Active Vibration Control System for a Solar Panel Wing

HARDWARE AND SOFTWARE RELIABILITY CONSIDERATIONS

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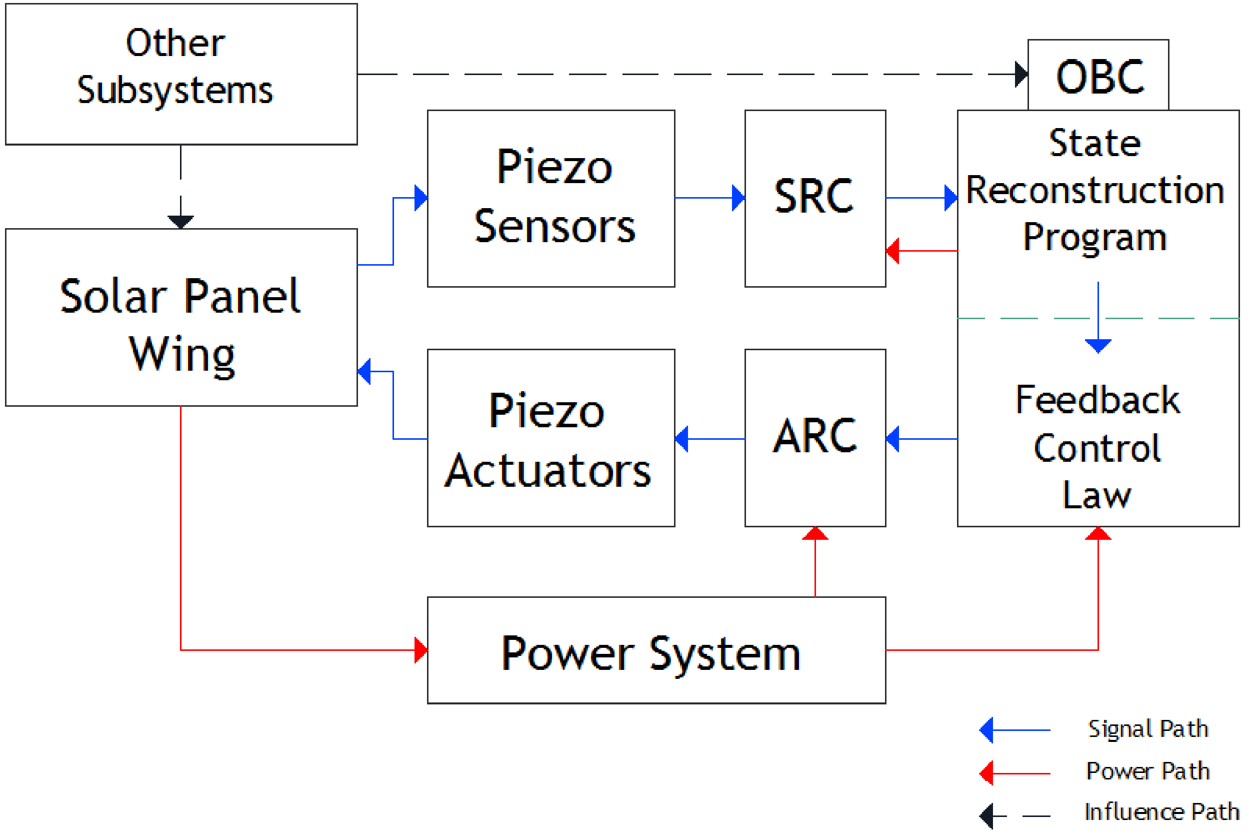
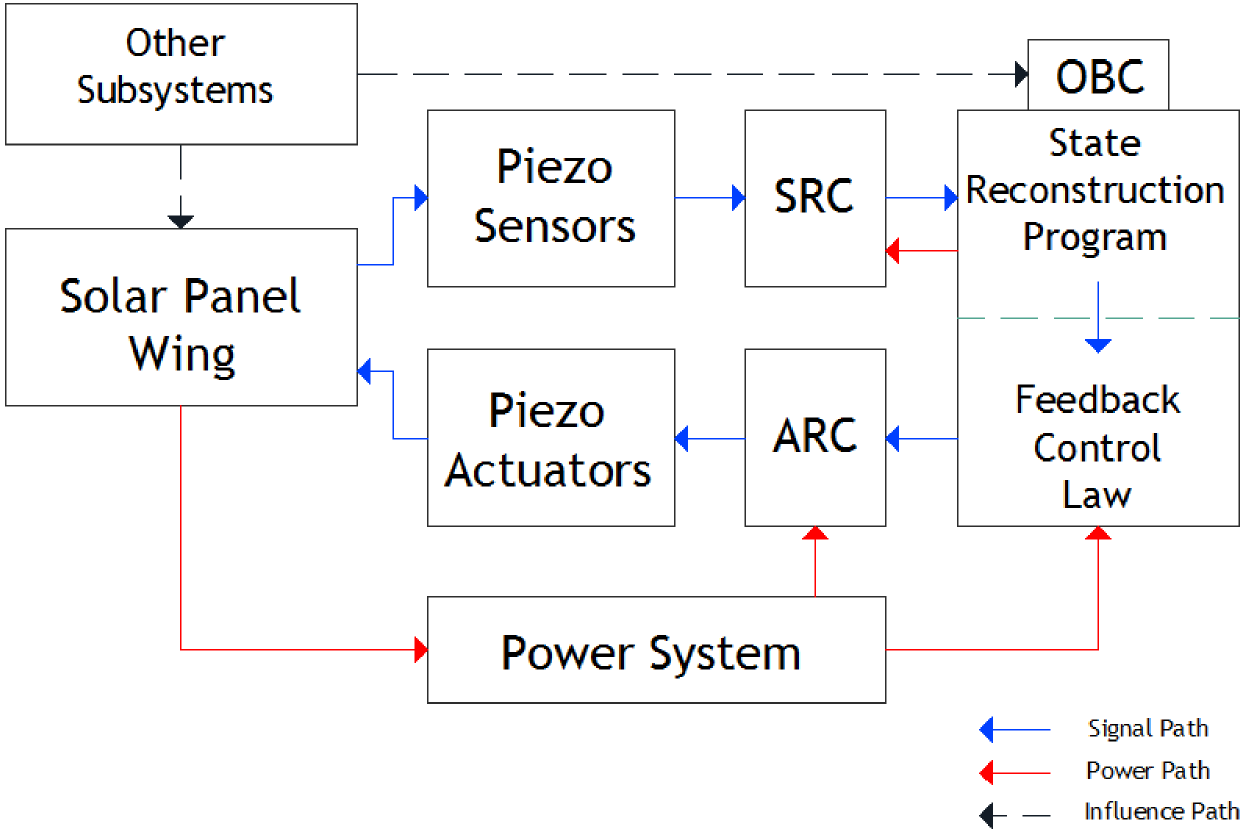
System Overview (1/3)

- Real-time determination of the flexible dynamics of a Solar Panel Wing (SPW)
  - Piezoelectric Sensors (PSs) – attached on the SPW they follow its deformations and send proportional charge signals through pairs of electrodes.
  - Sensing Regulation Circuitry (SRC) – smooths, transforms and amplifies the signals from the PSs.
  - On-Board Computer (OBC) – provides the power (3.3 V) and ground (0 V) lines for the SRC, reads the signals from the PSs and reconstructs the momentary deformed state of the SPW.

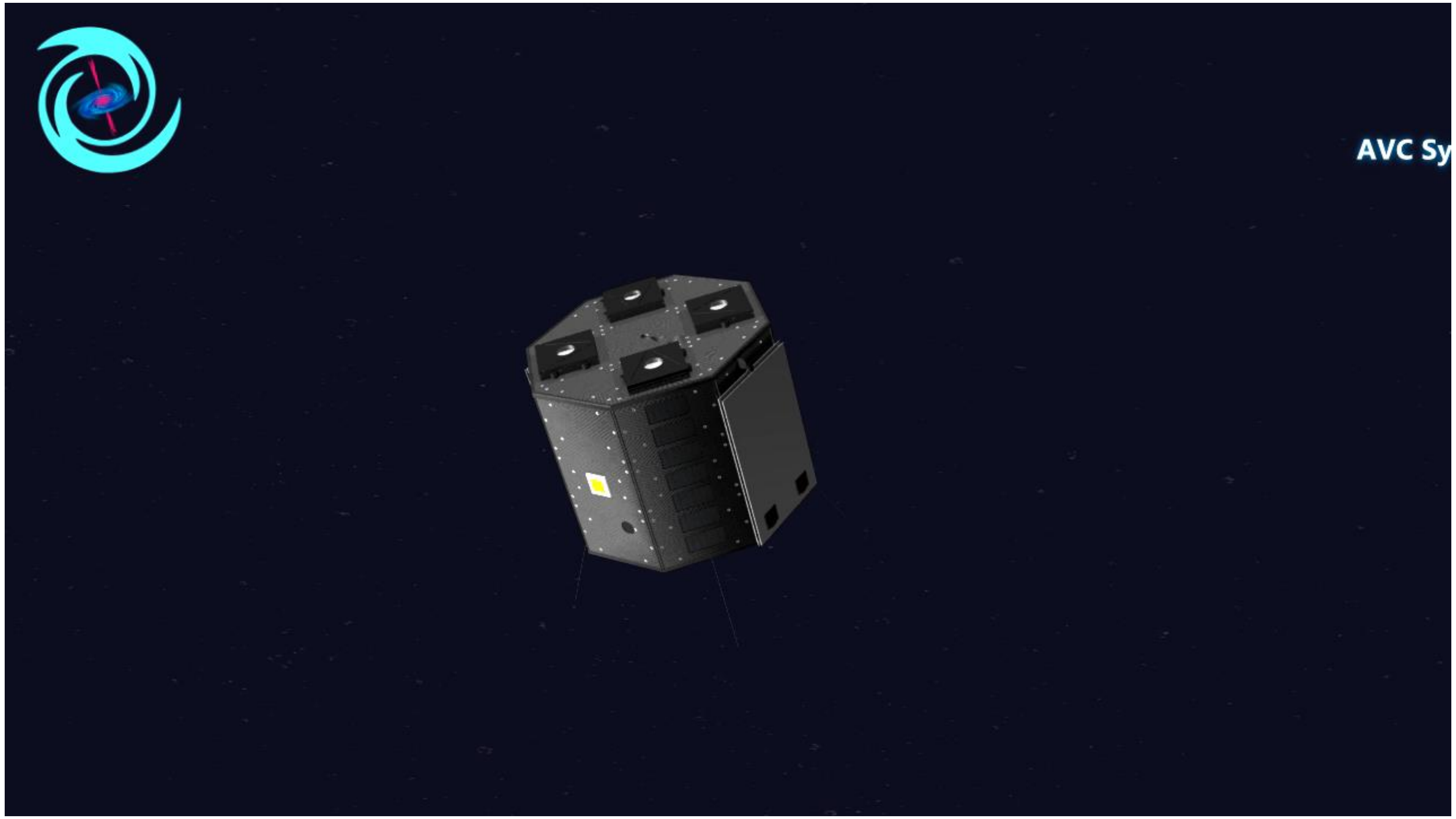


System Overview (2/3)

- Active vibration damping of the Solar Panel Wing's flexible dynamics
  - On-Board Computer (OBC) – uses the reconstructed deformed state in a feedback control law on the natural vibration modes of the SPW (most significant, observable and controllable modes).
  - Actuation Regulation Circuitry (ARC) – transforms the signals from the control program of the OBC to the necessary voltages for actuation and provides power for the actuation.
  - Piezoelectric Actuators (PAs) – deform proportionally to the actuation voltages and drive the vibrations of the SPW to zero (damping).



System Overview (3/3)

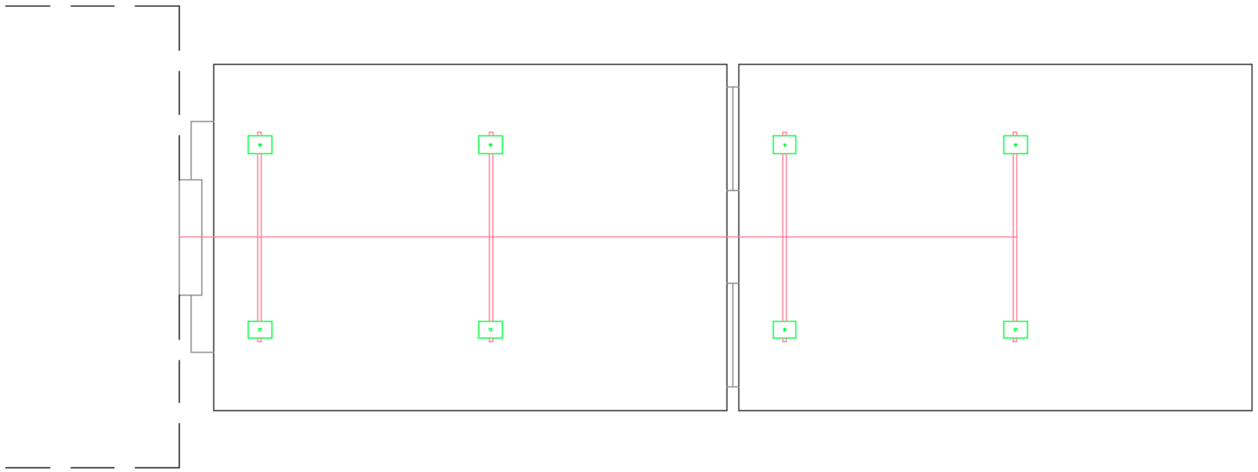


System Specification (Function)

- Ensure vibration attenuation after SPW deployment within given time;
- Provide protection from thermo-mechanically induced oscillations near the natural frequencies of the SPW (resonance) – the system must be able to shift the vibrational frequencies away from resonance;
- Ensure asymptotically stable flexible dynamics;
- Ensure observability and controllability of at least 5 (n) most significant natural modes.

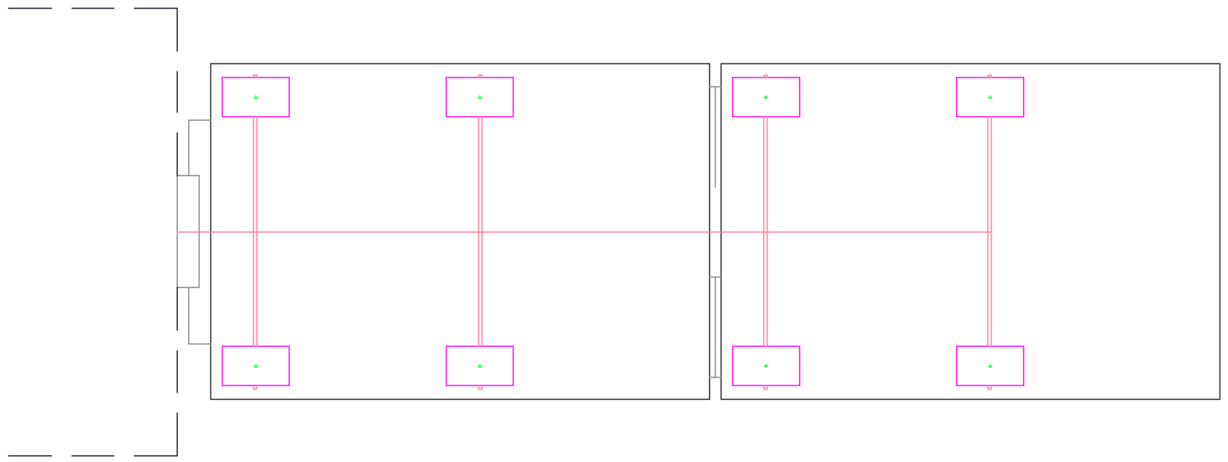
Hardware Design: Piezoelectric Sensors

- Piezoelectric Sensor configuration
  - Chosen for observability of at least 5 natural vibration modes (including torsional)
  - Sensors attached on both surfaces of the SPW structure (double-sided)



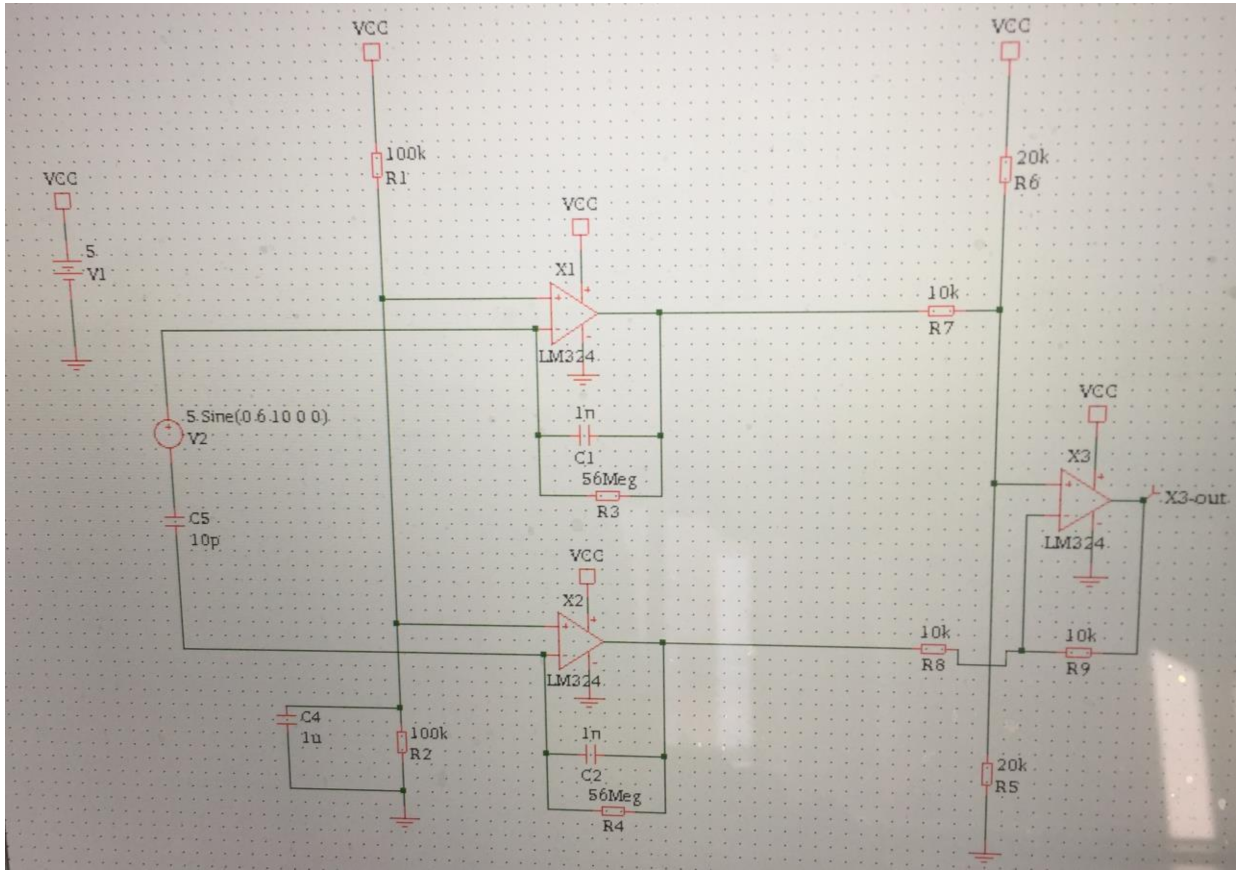
Hardware Design: Piezoelectric Actuators

- Piezoelectric Actuator configuration
  - Chosen for controllability of at least 5 natural vibration modes (including torsional)
  - Actuators attached on both surfaces of the SPW structure (double-sided)



Hardware Design: Sensing Regulation Circuitry

- Components
  - Op-Amps – differential amplifying
  - Resistors
  - Capacitors



Hardware Design: Actuation Regulation Circuitry

- Schematics of the circuit (N/A)
- Components
  - Op-Amps
  - Resistors
  - Capacitors

Hardware Design: On-Board Computer Interfaces

- Hardware connections to sensing and actuation circuitry
  - On the input pins for sensor signals
  - On the output pins for actuator signals
  - Ground and power connections

Hardware Design: Interfaces to other Subsystems

- Power System
  - Power from the Solar Panel Wing
  - Power lines to the Actuation Regulation Circuits
  - Power to the OBC
  - Batteries Charge/Discharge Regulator switching
  - Slip-rings in the Solar Panel Wing
- Thermal Control System – to dissipate heat and keep the AVCS within temperature ranges
- Attitude Determination and Control System – anticipation of hard maneuvers from the OBC
- Structures and Mechanisms – deployment mechanism, frozen hinges, etc.
- Telecommunication System – updates on the AVCS control laws

Software Design: On-Board Computer Control Programs

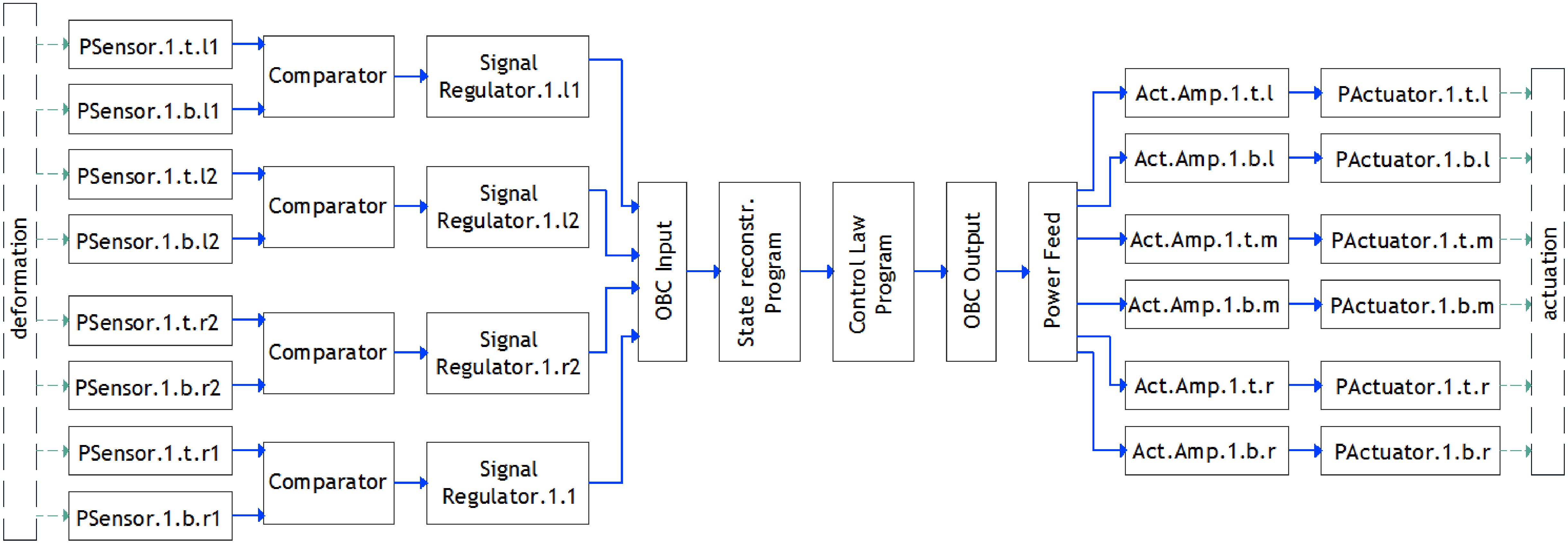
- State reconstruction algorithm (program):

Voltage Signal Input → ADC → Deformations to Modal Amplitudes → Deformed state Output

- Feedback Control Law algorithm (program):

Deformed state Input → PID Control Law → Necessary Control Forces → DAC → Voltage Signal Output

Reliability Block Diagram of the AVCS
(First Iteration)



Environmental Effects (1/2)

- Electro-Static Discharge (ESD)
  - Logic changes, command errors
  - Electronic component failures (burn-outs)
- Heating from Sun and Earthshine
  - Sensors and Actuators running close to temperature range limits
  - Induced vibrations on the SPW
- Movement through Magnetic Field
  - Causing potentially small currents in looped circuits
- Micrometeoroids and space debris
  - Induced vibrations on the SPW
  - Damage to AVCS components

Environmental Effects (2/2)

- Total Ionizing Dose Effects:
  - Degradation of electronics, threshold shifts
  - Mechanical degradation of Sensors and Actuators close to external surfaces
- Displacement Damage Effects:
  - Degradation of performance in Sensors and Actuators
- Single Event Effects:
  - Single Event Upset (SEU) on the OBC logic (memory cells and registers) – MBU (data corruption)
  - Single Event Transient (SET) in Op-Amps and in signals from the Sensors and to the Actuators
  - Single Event Functional Interrupts (SEFI) – temporary loss of functionality in the OBC, recovered by reset or power cycle
  - Current pulses

Possible Failures (1/4)

- Piezoelectric Sensors
  - Separation from the SPW structure or electrode tear (single sensor loss)
  - Functional fatigue (degradation of performance, reduction of the piezoelectric constant)
  - Single event upset (SEU) – erroneous signal on the electrodes prior to amplification
  - Change of properties due to temperature limit approach
- Sensing Regulation Circuitry
  - Component failing short
  - Component failing open
  - Loss of amplification ability
  - Loss of smoothing ability (noisy signal)
  - Parameter-shift of the Op-Amps
  - Overcharge (ESD) from sensors' assembly, when the circuit is offline

Possible Failures (2/4)

- On-Board Computer:
  - OBC’s state reconstructing program
    - Faulty Inputs from the ADC
    - Faulty address location of results (overwrite)
    - Corrupted data
    - Threshold shift in the activation of the program
  - OBC’s Control law program
    - Computed gains lead to instability
    - Computation is using outdated values (from previous clock) (delay)
    - Faulty outputs from the DAC
    - Premature activation of program (e.g. during launch)

Possible Failures (3/4)

- Actuation Regulation Circuitry
  - Induced currents from motion through magnetic field (loops)
  - Loss of power
  - Similar failures to the SRC
- Piezoelectric Actuators
  - Loss of an actuator (due to detachment, tear of electrodes, etc.)
  - Functional fatigue of an actuator
  - Change of properties due to temperature limit approach
  - Erroneous signal directly on the electrodes (SEE)
  - Inversion of polarity in the presence of a strong electric field

Possible Failures (4/4)

- In other interfaced Subsystems:
  - Voltage surges from the solar panel busses
  - Structural damage to the SPW
  - Damage to the hinges and/or slip-rings of the SPW
  - Failure in the Thermal Control System to keep the temperature ranges
  - Interference of other Subsystems with the OBC usage (Telecom, ADCS)
  - Power loss
  - ADCS failure leading to resonance oscillations

FMECA Incomplete

Assembly: Solar Panel Wing										
Assembly Function: Power generation										
Component: Piezoelectric Sensors									Quantity	16
Component Function: to detect deformations of the SPW										
Failure Mode	**Possible Cause**	**Failure Effect**			**Importance**	**Verification Effectiveness**	**Probability Class**	**Severity Group**	**Criticality**	**Remarks**
		On AVC System	**On Assembly**	**On Satellite**						
N - No function	Dettachment of the sensor or tear of the electrodes	Loss of observability	Reduced attenuation of certain higher vibration modes	none	II	3	D	1	-	Is redundant.
L - Loss of function	Dettachment of the sensor or tear of the electrodes	Sudden loss of observability	Reduced attenuation of certain higher vibration modes	none	II	3	E	1	-	Introduced robustness in the OBC programs to account for the sudden loss, and to stop propagating it to the Assembly or System
D - Degraded function	Wear-out due to displacement damage or TID	A possible common failure for the piezoelectric sensors that could degrade the performance of the AVCS	Increased vibration damping times	Possible influence on Attitude Determination and Control System performance and maximum power generation	III	2	D	1	-	Sensor degradation may be accounted for in the OBC program algorithms
	Working away of temperature ranges	Reduced effectiveness of the control laws at different time periods.	Increased vibration damping times	Possible influence on Attitude Determination and Control System performance and maximum power generation	III	2	C	1	-	Adjustments of the control laws for the different performances are more difficult to implement in the OBC
U - Untimely function start	Erroneous signal due to SEE or a current pulse	Makes the reconstructed state and the control law invalid/improper	Possible dynamical instability of the SPW	Possible loss of the mission	IV	2	D	3	C	Very critical for the mission and asks for redundancy in both sensors and OBC control to be implemented, and for robust Design Control

AVCS Reliability Improvements (1/5)

- Piezoelectric Sensors
  - Higher single component reliability (sensors with better quality)
  - Duplication with comparison (double-sided placement)
  - Pair-and-spare redundancy with another row of sensors – switching mechanism trade-off
  - Generalized pair-and-spare redundancy with four sensors (second row + model)
  - Triple Modular Redundancy (or Adaptive Majority Logic) – but problems with degrading sensors
  - Electrode path management
  - Possibilities to install them inside the SPW structure (inner layer of the composite beam)

AVCS Reliability Improvements (2/5)

- Piezoelectric Actuators
  - Higher single component reliability (higher manufacturing quality actuators)
  - Use of more powerful actuators able to pick up the load of a failing one (also derating, stress/strength)
  - Use of actuators in parallel redundancy
    - E.g. three in parallel (per sensing-actuation node) which are able to share the actuation load @ 1/3 of their force capacity
    - Cold-spare in the middle of the beam
    - Self-purging redundancy
  - Protection from current, voltage, power surges, other interferences from the solar-cells

AVCS Reliability Improvements (3/5)

- Sensing Regulation Circuitry
  - Higher single component reliability (higher quality Op-Amps)
  - Open/short redundant paths (Bimodal redundancy of resistors/capacitors)
  - Conformal Coating against tin-whiskers
  - Could employ a comparator in case of Duplex redundancy, pair-and-spare, etc. with a higher quality
  - Shielding (Packaging, Faraday cage)
  - Reducing volume (reduction of number of boards for the entire set of sensors)
- Actuation Regulation Circuitry
  - Radiation hardened transistors
  - Switch to turn-off system instead of lead it to instability (fail-safe, fail-controlled)
- Interaction with other Subsystems:
  - Selection of proper materials for passive thermal control (keep components in temperature range)

AVCS Reliability Improvements (4/5)

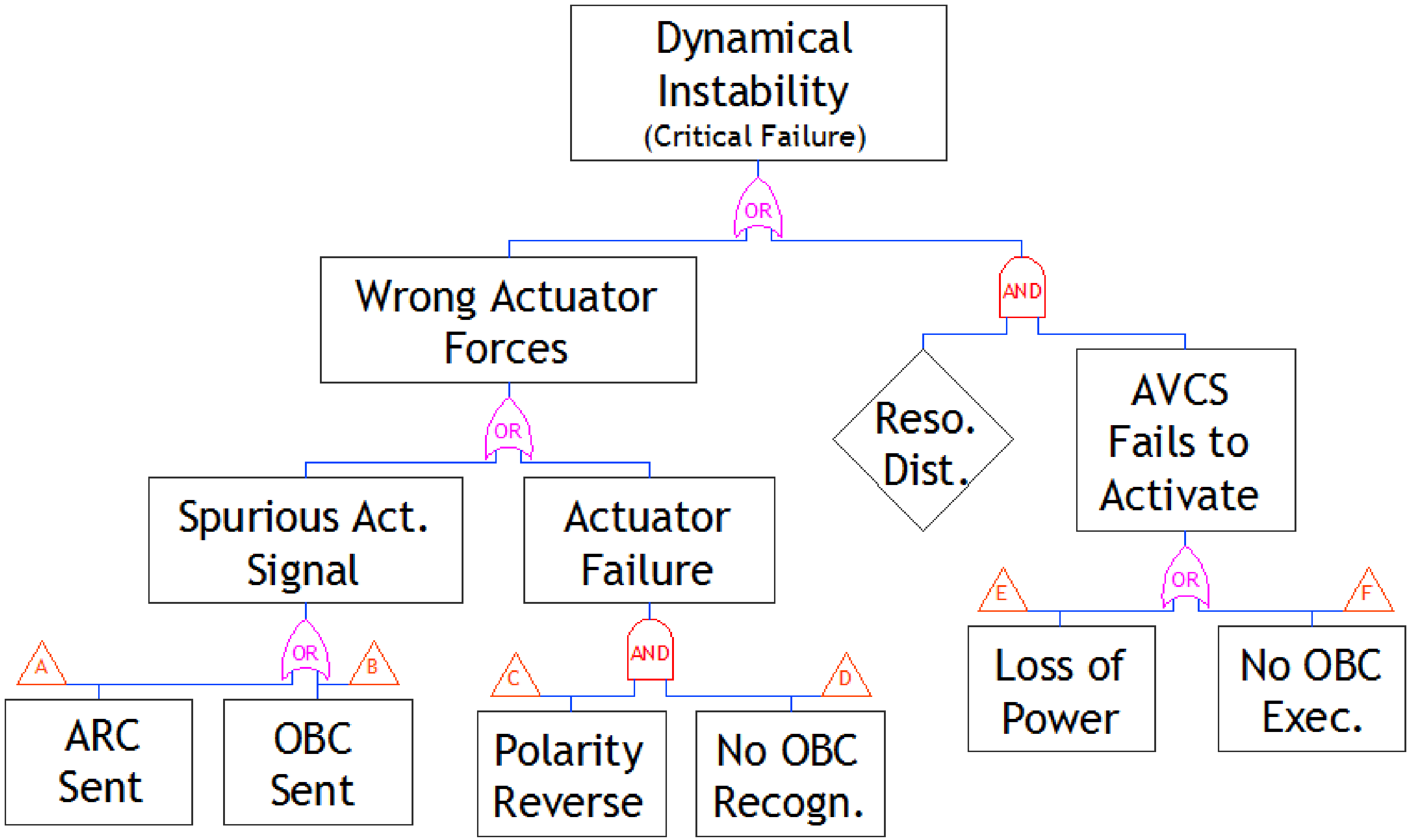
- OBC
  - Fail-safe interrupt to avoid dynamical instabilities
  - Fault detection and isolation of a faulty sensor path (in-case of entirely failed sensor train) + Decision to confine the faulty sensor path and reconfigure the actuating control law accordingly (Reprogram at reduced observability as long as within specifications)
  - Fault detection and isolation of the faulty actuator path + Reconfiguration of the control law (Reprogram at loss of controllability levels as long as within specifications) + Purging of a failed actuator
  - Watchdog to reload the program and stop a faulty or outdated execution
  - Checks for the proper execution of the control law through feedback signals coming back to the OBC
  - Checks for activation of the AVCS
  - Software voter/comparator for TMR (trade-off – slows down the system)
  - Radiation hardening
  - Shielding (packaging)

AVCS Reliability Improvements (5/5)

- Other means and considerations for Dependability improvement
  - Built-in self-test at system start-up for preemptive error and abrupt behavior detection
  - Also built-in test by an operator (telecommanded)
  - Design for testability to swiftly isolate faults
  - Design diversity implementation
    - Central SMA Actuator instead of piezoelectric (also consideration in common-mode failures elsewhere)
    - Introduction of redundant power line path, I/O bus for the SRC, ARC
  - Fault prevention through modularization of the sensor/actuator trains
  - Maintainability and Upgradeability of the sensors, actuators, electronics, control algorithms (for future larger systems)
  - On-site replacement of ageing piezoelectric sensors and actuators before suffering from functional fatigue (Fatigue prevention methods)

FTA Incomplete

- Graph for the FTA of the most critical AVCS failure:



Conclusions

- Fail-controlled (fail-safe) type of fault tolerance in the AVCS is paramount for overall mission success
- The reliability of the system is a function of its redundancy, but also complexity. Therefore balance between them should be sought after. Some components may be best replaced with a higher quality ones instead of introducing redundancy.
- Trade-offs in terms of volume, mass, power consumption, controllability/observability, cost and reliability must be considered for optimal design and implementation
- AVC System interaction with other Spacecraft subsystems must be taken into account in every phase of the design (concurrent)

Thank you!