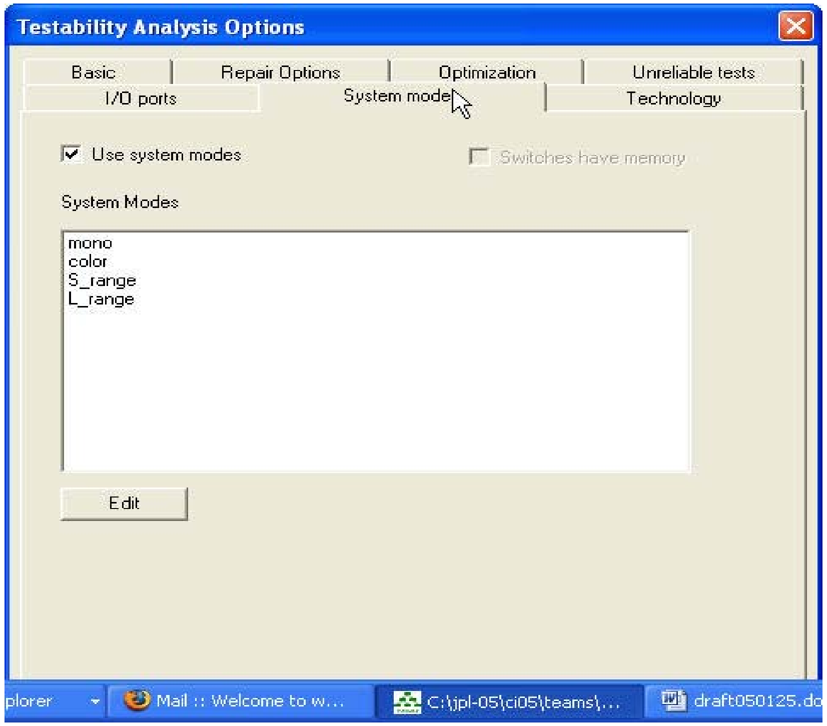
Number of Inputs:	2	Number of Outputs:	1
Repair Cost:	0	Rectification Cost:	0
Repair Time:	0	Rectification Time:	0

Submodules within this Model

Camera_L_gyscl [1]<-small_stereo
Camera_R_gyscl [2]<-small_stereo
Laser_range_proc [2]<-Vision_computer [4]<-small_stereo
SICK_LRF [5]<-small_stereo
Stereo_processing [1]<-Vision_computer [4]<-small_stereo

Properties for each function, switch & test-point are entered into the TEAMS tools

TEAMS builds a Dependency Matrix in which each row is a fault source (e.g., a camera that can fail) and each column is a test (e.g., whether we have a good Stereo image). Here, we select the normal or contingency scenario (camera OK or not) for the analysis.



Testability Analysis Options

Basic | Repair Options | Optimization | Unreliable tests | I/O ports | System modes | Technology

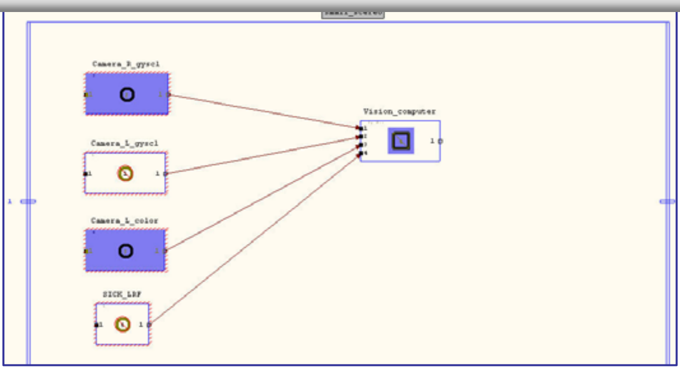
☑ Use system modes ☐ Switches have memory

System Modes

mono
color
S_range
L_range

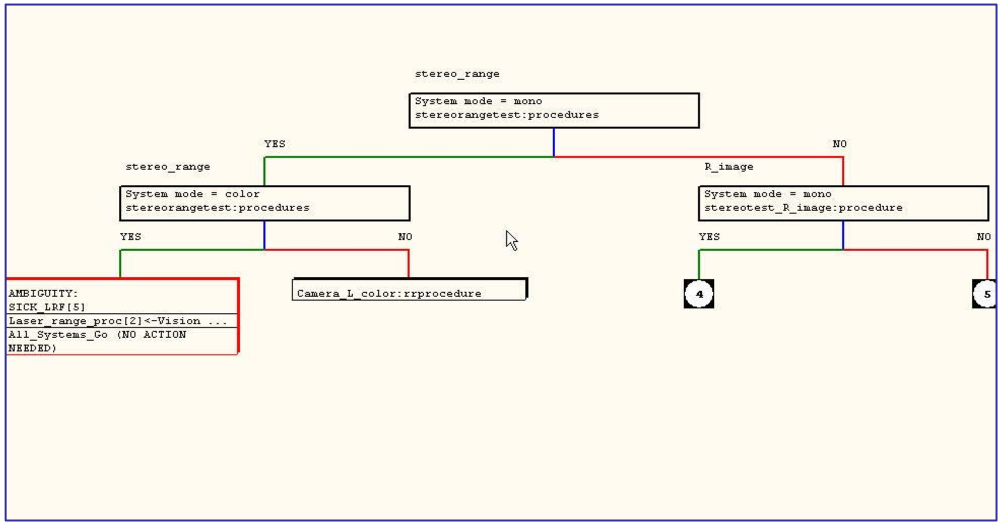
Contingency Software in Autonomous Systems

Results



Executing the Contingency scenario, we check that the behavior is correct: left COLOR camera is available (no red slash) & being used; confirm that tests can isolate failure to which camera.

Most useful: the *automatic Diagnostic Tree*:
--Shows best sequence of checks to detect & isolate
--Shows indistinguishable failures (“ambiguity groups”)



stereo_range
System mode = mono
stereorangetest:procedures
YES
NO
stereo_range
System mode = color
stereorangetest:procedures
R_image
System mode = mono
stereotest_R_image:procedure
YES
NO
YES
NO
AMBIGUITY:
SICK_LRF[5]
Laser_range_proc[2]<-Vision ...
All_Systems_Go (NO ACTION NEEDED)
Camera_L_color:rrprocedure
4
5

```
</LABEL>
  <SYMPTOM />
- <NODE LABEL="1"
TYPE="TEST"
ID="T.small_stereo_0.1.2.4.0
" PASS="YES" FAIL="NO">
- <PARA>
- <![CDATA[
```

--*XML output option* auto- translated into rotorcraft’s planning language (APEX) to simulate contingencies on the vehicle

Contingency Software in Autonomous Systems

Potential applications

- Contingency management is essential to the *robust* operation of complex systems such as spacecraft and Unpiloted Aerial Vehicles (UAVs)
- Automatic contingency handling allows a *faster* response to unsafe scenarios with reduced human intervention on low-cost and extended missions
- Results, applied to the Autonomous Rotorcraft Project and Mars Science Lab, pave the way to more resilient *autonomous* systems

Contingency Software in Autonomous Systems

Next Steps

- Investigate and model with TEAMS key contingencies involved in safe software reconfiguration of power distribution systems to support autonomous operations
- Demonstrate and verify a subset of the contingency responses we have developed on available platforms
- Support transfer to other NASA projects

Contingency Software in Autonomous Systems

Relevance to NASA

ARC

ARC

JPL

- **Improved contingency handling needed to safely relinquish control of unpiloted vehicles to autonomous controllers**
- **More autonomous contingency handling needed to support extended mission operations**