Technology Needs for Development of the Ultra Long Life Missions

Consortium of Universities Developing Low Power CMOS Integrated Circuits for Instruments and Sensors for NASA's Missions, Research Workshop

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Dr. Savio Chau

Jet Propulsion Laboratory

California Institute of Technology

Why Ultra Long Life Systems?

- After decades of Solar System exploration, NASA has almost completed the initial reconnaissance.
- In-situ exploration such as landing and sample return is the focus of current generation of missions.
- The next logical step of space exploration is to expand the frontier into the interstellar space or even other stars. Such missions can easily last for more than 50 years.

Objectives

- Primary:

  Develop ultra reliable and evolvable spacecraft for very long life missions (>50 years) at low cost.

- Secondary:

  Spin off ultra high-reliable technologies that benefit near term deep space missions

Applications of Ultra Long Life Systems

- Exploration of interstellar space and other stars
- Long term missions in Solar System
- Ultra high-reliability applications for short-life (<15 years) missions

For classes of ultra long life systems and their applications:

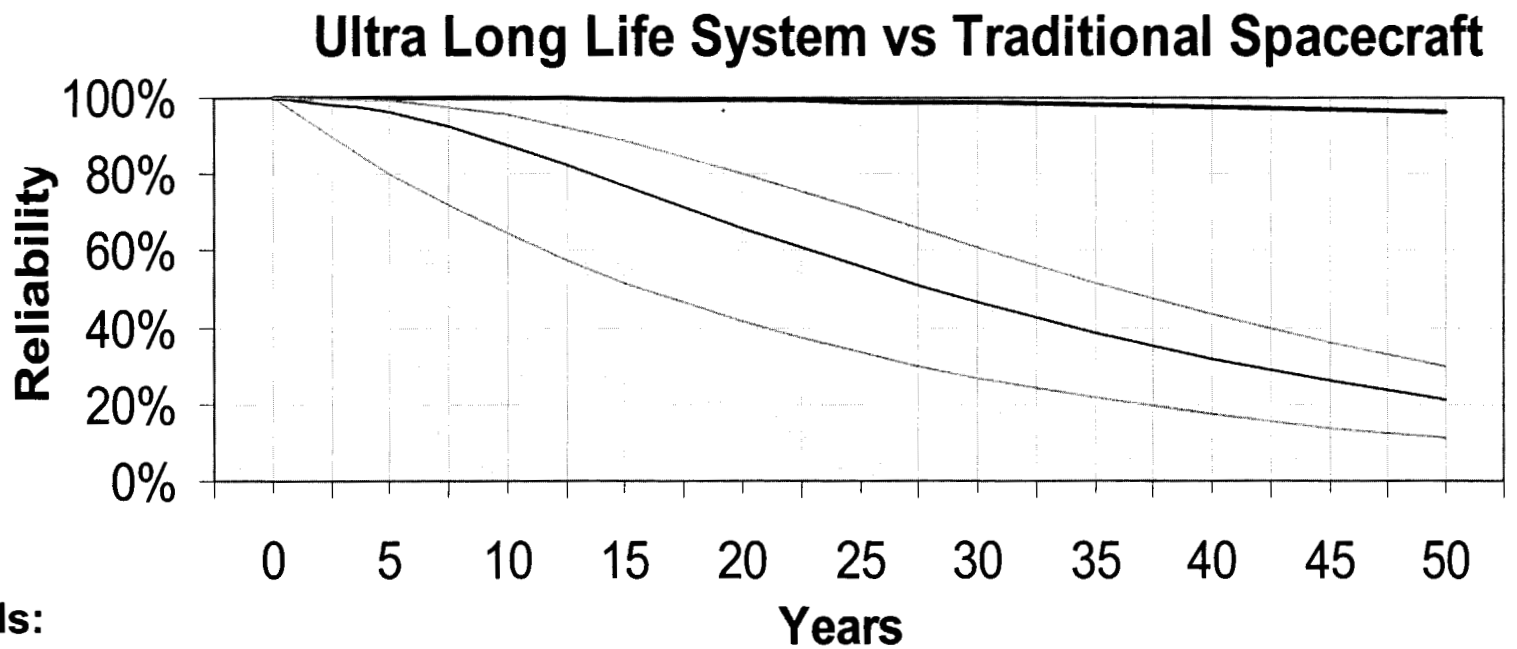
ULL Class	Description	Application
Class A	Restrained in both fuel and power	Interstellar missions, mission to Alpha Centauri
Class B	Restrained in fuel but have ample power available	Relay spacecraft for outer planet spacecraft, Asteroid or comet hopper
Class C	Restrained in power but do not require significant amount of fuel	Robot colony on permanent dark side of planets and satellites
Class D	Do not require significant amount of fuel and have ample power available	Robot colony on planets and satellites where sunlight is plentiful

Four Areas of Technology Needs for Ultra Long Life Missions

- Survivability
  - Need to handle random failures and design errors.
  - Aging effect of the materials and components will eventually dominate in ultra long life missions.
- Consumable Resource Acquisition and Management
  - On-board consumable resources such as power and fuel are the limiting factors of ultra long life systems and need to be managed very carefully.
  - Ultra long life systems have to acquire consumable resource from environment
- Long Term Flight Operations
  - High level of on-board autonomy for ultra long life mission is required to reduce cost and circumvent communication delay. Need infallible autonomy and validation techniques.
- Adaptability and Evolvability
  - On-board technologies will become archaic and difficult to operate long before the mission ends. Need built-in upgradeable design to minimize the gap between on-board and ground technologies.
  - Mission objectives may change during the long mission duration. Need built-in capability to reconfigure the spacecraft for different science objectives.

State-of-the-Art in Survivability

- Most current spacecraft design are using either dual-string or triple-modular-redundancy to improve system reliability.



Legends:

- Single String
- Dual String
- TMR with 1-out-of-3
- Ultra Long Life System

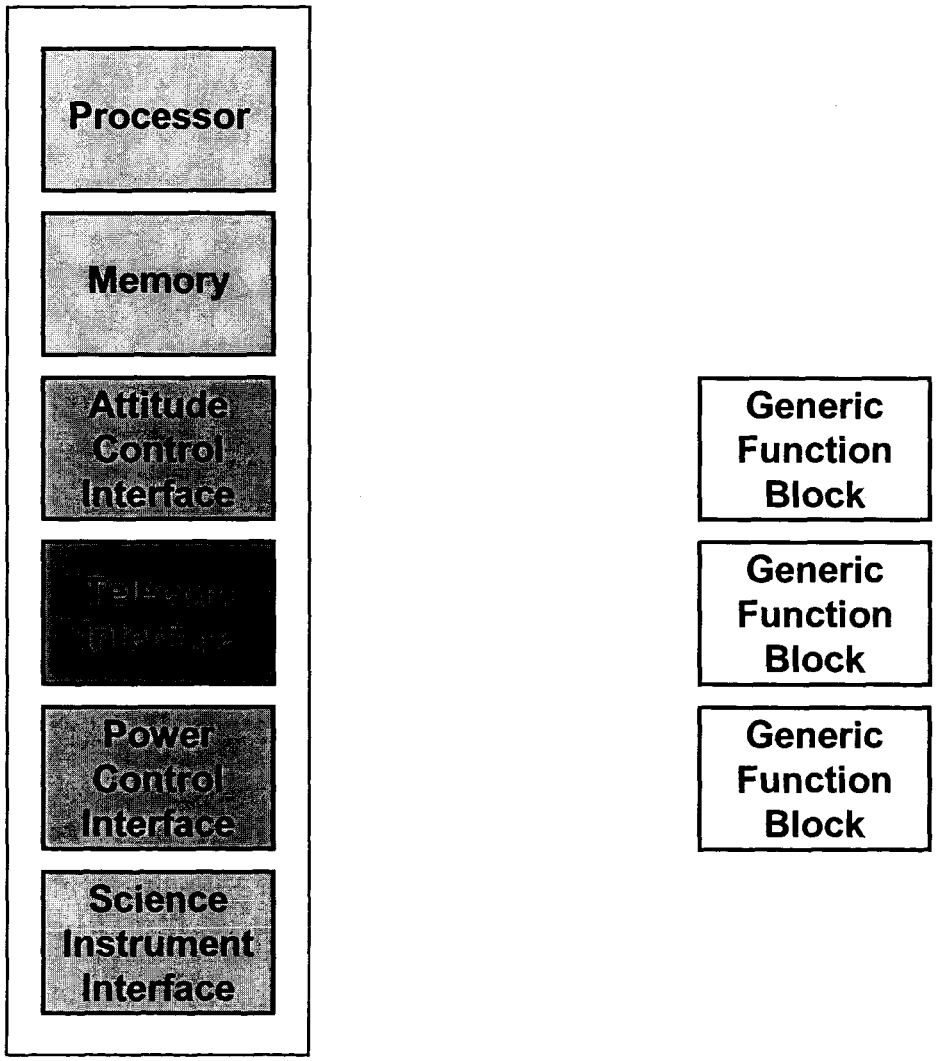
Examples of Survivability Technologies

- Highly Efficient Fault Tolerance Design
  - Generic Redundant Blocks — redundant components are generic and can be programmed to replace any type of failed components
    - High capacity FPGA
    - High bandwidth free space interconnection
  - Adaptive Fault Tolerance — work around failures instead of replacing failed components with spares (i.e., similar to what the mission operation teams have been doing for all missions)
    - On-board mission operation
- Self-Repair/Self-Healing
  - Self-Repair Components
    - Self-repair with nano technologies
    - Self-healing with biologically inspired technologies (e.g. DNA computing)
  - Regenerative System
    - Modular regrow with biologically inspired technologies
- Ultra Long Life Reliability Verification Techniques

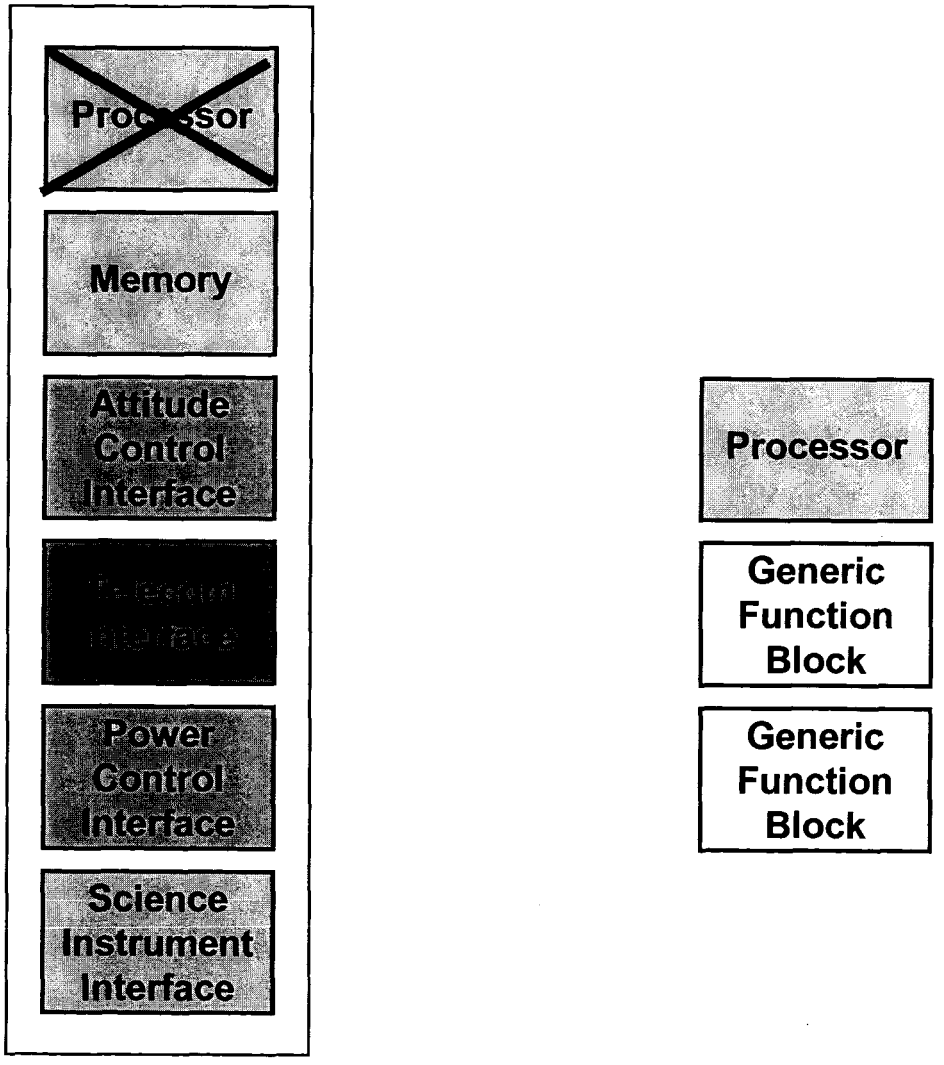
An Example of Highly Efficient Fault Tolerant Avionics System

- Use "Generic Function Blocks" that can be reconfigured to replace any type of failed components
- Use wireless interconnection to facilitate reconfiguration of connectivity among components
- Use Distributed Autonomous Testing for fault detection rather than a centralized fault detector

Generic Function Block



Fault-Tolerant Avionics Architecture Using Generic Function Block



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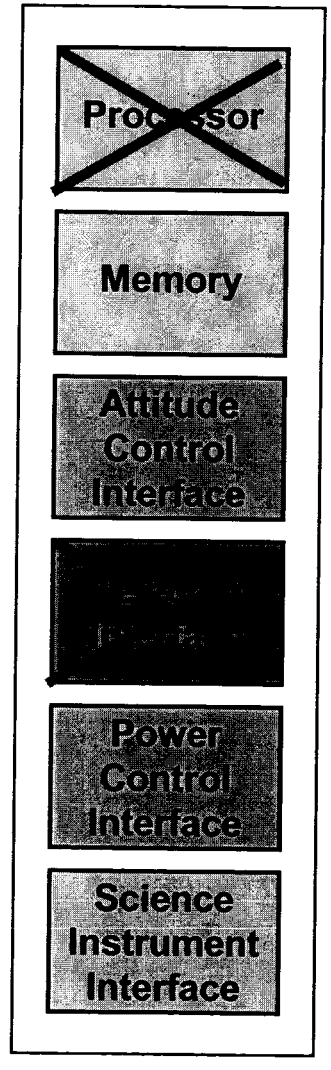

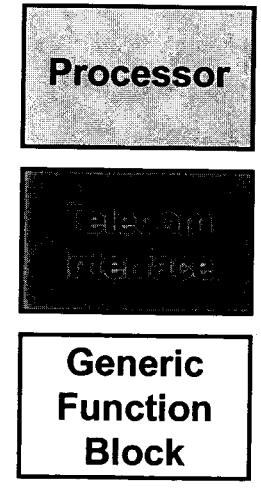

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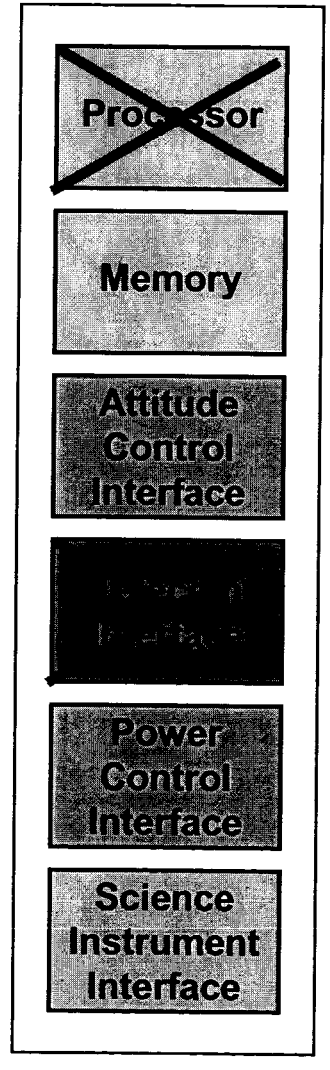
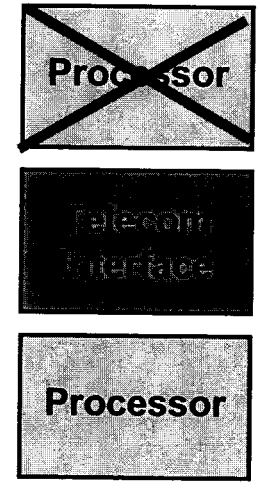
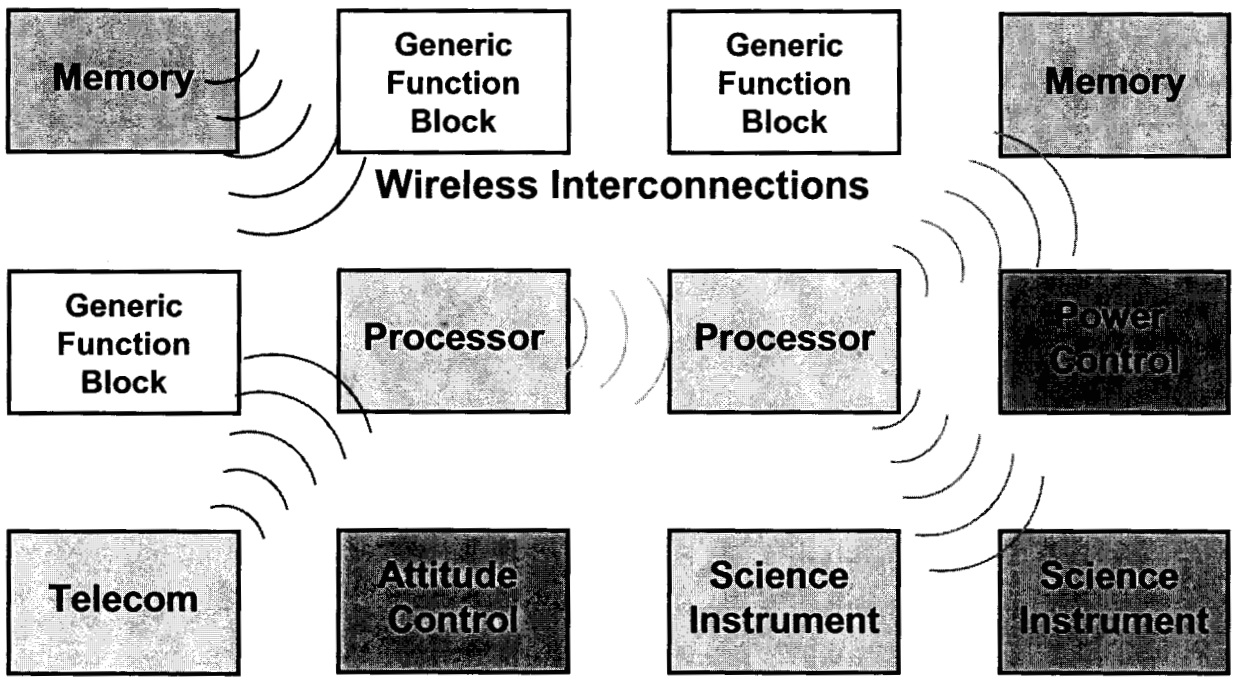




Reconfiguration with Wireless Connections



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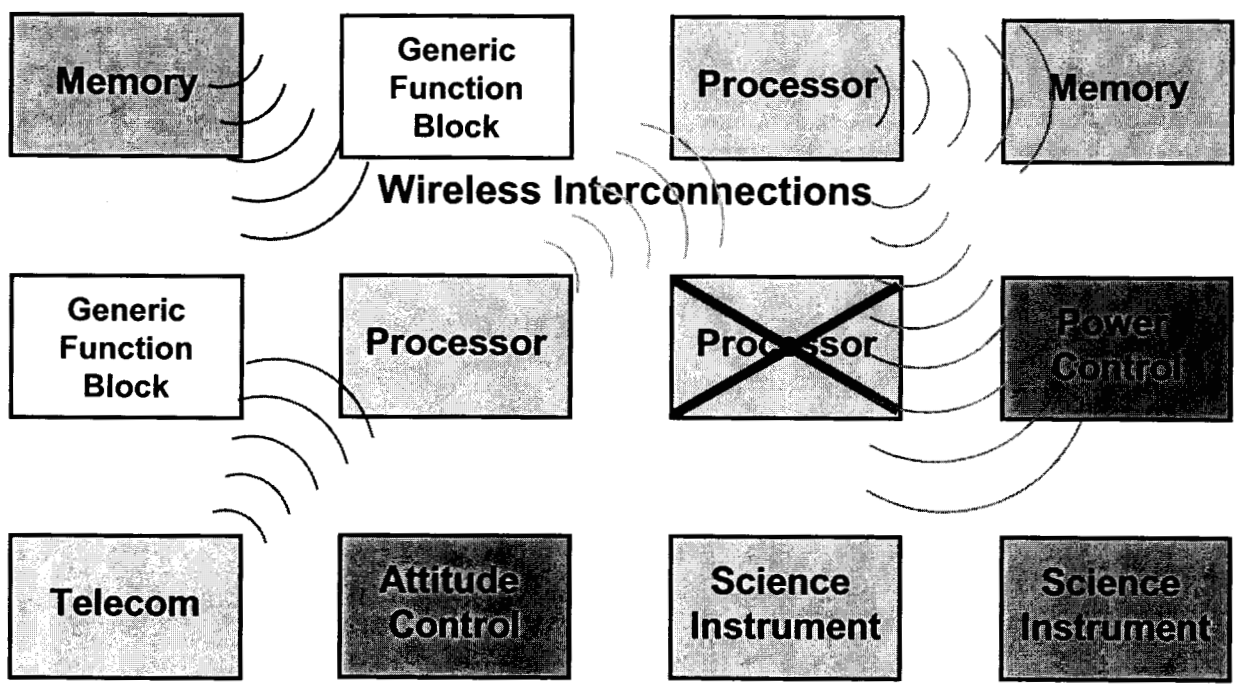
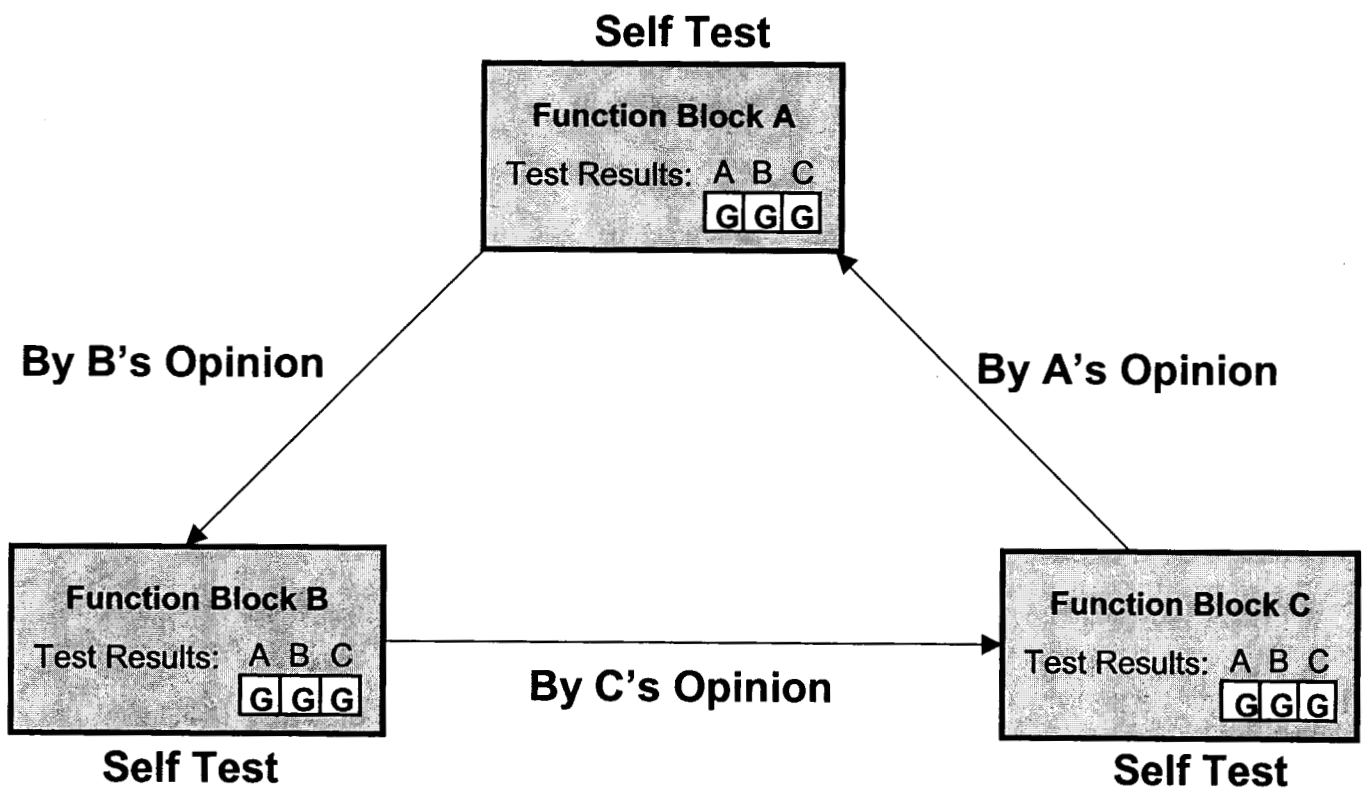


Autonomous Testing (Fault Free Case)

Fault Detection Capability of a 3-Node System: t = (3 – 1) / 2 = 1



Autonomous Testing (with Faulty Component)

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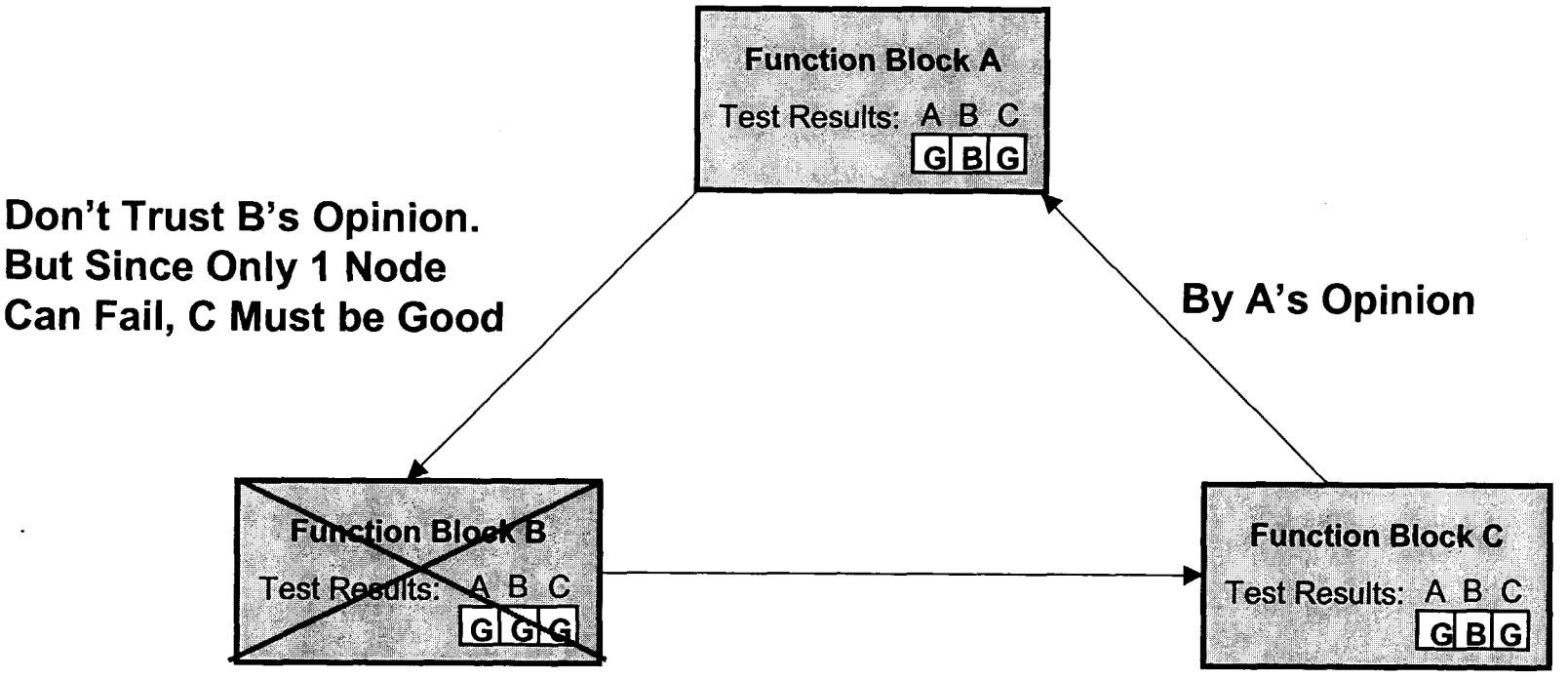

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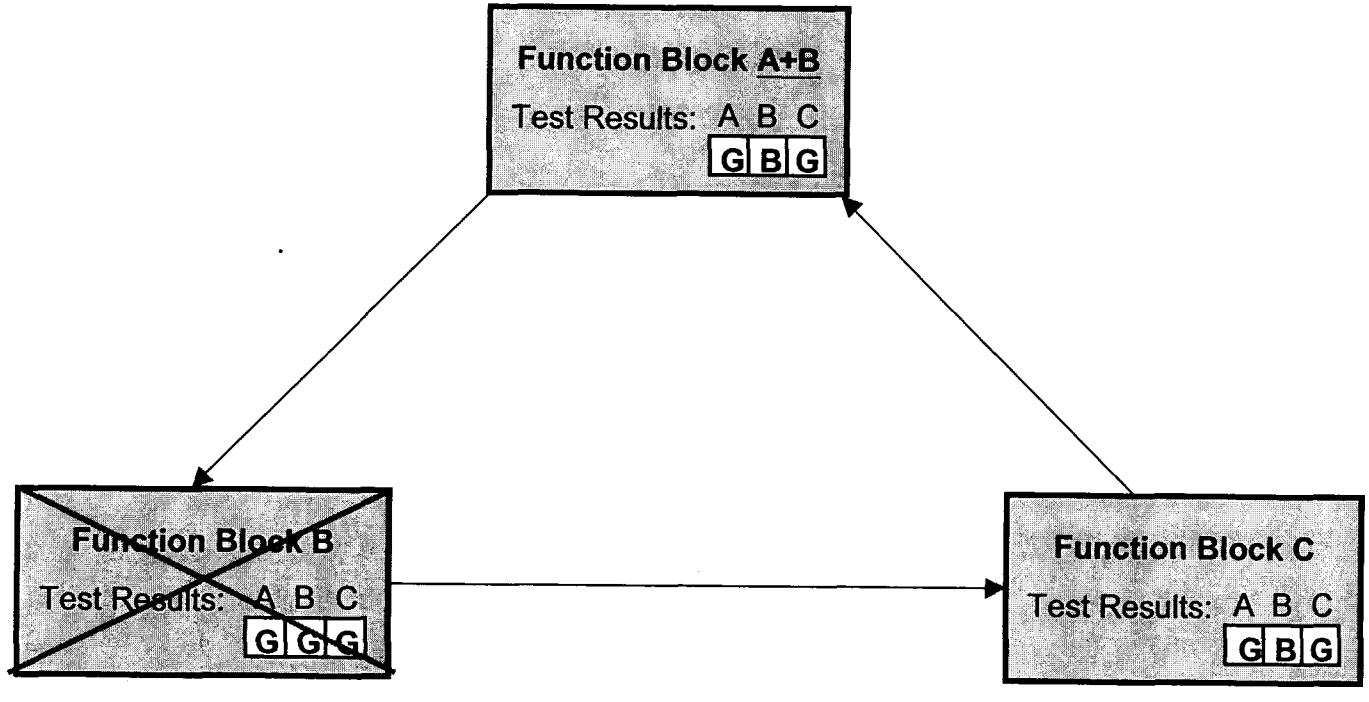
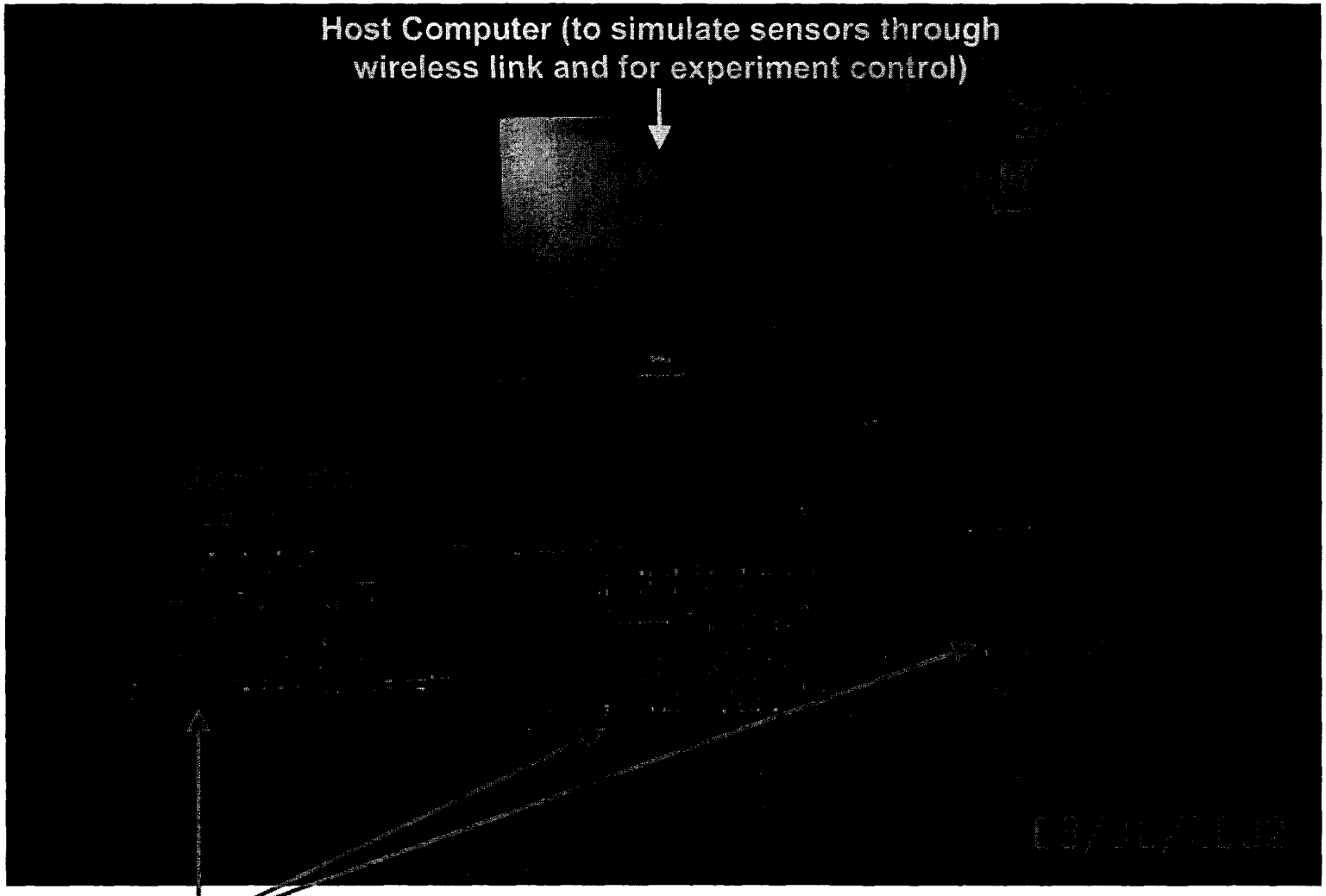


- Recovery Actions:
  - Function Block A (upstream node) takes over Block B's tasks
  - Block B's messages are ignored
  - Autonomous testing continues just in case Block B is alive again

A Navigation System Prototype



Generic Function Blocks

Screen Display After Fault Injection

Fault Detected

Upstream Healthy Generic Function Block
Takes Over Tasks of the Failed Block

Examples of Consumable Resource Acquisition and Management Technologies

- Examples of consumable resources
  - Power, fuel, mechanically wearable parts (e.g., gyro), spare components
- Acquisition technologies
  - Nuclear fission and fusion technologies
  - Acquire power and thrust from Earth (e.g., light sail with laser)
  - Convert resources from environment to fuel (e.g. convert methane on Titan into fuel)
  - Harvest star light and planetary/cosmic radiation energy
  - Convert unused structure (e.g., failed parts) into fuel
- Management technologies
  - Power aware architecture
  - Ultra long life battery
  - Workload sensitive clock frequency and power supply
  - Ultra high specific impulse fuel
  - Extending shelf life (in benign storage) of spare components

Examples of Long Term Flight Operation Technologies

- Highly intelligent on-board autonomy
- Spacecraft initiated communication (e.g., beacon mode operation)
- Highly intelligent autonomous ground operation
- Guarded software/hardware upgrade
- Super high speed uplink/downlink with optical communication
- Use of relay spacecrafts to buffer and repeat signals long distance spacecrafts, also provides more flexibility in mission operation

Examples of Adaptability and Evolvability Technologies

- Adapt to change of science objectives
  - Reconfigureable avionics architecture
  - Equipment with reconfigureable characteristics
  - Goal oriented software
- Adapt to change of technologies
  - On-board upgradeable computer systems
  - Reconfigureable analog/mixed-signal components
  - Upgradeable sensor/actuator
- Adapt to change of environment
  - Biologically inspired adaptive sensors/actuators
  - Regenerative sensors/actuators
  - Self-learning algorithms
  - Genetic algorithms

Summary

- Ultra long life system is a critical technology for human's next step of space exploration.

- Four areas of technologies that are required by ultra long life missions have been identified. Examples in each area have been provided.

- A specific example on highly reconfigureable system using generic function blocks, wireless interconnection, and autonomous testing have been described in details.