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Reliability Estimation of an Earthquake Prediction Satellite

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Abstract
Satellite for earthquake prediction includes Electrical Power, Attitude Determination and Control, Telemetry, Tracking and Command, Command and Data Handling, Thermal and Structures and Mechanism subsystems. The satellite will be reliable if the reliability of its subsystems is enough. In other words, the reliability of each subsystem should be determined, in order to eliminate or limit failures to acceptable levels. In this paper, different subsystems of a satellite for earthquake prediction have been reviewed. Then, reliability of satellite subsystems has been determined by using FMECA analysis. Finally, with reliability comparison between centralized and ring architecture, most reliable configuration has been proposed. According to the calculations with FMECA method, the centralized architecture is more reliable than ring architecture.
Keywords: *earthquake- centralized architecture- reliability - ring architecture -FMECA*.

Introduction

Violent movement of the earth's surface as a result of the energy release can destroy towns and claim lives of many people. The matter of predicting disasters has always been one of the hottest and most challenging tasks in geology. Earthquakes are most destructive among all the natural hazards. Occurring often without any warning and are the most feared and unpredictable natural phenomena. In recent years with the emergence of satellite for earthquake prediction, geologists interested themselves to define accurate and reliable procedures to foresee disasters using this technology. A satellite for earthquake prediction is intended to provide advance warning of earthquakes.

With the recent advances in space-borne data collecting methods which have made it possible monitoring the earth surface with satellite, scientists are now able to better study the causes and signs of earthquakes. Current researches are moving in the direction of pre-earthquake deformation detection.

Earthquakes are not the same in terms of origins, places (depth) and effects. Therefore remote sensing methods will used to predict tectonic earthquakes. According to the types of measurements, remote sensing methods can be categorized in three main types; crust displacement, thermal and electromagnetic detecting techniques. Regarding the area's geological characteristics, satellites with optical and/or Synthetic Aperture Radar (SAR) sensors applications could be used in prediction of large-scale natural disasters.

In order to make successful prediction, all the related data must be collected from different space-borne sensors and ground-based stations. Past earthquakes should also be investigated for any phenomena that can occur before an earthquake. Surface deformation data are provided by GPS and SAR imaging, land surface temperature changes, different types of cloud studies, electromagnetic and ionosphere anomalies by ground passive stations and radon gas emissions in the faults areas by solid on the ground detectors.

There are different signs for earthquake prediction. Strong seismic activity often causes electromagnetic anomalies in earth's atmosphere and magnetic field, which helps in the monitoring and prediction of earthquakes. Enhancement of seismic activity produces DC electric field disturbances in ionosphere over an area of hundreds of kilometers diameter. When the earth’s magnetic field is disturbed, it should be determined if this is a precursor for an impending earthquake or it is due to some other factor. This will carry out by comparing the recorded data from the satellite with data at the same location at other times. If the data is comparable with the previous recorded one, then it will be reliable.

Pure seismic monitoring and seismic risk methods could give estimations of the magnitude of the future earthquake, it is possible to determine the position of future epicenter, but no technique could give an exact time of occurrence on scale of days [1].

Due to lack of statistical reliability analysis of earthquake precursors, earthquake prediction from ionospheric parameters is considered to be controversial. In [2], reliability of earthquake prediction is investigated using dense total electron content (TEC) data estimated from the Turkish National Permanent GPS Network. Also the ultra-low frequency (ULF) electromagnetic (EM) emissions, a short-term or operative parameter under observation for diagnosing seismic regimes have been examined for their reliability with efforts aimed to consider them as a reliable diagnostics [3]. In [4] a new method for high-precision real-time earthquake monitoring that focuses on station velocity using single-frequency GPS receivers is proposed. By means of GPS absolute velocity determination (AVD), the co-seismic displacement can be instantaneously recorded by the velocity changes.

In the rest of paper, first different subsystems of earthquake satellite will reviewed, and then the reliability of these subsystems will be calculated with Failure Mode and Effects Analysis with Critically Analysis (FMECA) technique. Finally reliability for

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each subsystem will calculate and with respect of two different centralized and ring architectures, earthquake satellite reliability will estimate.

Subsystems of Earthquake Satellite

A. Attitude Determination and Control (ADC)

The ADC subsystem stabilizes the satellite and orients it in desired directions during the mission despite the external disturbance torques acting on it. This requires that the satellite determine its attitude, using sensors, and control it, using actuators. Fig. 1 shows the functional block of ADC subsystem.

According to Fig. 1, ADC subsystem has different blocks; sensors block to get attitude information, Analog to Digital (AD) Convertor to change analog sensor output data to digital, Attitude Control Software (ACS), Controller block to make an output for actuators. Different sensors and actuators of ADC subsystem is shown in Table 1. The ADC subsystem often is tightly coupled to other subsystems, especially the propulsion and navigation functions [5].

B. Telemetry, Tracking and Command (TT&C)

The TT&C or communications subsystem provides the interface between the satellite and ground station systems. Payload mission data and satellite housekeeping data pass from the satellite through this subsystem to operators and users at the operations center. Operator commands also pass to the satellite through this subsystem to control the satellite and to operate the payload. The subsystem functions include the following:

- Carrier tracking (lock onto the ground station signal)
- Command reception and detection (receive the uplink signal and process it)
- Telemetry modulation and transmission (accept data from satellite systems, process them, and transmit them)
- Ranging (receive, process, and transmit ranging signals to determine the satellite's position)
- Subsystem operations (process subsystem data, maintain its own health and status, point the antennas, detect and recover faults)

At the subsystem level, the TT&C subsystem interfaces directly with every subsystem except propulsion subsystem. Fig. 2 shows the block diagram of a generic TT&C subsystem. This subsystem has full redundancy includes two transponders with parallel transmit and receive signal paths. The diplexer allows the same antenna to be used for transmitting and receiving. The band-reject filter attenuates spurious signals originating from the transmitter at the receiver’s center frequency to help the diplexer isolate the receiver from the transmitter [6].

C. Command and Data Handling (C&DH)

The C&DH subsystem performs two major functions. It receives, validates, decodes, and distributes commands to other satellite systems and gathers, processes, and formats satellite housekeeping and mission data for downlink or use by an onboard computer. This equipment often includes additional functions, such as satellite timekeeping, computer health monitoring (watchdog), and security interfaces.

Table 1: ADC subsystem components

Sensors	Sun
	Earth
	Magnetometers
	Star
	Inertial (Gyros)
Actuators	Momentum/Reaction Wheels
	CMGs (Control Moment Gyros)
	Electromagnets
	Thrusters

While it normally provides independent functions, the combination of command and data handling into a single subsystem provides an efficient means for autonomous control of satellite functions. An onboard computer or microprocessor can send commands and monitor telemetry over a single interface with the C&DH system, allowing the control of multiple subsystems. Fig. 3 shows the generic block diagram of CD&H subsystem [6]. This block diagram contains following described sub-blocks.

1) High-Level Analog

A telemetry channel with information encoded as an analog voltage, typically in the range of 0 to 5.2 V named High-Level Analog. These are active analog inputs in that the command and data handling system does not provide measurement excitation. This information will convert to digital form with AD converter.

2) Low-Level Analog

Low-Level analog is a telemetry channel with information encoded as an analog voltage which the signal range is low enough to require amplification before the information is encoded into digital form. Typical gain values are between 100 to 300. Because of the signal's low voltage range, it is subject to noise contamination and thus uses an interface in which the telemetry information is the difference between signal and reference inputs to the C&DH system.

3) Passive Analog

A passive analog is a telemetry channel with information encoded as a resistance which C&DH system supplies a constant current to the resistive sensor and encodes the resulting IR voltage drop into a digital word. All analog telemetry is converted to digital then data resolution will be determined by the number of quantization levels.

4) Bi-Level (Discrete) Input

This input is a telemetry channel that conveying two state information (such as on/off or enable/disable). Information is encoded as voltages, but may be encoded as a resistance or the presence or absence of a signal.

5) Serial Telemetry (Digital) Interface

This is a 3-signal interface used to transfer digital data from an external source to the data handling equipment. The C&DH system provides a shift clock and an interface enable signal to control data transfer. Interface circuits may be differential line drivers or single ended. Serial rather than parallel interfaces are preferred on satellite, because they simplify cable design and require fewer interface circuits.

D. Electrical Power

As shown in Fig. 4, the electrical power subsystem (EPS) would breakdown to four blocks of provision, storage, distribution and regulation & control satellite electrical power.

The most important requirements are the supply of average and peak electrical power. First of all, we should identify the electrical power loads of satellite mission at Beginning-Of-Life (BOL) and End-Of-Life (EOL). In many missions, the EOL power demands must be reduced because solar array performance will degrade at EOL.

Usually to obtain peak power requirements for attitude control, payload, thermal and EPS (when charging the batteries), we multiply average power by 2 or 3. Fortunately, all the subsystems of satellite do not require peak power at the same time during the mission.

E. Thermal

The role of the thermal control subsystem (TCS) is to maintain all satellite and payload components and subsystems within their required temperature limits for each mission phase. Temperature limits include a cold temperature which the component must not go below and a hot temperature that it must not exceed. Two limits are frequently defined: operational limits that the component must remain within while operating and survival limits that the component must remain within at all times, even when not powered. Table 2 gives typical component temperature ranges for representative satellite components. Thermal control is also used to ensure that temperature gradient requirements are met.

F. Structures and Mechanisms

The structures and mechanisms subsystem mechanically supports all other satellite subsystems, attaches the satellite to the launch vehicle, and provides for ordnance activated separation. The design must satisfy all strength and stiffness requirements of the satellite and of its interface to the booster. Primary structure carries the satellite's major loads. Secondary structure supports wire bundles; propellant lines, nonstructural doors, and brackets for components typically under 5 kg [6].

Types of Architecture

To connect subsystems of satellite, two different architectures could be used. This section will describe these two architectures and compare them together.

A. Centralized Architecture

Centralized architecture has point-to-point interfaces between processing units and a single management computer, or central node, or hub. Fig. 5 shows an example of ADC subsystem with centralized architecture.

Table 2: Typical thermal requirement for satellite components

Component	**Typical Temperature Ranges (°C)**	
	Operational	***Survival***
Batteries	0 to 15	-10 to 25
Power Box Baseplates	-10 to 50	-20 to 60
Reaction Wheels	-10 to 40	-20 to 50
Gyros/IMUs	0 to 40	-10 to 50
Star Trackers	0 to 30	-10 to 40
C&DH Box Baseplates	-20 to 60	-40 to 75
Hydrazine Tanks and Lines	15 to 40	5 to 50
Antenna Gimbals	-40 to 80	-50 to 90
Antennas	-100 to 100	-120 to 120
Solar Panels	-150 to 110	-200 to 130

This architecture works best with a few, well-defined systems which all interfaces directly are connected with the central computer. This architecture is high reliable where failures along one interface will not affect the other interfaces.

To add a new node requires both hardware and software changes in the central node. Wiring harnesses become large because each node has duplicate transmission wires if data are sent to multiple receivers.

B. Ring Architecture (Distributed)

The ring architecture establishes a way to arbitrate information flow control as the data are passed in a circular pattern. Fig. 6 shows ADC subsystem with distributed architecture.

In this architecture in comparison to centralized architecture, wiring harnesses are smaller and can be distributed throughout satellite structure. This architecture is less reliable since each node is in-line and thus required to achieve transmission to the next node.

Reliability Concept

A satellite can cease due to failure or because it has reached to the end of its lifetime. Reliability is a measure of the probability of failures and depends on the reliability of the equipment and any architecture used to provide redundancy. Effect of failures can be reduced and reliability increased by changing the design scheme, selecting more reliable hardware or adding redundant hardware and software to the system [7].

When a bulb in our desk lamp burns out, it is easily replaced. When the switch that controls the bulb fails, the replacement is not quite as simple but still within the capabilities of most people. We expect a higher reliability of the switch than of the lamp because it requires more effort to repair a failure. When a satellite subsystem fails on orbit, the satellite mission will lost. Therefore the subsystems of satellite have to be much more reliable than the light bulb or the switch on the desk lamp.

Searching for and identifying the ways in which equipment can fail is a basic part of design for reliability. This process, called Failure Modes Effects and Criticality Analysis (FMECA) assumes that we can identify the ways in which equipment can fail and analyze the effect. The key to this process is identifying and eliminating single point failure modes failures that by themselves can kill satellite mission. If we cannot eliminate them, we must minimize their probability of occurrence during the satellite mission. The elementary expression for the reliability of a single item is

$$R = e^{-\lambda t} \quad (1)$$

where λ is the failure rate and *t* is the time. Here *R* is the probability that the item will operate without failure for time *t*. Therefore the probability of failure, *F*, is given by:

$$F=1-R \quad (2)$$

Generally satellite failure probabilities (λt) is less than 0.1 or reliability is greater than 0.9, therefore following approximation is frequently used

$$e^{-\lambda t} \approx 1 - \lambda t \quad (3)$$

Most reliability computations, particularly prior to detailed design, use failure probabilities (which can be summed) rather than reliability values (that must be multiplied).

Where a system consists of *n* elements in parallel and each of these elements can by itself satisfy the requirements, the parallel reliability, R_p, is given by

$$R_p = 1 - \prod_1^n (1 - R_i) \quad (4)$$

If we assume the reliability of the parallel elements is equal to R_a, the above equation simplifies to

$$R_P = 1 - (1 - R_a)^n \quad (5)$$

In global applications it is customary to distinguish between active and inactive failure rates, the latter being about one tenth of the active rates. This reduction accounts for the absence of electrical stress when a component is not energized. However the high reliability requirements of the space environment cause components to be safe so that the failure probability due to electrical stresses even in the active mode is quite small. The distinction between active and inactive failure rates is therefore much less important for satellite.

Reliability Estimation

Failure Mode and Effects Analysis (FMEA) or FMECA is an analysis technique which facilitates the identification of potential problems in the design or process by examining the effects of lower level failures. Recommended actions or compensating provisions are made to reduce the likelihood of the problem occurring and mitigate the risk, if in fact, it does occur.

The FMEA determines, by failure mode analysis, the effect of each failure and identifies single failure points that are critical. It may also rank each failure according to the criticality of a failure effect and its probability of occurring. The FMECA is the result of two steps FMEA and Criticality Analysis (CA).

Criticality Analysis

The purpose of the CA is to rank each failure mode as identified in the FMEA, according to each failure mode's severity classification and its probability of occurrence. MIL-STD-1629 is an excellent data source for the implementation of a CA. The result of the CA will leads itself to the development of a Criticality Matrix.

The failure mode criticality number for each specific failure mode (C_m) is calculated as follows:

$$C_m = \beta . \alpha . \lambda_p . t \quad (6)$$

where C_m is failure mode critically number, β is conditional probability of failure effect, α is failure mode ratio, λ_p is part failure rate per million hours and *t* is duration of the relevant mission phase (operation) e.g. 20 hours.

The criticality number of each assembly (or system) is calculated per each severity category. This criticality number is the sum of the specific failure mode criticality numbers related to the particular severity category:

$$C_r = \sum_{n=1}^{j} \left(\beta . \alpha . \lambda_p . t\right)_n \quad (7)$$

where *n* is the current failure mode of the item being analyzed and *j* is the number of failure modes for the item being analyzed. The resulting FMECA analysis will enable a criticality matrix to be constructed. The criticality matrix displays the distribution of all the failure mode criticality numbers according to the severity category and referring to the criticality scale.

According to MIL-STD-1629 the scale is divided into five levels; Level A – frequent, Level B - reasonable probable, Level C - occasional probability, Level D - remote probability and Level E - extremely unlikely probability. Also a severity classification category assigned to each failure mode depending upon its effects of an equipment and/or system operation. The severity classification is consistent between MIL-STD-1629 and MIL-STD-882, which are Category I – catastrophic, Category II – critical, Category III – marginal and Category IV – Minor.

Applying FMECA to Earthquake Satellite Subsystems

In this section, for each earthquake satellite subsystems required parameters for FMECA is calculated. These parameters are failure rate, failure mode, failure mode ratio, C_m and C_r of different subsystems of earthquake satellite. For calculations, Eq. (1) to Eq. (7) is used and results are inserted into the Table 3, Table 4 and Table 5.

Table 3: Definition of parameters failure rate, failure mode, failure mode ratio, C_m and C_r of ADC subsysytem

Block Name	λ_p	Failure Mode	α	β	C_m	C_r
Sensors	0.010	Open	0.90	0.90	0.00810	0.01000
		Open	0.90	0.10	0.00090	
		Short	0.10	0.85	0.00085	
		Short	0.10	0.15	0.00015	
AD Converter	0.002	Open	0.85	0.80	0.00136	0.00203
		Open	0.70	0.20	0.00028	
		Short	0.15	0.70	0.00021	
		Short	0.30	0.30	0.00018	
ACS Software	0.001	Open	0.50	0.50	0.00025	0.00100
		Open	0.50	0.50	0.00025	
		Short	0.50	0.50	0.00025	
		Short	0.50	0.50	0.00025	
Controller	0.002	Open	0.70	0.80	0.00112	0.00216
		Open	0.30	0.20	0.00012	
		Short	0.30	0.60	0.00036	
		Short	0.70	0.40	0.00056	
Actuators	0.010	Open	0.90	0.90	0.00810	0.01000
		Open	0.90	0.10	0.00090	
		Short	0.10	0.85	0.00085	
		Short	0.10	0.15	0.00015	

In the calculations, equal failure probability is considered for blocks of all subsystems, although it is a rough approximation for reliability calculation. Also two conditions for each component which is open circuit or short circuit is assumed, although they may be in the middle state, but generally these two conditions are exist. With using the FMECA parameters, satellite reliability is calculated for two different centralized and ring architectures. Table 6, shows the reliability number for subsystems of earthquake satellite includes ADC, TT&C, C&DH and EP subsystems. Other subsystems functions such as thermal, structure and mechanism are included in these four subsystems reliability. In Table 7, reliability of two different architecture, centralized and ring are shown which according to parallel and series elements their reliabilities are calculated. As it was clear from this table, centralized architecture is more reliable than ring architecture, with its limitation which mentioned before.

Conclusion

Earthquake prediction is an essential problem these days. One of the effective devices which may use for prediction of it, is a satellite. The reliability of satellites always is a big issue especially for earthquake satellite which is related to life of many people. In this paper, the reliability of earthquake satellite is estimated with use of different satellite subsystems. These reliabilities are calculated with FMECA method that is a standard method for reliability calculation. Also two different centralized and ring architectures are investigated and finally proved that centralized architecture has a better reliability than ring architecture.

Acknowledgment

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Table 4: Definition of parameters failure rate, failure mode, failure mode ratio, C_m and C_r of TT&C subsysytem

Block Name	λ_p	Failure Mode	α	β	C_m	C_r
Transmitter Transponder Receiver	0.001	Open	0.70	0.90	0.000630	0.00100
		Open	0.80	0.10	0.000080	
		Short	0.30	0.85	0.000260	
		Short	0.20	0.15	0.000030	
Low Pass Filter	0.001	Open	0.85	0.80	0.000680	0.00101
		Open	0.75	0.20	0.000150	
		Short	0.15	0.75	0.000110	
		Short	0.25	0.25	0.000063	
Band Reject Filter	0.001	Open	0.85	0.80	0.000680	0.00101
		Open	0.75	0.20	0.000150	
		Short	0.15	0.75	0.000110	
		Short	0.25	0.25	0.000063	
Transmit RF Switch	0.001	Open	0.50	0.75	0.000380	0.00100
		Open	0.50	0.25	0.000130	
		Short	0.50	0.70	0.000350	
		Short	0.50	0.30	0.000150	
Receiver RF Switch	0.002	Open	0.60	0.40	0.000480	0.00202
		Open	0.70	0.60	0.000840	
		Short	0.40	0.50	0.000400	
		Short	0.30	0.50	0.000300	
Diplexer	0.005	Open	0.85	0.80	0.003400	0.00495
		Open	0.90	0.20	0.000900	
		Short	0.15	0.60	0.000450	
		Short	0.10	0.40	0.000200	
Antenna	0.010	Open	0.90	0.90	0.008100	0.01000
		Open	0.90	0.10	0.000900	
		Short	0.10	0.85	0.000850	
		Short	0.10	0.15	0.000150	

Table 5: Definition of parameters failure rate, failure mode, failure mode ratio, C_m and C_r of C&DH subsysytem

Block Name	λ_p	Failure Mode	α	β	C_m	C_r
High-Level Analog	0.010	Open	0.9	0.9	0.00810	0.01020
		Open	0.8	0.1	0.00080	
		Short	0.1	0.7	0.00070	
		Short	0.2	0.3	0.00060	
Low-Level Analog	0.010	Open	0.85	0.85	0.00723	0.01020
		Open	0.75	0.15	0.00113	
		Short	0.15	0.65	0.00098	
		Short	0.25	0.35	0.00088	
Passive Analog	0.010	Open	0.85	0.8	0.00680	0.01020
		Open	0.75	0.2	0.00150	
		Short	0.15	0.6	0.00090	
		Short	0.25	0.4	0.00100	
Bi-level	0.010	Open	0.85	0.75	0.00638	0.01005
		Open	0.75	0.25	0.00188	
		Short	0.15	0.7	0.00105	
		Short	0.25	0.3	0.00075	
Serial Digital	0.010	Open	0.9	0.9	0.00810	0.01000
		Open	0.9	0.1	0.00090	
		Short	0.1	0.6	0.00060	
		Short	0.1	0.4	0.00040	
Analog to Digital Converter	0.002	Open	0.85	0.8	0.00136	0.00198
		Open	0.9	0.2	0.00036	
		Short	0.15	0.55	0.00017	
		Short	0.1	0.45	0.00009	
Data Formatter & Control Logic	0.005	Open	0.9	0.85	0.00383	0.00500
		Open	0.9	0.15	0.00068	
		Short	0.1	0.9	0.00045	
		Short	0.1	0.1	0.00005	

Table 6: Satellite subsystem reliability estimation

Subsystem	Reliability Criteria	Description
ADC	0.975	According to Table 3
TT&C	0.984	According to Table 4
C&DH	0.995	According to Table 5
EP	0.993	According to [8]

Table 7: Reliability estimation of different architectures

Architecture Type	Reliability Criteria
Centralized	0.995
Ring	0.948

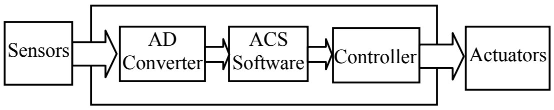

Fig. 1: ADC Functional block diagram.

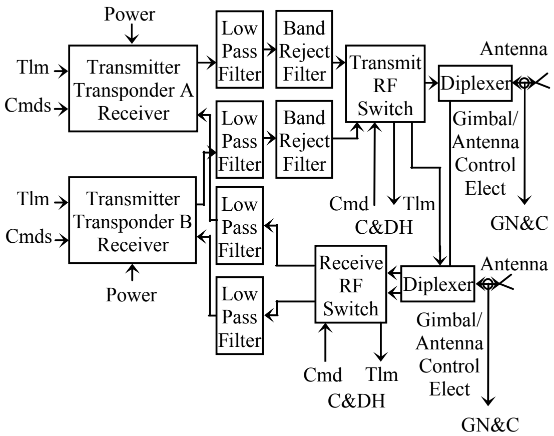

Fig. 2: Block diagram of a generic TT&C subsystem.

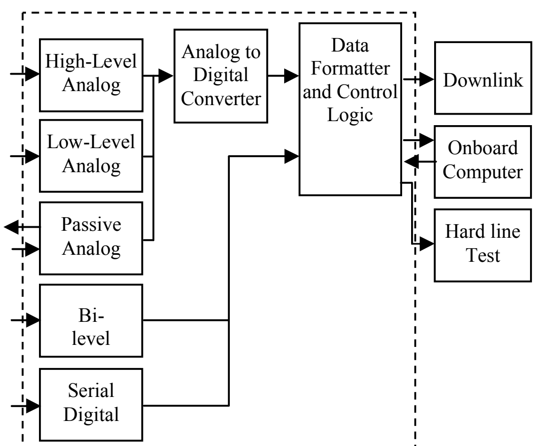

Fig. 3: Data handling unit block diagram.

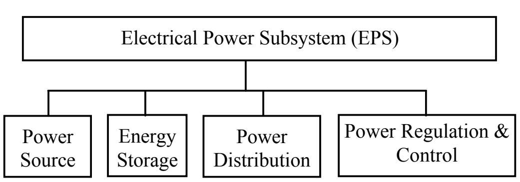

Fig. 4: Functional block diagram of Electrical Power Subsystem.

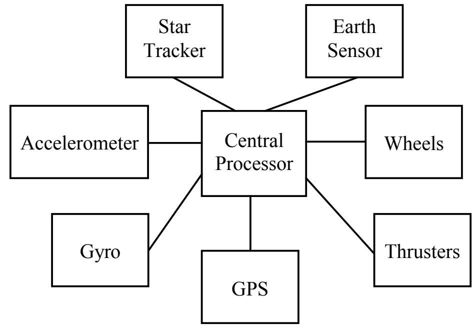

Fig. 5: Centralized architecture.

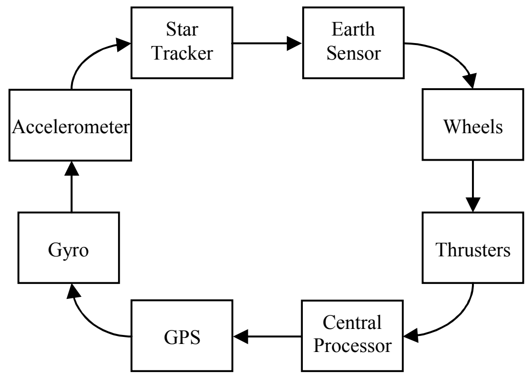

Fig. 6: Ring architecture.

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