DEMONSTRATION OF SMALL SATELLITE TECHNOLOGIES BY THE BIRD MISSION

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1 Rationale

The first satellites at the beginning of the space age were small satellites. Primarily because of the fact that the launch capacity was small. Later on the launchers and satellites grew, and today a lot of big missions with a high complexity are in space. These missions serve the science, the military and defense, commercial and operational users as well as public and private interests. Today's technology allows the supplement of the big missions by small satellite missions. By exploring new technologies and methods small satellites can prepare new experiments and technologies for big missions or solve complementary questions. Small satellites have several advantages, e. g.
- extremely smaller budgets,
- shorter development and manufacturing time,
- more dedicated mission objectives,
- smaller user communities,
- implementation of new technologies with higher risks.

Small satellites have to meet a big challenge: to answer high performance requirements by means of small equipment and especially of small budgets. Out of all aspects the cost aspect is one of the most important driver for small satellite missions. Usually, the largest part of the total mission costs are the spacecraft costs (user segment excluded). They will be followed by the launch cost (20-50 % of the total costs) and cost for ground segment including operations (up to 15 %) [1]. And of the spacecraft the attitude control system is usually the most expensive subsystem. This general experience with satellites is also valid for small satellites, for instance mini-satellites with a total mass up to 500 kg and micro-satellites with a total mass between 30 and about 130 kg. With regard to the mentioned cost drivers the group of the micro-satellites seems to be the most appropriate solution to fulfill the challenging mission objectives under low-budget constraints because of:

1. feasibility of launch as piggy-back or as auxiliary payload (launch costs lower than for shared launch or dedicated launch – necessary for mini-satellites),
2. feasibility of high performance payloads for micro-satellites,
3. feasibility of high performance spacecraft busses.

The suppositions 2 and 3 can be sufficiently accomplished under low-budget constraints only by using:
- state-of-the-art technologies,
- a mixed strategy in the definition of the quality level of the EEE parts and components,
- a dedicated quality assurance plan,
- a risc management system,
- extensive redundancy strategies,
- extensive tests especially on system level,
- large designs margins (over-design),
- robust design principles.

To keep the costs within the low-budget frame (in comparison to big missions) the demonstration of new and not space-

qualified technologies for the spacecraft and especially for the attitude subsystem is one key point in fulfilling high performance mission requirements. Taking this into account the DLR micro-satellite mission BIRD has to demonstrate a high performance capability of spacecraft bus by using and testing new technologies basing on a mixed parts and components qualification level. The technology experiments of BIRD shall demonstrate the limits and the advantages of using new developed components, methods, algorithms and technologies.

2 Mission Objectives

For hot spot events as forest and vegetation fires, volcanic activity or burning oil wells and coal seams a dedicated space instrumentation does not exist. Sensors being used now for the observation of these events have some drawbacks because they are not designed for the hot spot investigation. For the near future there are missions planned with a new generation of cooled infrared array sensors. The German BIRD (Bi-spectral Infrared Detection) mission will answer a lot of technological and scientific questions related to the operation of a compact bi-spectral infrared push-broom sensor on board of a micro satellite and related to the detection and investigation of fires from space. Therefore, the BIRD primary mission objectives are:

- Test of a new generation of infrared array sensors adapted to Earth remote sensing objectives,
- Detection and scientific investigation of High Temperature Events such as forest fires, volcanic activities, and coal seam fires,

- Test and demonstration of new small satellite technologies, such as new board computers, star sensors, reaction wheels, on-board navigation system, and other.

The secondary mission objectives consist in:

- Test and demonstration of on-board classification by means of a neural networks circuit
- scientific issues related to the diagnostics of vegetation conditions and changes.

The payload is a new developed multi-sensor system designed to fulfill the scientific requirements under the conditions of a micro satellite. The sensor system consists of the following main parts: an infrared array sensor system basing on cooled CdHgTe-detectors with 2x512 pixels in a medium infrared channel (3.4-4.2μm) and in a thermal infrared channel (8.5-9.3μm), a CCD-pushbroom camera with a red and a near infrared channel, a CCD matrix camera, a payload data handling system with an 1 Gbit mass memory and an on-board neural network classificator. The new small satellite bus technologies demonstrated at the BIRD spacecraft are

- a failure tolerant board computer system with its own operating system,
- a high precision reaction wheel for micro satellites,
- a star camera for micro satellites,
- a state space representation based attitude control system,
- an on-board navigation system,
- a low-cost ground station and others.

The BIRD mission is a small satellite mission funded by DLR. The BIRD satellite is launched with the Indian PSLV-C3 at 22. October 2001 into a 572 km circular Sun-synchronous Low Earth Orbit.

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3 BIRD Spacecraft features

To operate the BIRD payload nearly all functions of a classical remote sensing spacecraft have to be fulfilled. Due to the high impact on cost and spacecraft size an early decision was to do without any propulsion system. So no active orbit maintenance can be provided and a consequence of that is the limited lifetime to approximately one year.

Other constraints are:

- the push-broom principle of the scientific instruments – slew rate of $< 1°/s$,
- requirement for pointing accuracy of $+ 5$

arcmin with a pointing knowledge of $+ 0.2$ arcmin per axis,

- the need for optimal Sun-pointing to generate sufficient power.

200 W peak power are needed for the detection mode. Together with the data volume constraints this mode is defined as the duty cycle which can be worked out in three adjacent orbits for 10 min each.

The BIRD satellite consists primarily of a spacecraft bus service segment, an electronics segment, a remote sensing payload segment and fixed and deployable appendages. The main BIRD spacecraft characteristics are given in Figure 1.
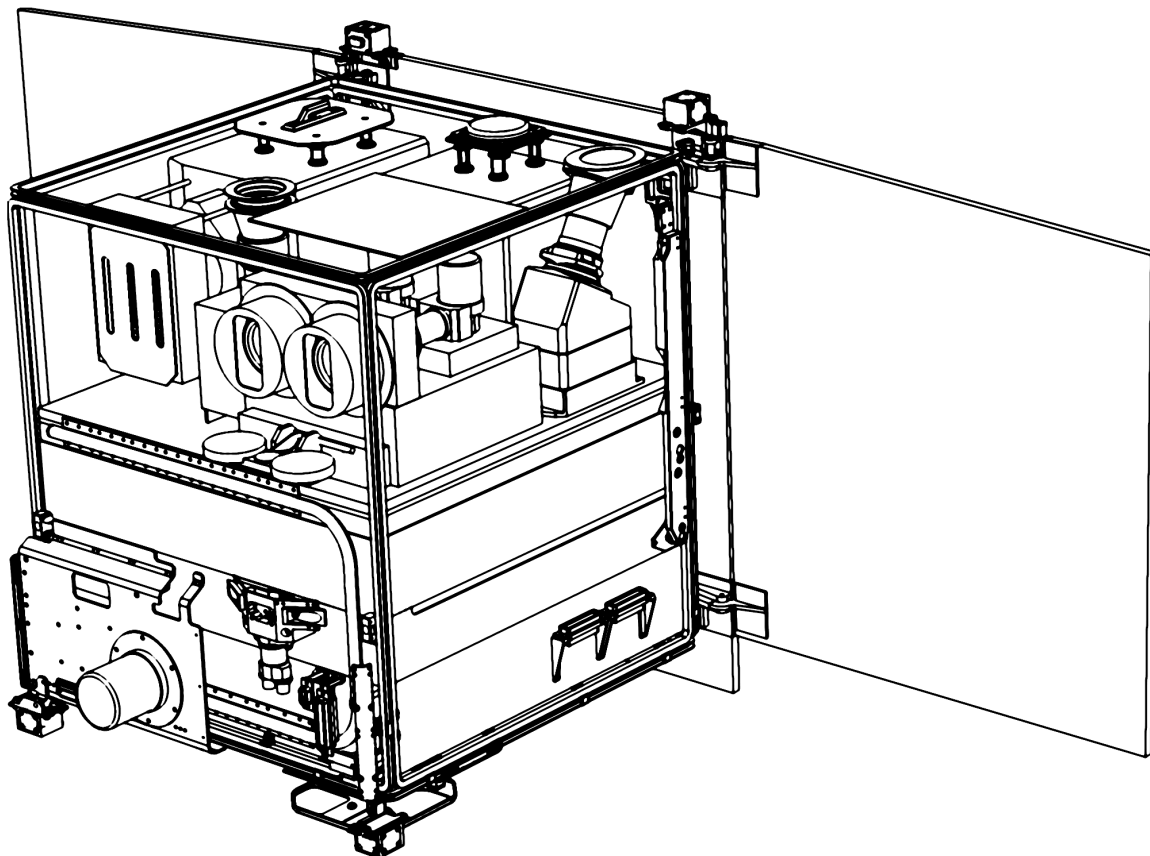
Figure 1   BIRD Satellite

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4 Enabling Earth-Technology for Space Applications

4.1 Overview BIRD Control System

According to the objectives of the BIRD mission, the satellite control system requires a powerful and flexible computation and communication infrastructure. The satellite control system allows for a far reaching autonomous operation of the satellite and at the same time it ensures the survivability of the satellite with highest priority. The on board computing system was realized as a distributed fault tolerant multi computer system which executes all control, telemetry, and monitor tasks as well as the application dependent tasks.

Technologically the board computer aims to derive benefits from using newest VLSI technology. The high integration density of modern microprocessors and memory devices allows to implement powerful computing systems with a high functionality consisting of only a small number of components. The extreme low power dissipation of low voltage components which are also used in battery-powered systems (notebook, camera, handy) results in minimal requirements for space, weight, cooling, and power supply which all are limited recourses in the context of small satellites. However, if we want to take these advantages we have to ensure that the use of newest VLSI technology may not diminish the reliability and availability of the board computer. In general, due to the optimized manufacturing process for high volume production, the reliability of modern VLSI components already attained a very high standard. Except for the radiation problems, the environmental conditions on board of a satellite in the low earth orbit (LEO) can be compared to the operating conditions assumed for industrial versions of such components. Therefore we implement special hardware and software measures in each node of the system to handle the radiation problems.
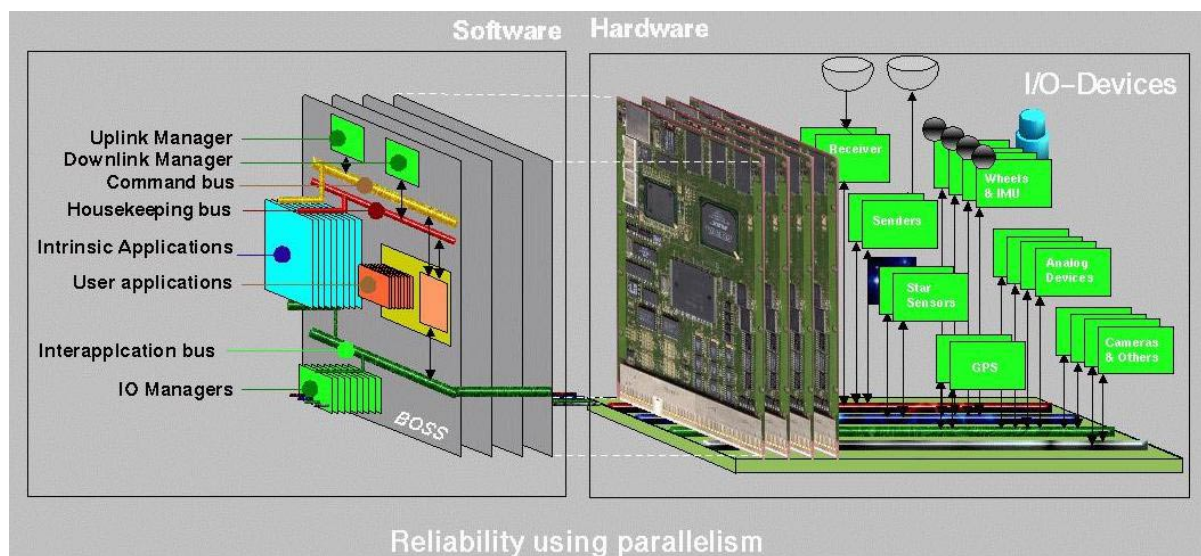

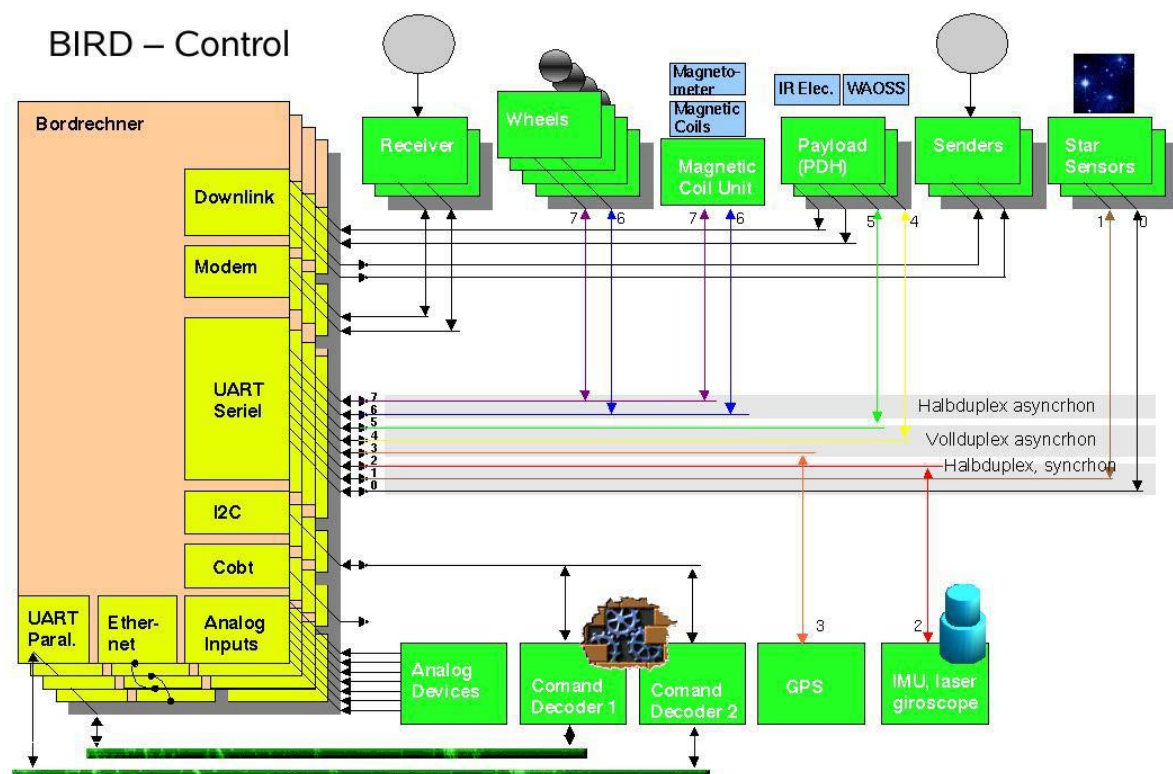**Figure 2 BIRD Spacecraft Bus Computer System, Overview**

4.2 Hardware of the BIRD Control System

The spacecraft bus is controlled completely by the dependable board computer of the satellite bus, which was developed from scratch, optimized for BIRD and using the most modern technology. A hardware-software co-design allowed us to minimize the development time and to use the
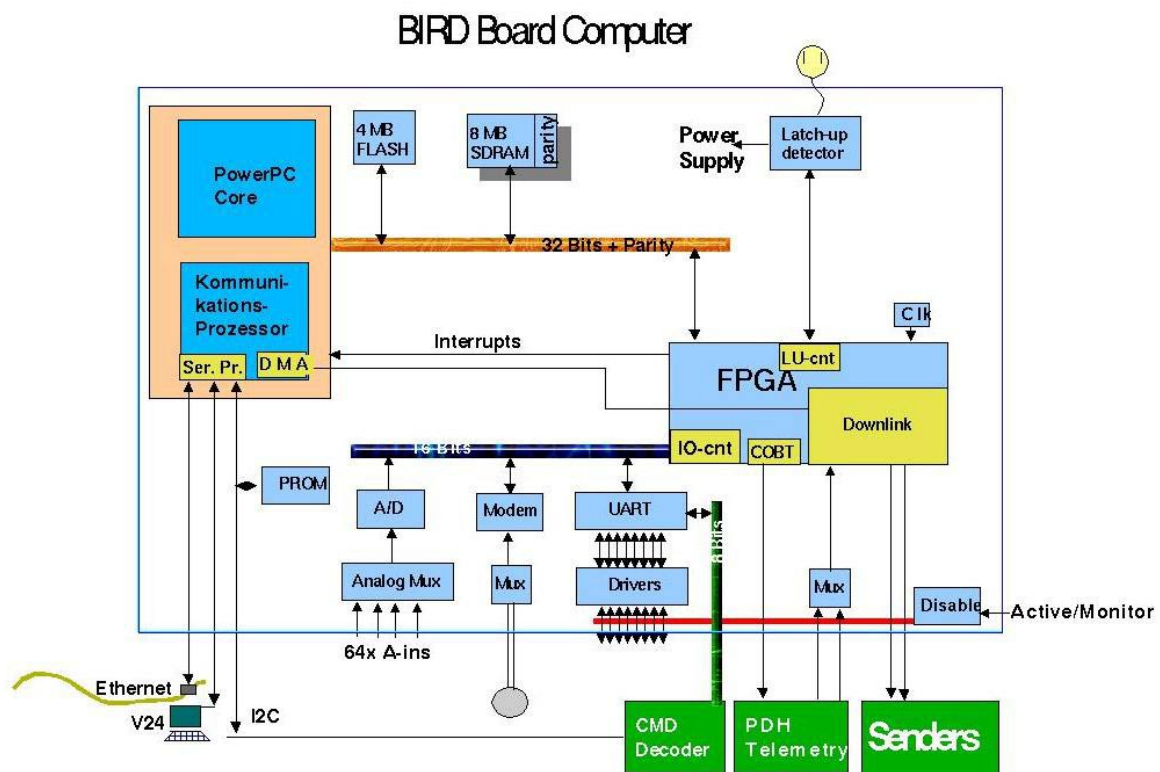
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resources optimally. If you develop separately software and hardware, the hardware people will invest a lot of time to implement very nice features which no one will use. Furthermore some times the software would wish some kind of hardware support which is not implemented and therefore the software implementations becomes much more complex (complexity implies lower dependability). Some functions can be easily implemented in hardware and some in software. To take the optimal solution we performed a co-design. To achieve a high dependability, safety, and lifetime, the board computer is formed of four identical computers (nodes). As shown in the block diagram below, the redundant nodes and all the devices of the satellite that have to be controlled by the board computer are interconnected by several bus systems with different protocols. Each node computer has following interfaces:

The architecture of the redundant control computer is totally symmetric, that means, each of the nodes is able to execute all control tasks. One node (the worker) is controlling the satellite while a second node (supervisor) is supervising the correct operation of the worker node. The two other node computers are spare components and are disconnected. Disconnected nodes have a longer life expectations because they do not degrade by the total doze radiation as fast as the connected nodes. The connected nodes worker and monitor build in team: If an anomaly of the monitor is detected by the worker, the worker forces the monitor to perform a recovery procedure, in the mean time the worker controls the satellite as usual. If an anomaly of the worker node is detected by the supervisor node the supervisor becomes the worker and takes over the control of the satellite.

Figure 3 Hardware Structure of the BIRD Control System

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The old worker node is enforced to execute a recovery function and, if there is no permanent error detected, it becomes the supervisor node. If the recovery procedure fails or if a permanent hardware error is detected, the faulty node computer will be switched off and replaced by one of the spare nodes. By this strategy up to 3 permanent node failures can be tolerated while the board computer stays operable.

The node computers are based on the PowerPC MPC623 processor. Each node has 4 MByte of FLASH memory and 8 MByte DRAM memory. The FLASH memory is large enough to hold several versions of the control software, each protected by a checksum.

The DRAM is parity protected and duplicated which allows for error detection and correction. The I/O devices, the interfaces to the satellite bus systems and the logic of the telemetry control system are realized within a complex FPGA device. To detect errors within the control logic, there are redundant implementations of the critical state machines and each data within the FPGA is protected by parity bits. All devices are protected against latch-ups. The latch-up protection is a programmable device. The software can set a current limit to each chip. If this limit is exceeded the power supply for the board will be turned off. The other (running) board computer will recognize this event and after a while it will turn the power of the failed board on and force a recovery.

**Figure 4 Structure of the BIRD Board Computer**

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5 Software of the BIRD Control System

The software and hardware architecture of powerBird follows the same approach to form a modular, distributed and highly redundant system architecture. Within each node, a small operating system (BOSS) provides the basic functionality for preemptive multi tasking, priority and real time based scheduling and communication. The modular structure of BOSS arises from the notion of a software back-plane which is formed out of two software busses. The software. All application of the satellite are implemented by dedicated tasks. The tasks have unified interfaces to the busses of the software back-plane. This allows to configure the system by simply plugging the software components in and out of the back plane. The command bus is used to distribute the commands and data, that have to be processed by the applications. The status/result bus collects the information and results of the applications which have to be sent down to the control stations on the earth.

Our highly modular operating system BOSS was implemented by using newest software technology and the critical parts have been formally verified. The applications running on top of BOSS are implemented by using object oriented technology, resulting in a highly modular application software. The BOSS operation system is available not only on the target system but also as a guest level implementation on top of Linux. This allows to implement and test all the application software on Linux workstations and move them to the target system without any change.
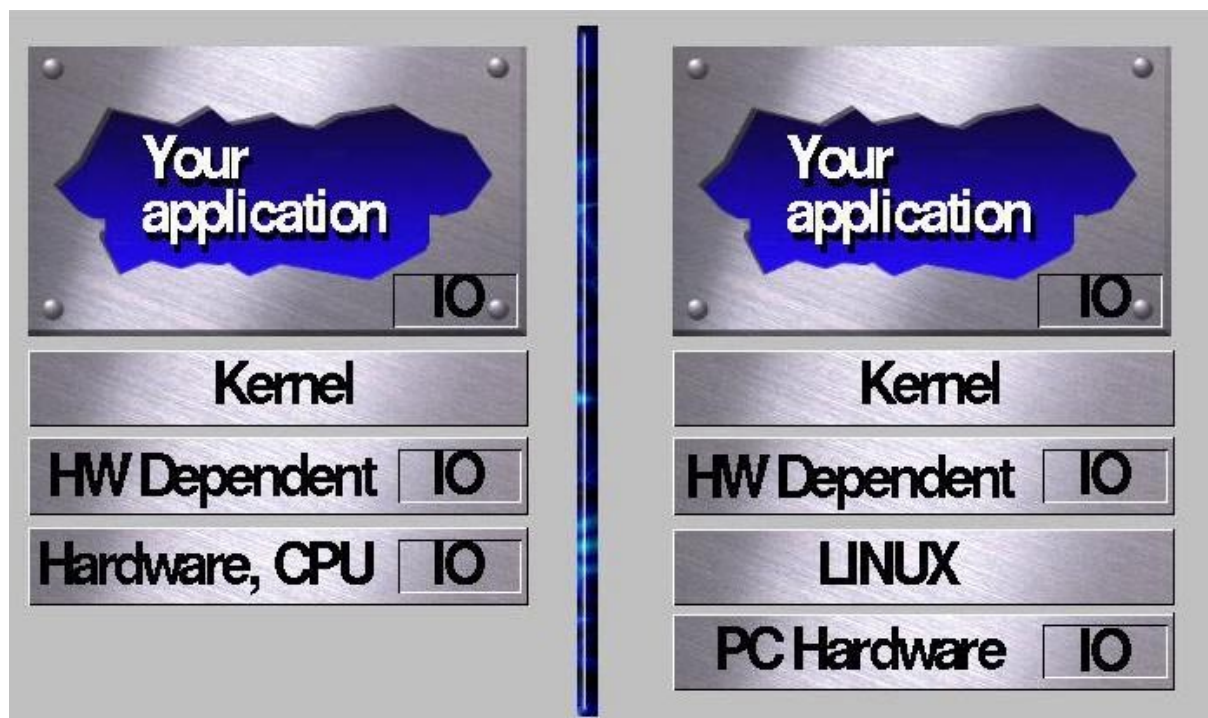
Figure 5 Modular Software Structure of the BIRD Control System

BOSS was keep a simple a possible. All operations are based on list management: remove from list and insert to list. The most important lists are: ready list (for the CPU), timer list (for thread waiting for a time point), semaphore lists, IO lists (for threads waiting for a IO event). This central operations were verified mathematically using a model checker.

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The control software is monitored using software watch dogs, and the software watchdog is monitored from an hardware watchdog. If an important task is not responding any more the board computer will be restarted, Extra care was taken to guaranty that not both nodes perform a recovery a the same time. While one node is performing a recovery the other board computer will take control over the satellite and after the restart, the new restarted board computer gets status information from the other, still running computer to synchronize their operations. To achieve well structured application system, we defined a software back plane formed out of two software busses. Each application implements an interface to each software bus. One software bus is used to distribute commands that have to be executed by the applications. The other bus collects the status information of the

applications which have to be sent down to the control stations on the earth. The principle of a software back plane allows an easy configuration of the system by simply plugging the software components in and out of the back plane. The following applications are required to control the satellite and are executed on the board computer:

Uplink and Commanding: get and execute/ distribute commands from earth
TimeManager: controls the on board time
On-board nav. (ONS): calculates the exact position of the satellite
Attitude Control (ACS): controls the position of the satellite
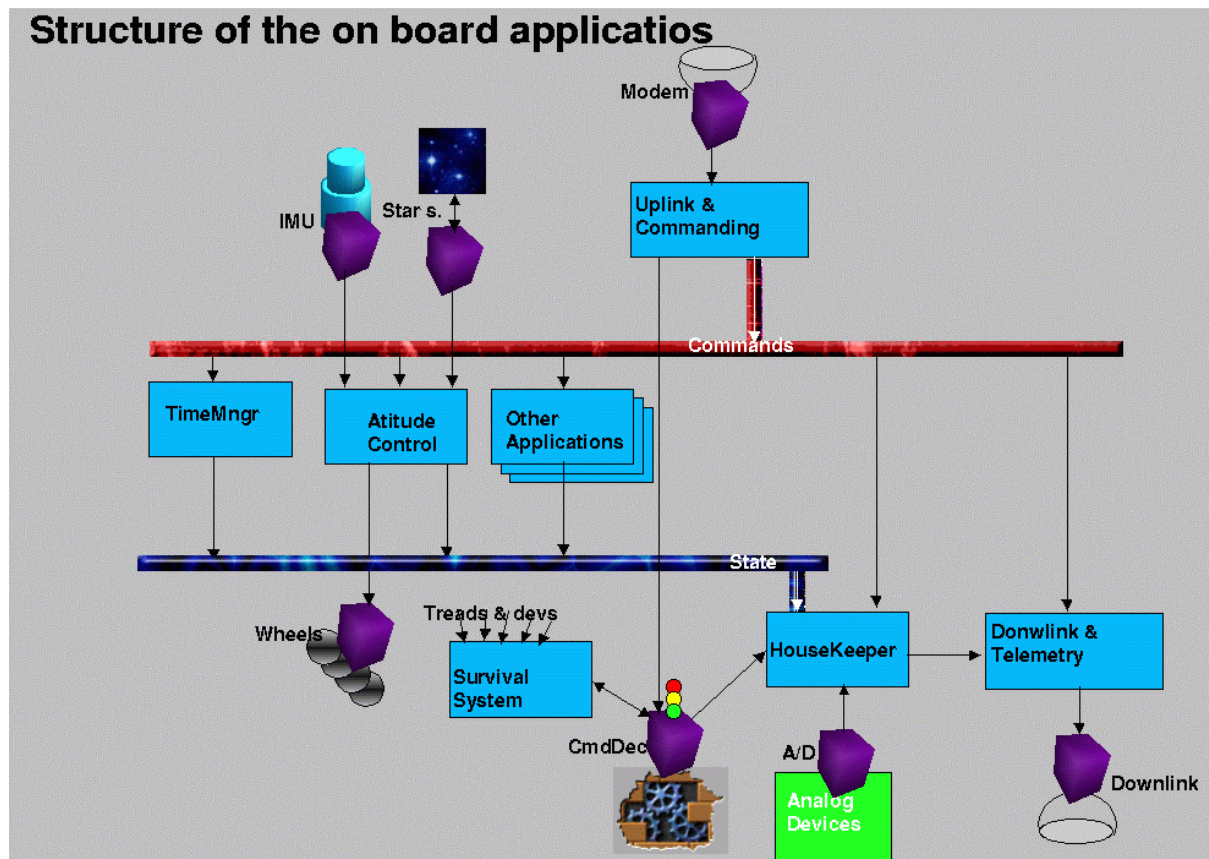**Survival:** controls the state of the vital devices
HouseKeeper: collects information to be sent to earth
Downlink: controls the senders

Figure 6 Basic Software Components of BIRD Spacecraft Bus Computer

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Figure 7 Structure of the BIRD Software Applications

All the basic applications and the common application layer have a strong object-oriented architecture, which consists of records, data mangers and threads. Records are objects which are used an a language for information exchange between data managers. In turn, data manager are the main objects, which keep data and organize data processing. Threads are objects, which allows to arrange processing of data as a collection of light-weight process running concurrently.

6 Experiences with the BIRD Control System

1. We can recommend one thing: simplicity is the best and most safe solution, for both software and hardware!

2. To be ready to handle any error is much better to try to prevent all of them (the second is not possible). Our board computers are not radiation hard therefore we expect many errors, but we are ready to catch and handle them.

After a few weeks in orbit, BIRD got its fire test with radiation. Several sun explosions raised the "normal" radioactivity to factor 200 thousand! BIRD toggled the function of the on board working computers and continued working properly.
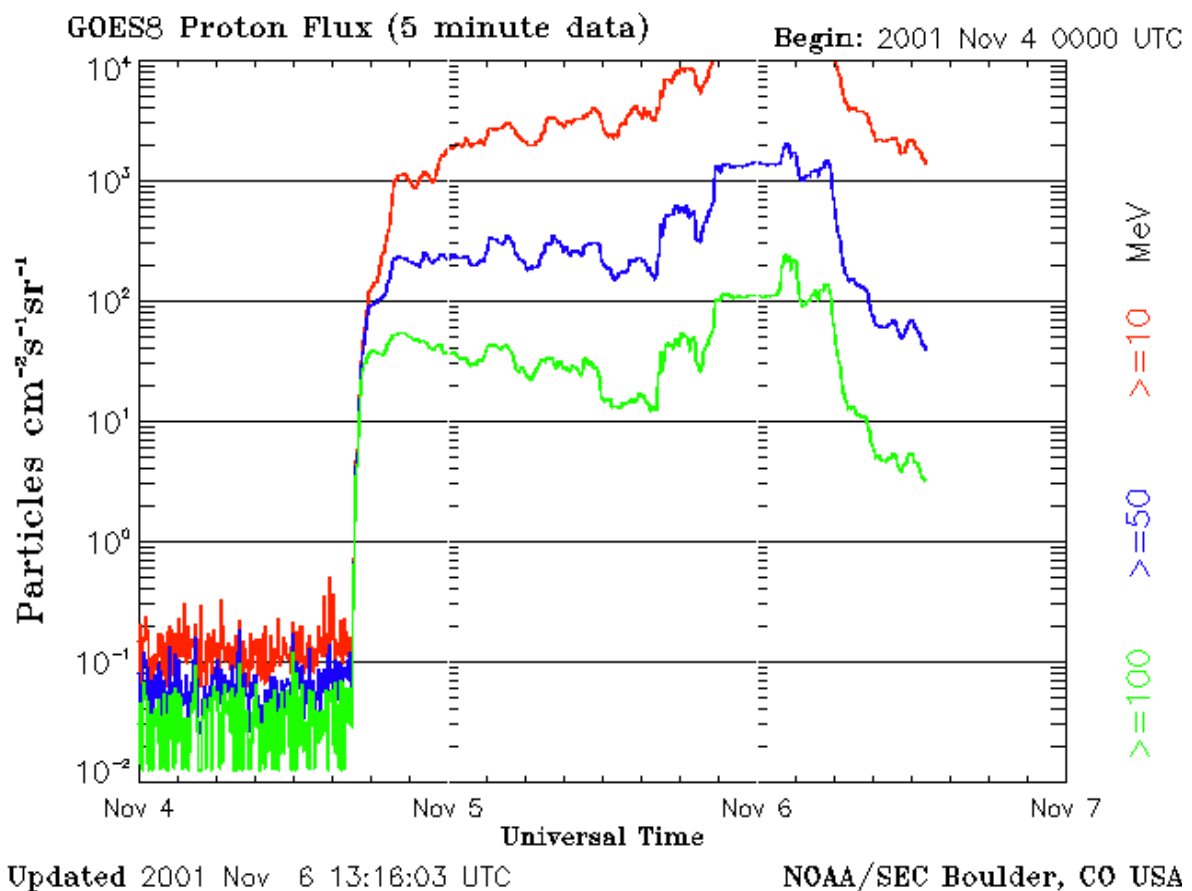
Figure 8 Increased Particle Density on November 06, 2001

References

[1]   Martinez de Aragon, A., Mura, F., Dionisio, C., Howes, S., Slim, R., Erickson, P. D. (1998) Future Satellite Services, Concepts and Technologies, ESA Bulletin - Future Satellite Services

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