REVOLUTIONARY SYSTEMS AND TECHNOLOGIES FOR MISSIONS TO THE OUTER PLANETS

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Abstract - The Advanced Deep Space System Development Program is managed by the Jet Propulsion Laboratory for NASA and is also called X2000. X2000 is organized to create advanced flight and ground systems for the exploration of the outer planets and beyond; it has been created to develop the engineering elements of flight and ground systems. Payloads will be developed by another team. Each X2000 delivery gets its requirements from a set of planned missions, or "mission customers".

The X2000 First Delivery Project supports missions to the Sun (to 4 solar radii), Europa (looking for a liquid ocean), Mars (in support of several Mars missions including a sample return), a comet (including a sample return), and Pluto followed by a trip into the Kuiper belt. This set of missions leads to some outstanding requirements:

1. Long-life (10-12 years)
2. Total Ionizing Dose of 4 Mrad (for a Europa Orbiter)
3. Average power consumption less than or equal to 150 Watts
4. Autonomous operations that result in an extreme reduction in operations costs

This paper describes the X2000 first delivery and its technologies following a brief overview of the program.

1 INTRODUCTION

X2000 was conceived to "fill the gap" between research and the immediate needs required to fly evermore challenging sets of deep space missions. For many years research has been conducted at NASA, some without a strong link to planned space missions, some ended before a viable technology could be architected into a flight and ground system. The X2000 Program selects technologies to incorporate into flight and ground systems and brings them to maturity for a set of missions.

Each mission set will use a flight and ground system incorporating technologies found in research labs at JPL and NASA centers and national labs. To do this, a survey of the latest technologies is regularly conducted and technologies are selected that could benefit a given set of missions. X2000 enlists the help of JPL's Center for Integrated Space Microsystems (CISM) and the Advanced Radioisotope Power System (ARPS) to do this. CISM is JPL's center of excellence for avionics and ARPS is a program funded by NASA and managed by the Department of Energy to produce next generation power sources for deep space missions. Once a plan has been put in place to bring these technologies to maturity, a clear architecture incorporating the technology has been conceived, and a schedule to produce a revolutionary flight and ground system has been written, the X2000 Program office spins-off a Project to engineer and produce the new flight and ground system.

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The First Delivery Project (FDP) for the X2000 Program was initiated in January 1998 and is chartered with delivering a flight and ground system for the following mission set:

1. Pluto/Kuiper Express
2. Europa Orbiter
3. Solar Probe
4. DS4/Champollion
5. Mars Sample Return

Requirements and designs produced by the FDP must meet the needs of this mission set--the FDP designs will be copied for each mission and thereby lower the cost of developing the flight and ground systems. Mission specific requirements or designs will not be included in the FDP or future deliveries. Missions must bear the non-recurring engineering costs of mission specific requirements. Ergo, the FDP will produce a core architecture for the mission set.

2 MISSION SET OVERVIEW

The mission set was derived from NASA's Solar System Exploration Subcommittee's (SSES) plan for the exploration of the solar system and by identifying the immediate needs of the New Millennium Program and Mars Exploration Program. The SSES has settled on the flight of the Pluto/Kuiper Express, Europa Orbiter, and Solar Probe as preeminent missions for early in the next decade. The New Millennium Program has selected DS4/Champollion for the same time period and the Mars Exploration office is set to conduct the Mars Sample Return mission circa 2003. Sample spacecraft configurations are shown in figure one.

The missions cover a wide range of targets, science goals, and environmental conditions. Solar Probe operates within 4 solar radii of the sun (at 3,000 times the solar incidence at Earth) while the Pluto/Kuiper Express mission will operate out to beyond 40 AU (where the solar incidence is 0.0006 times that at Earth). The Europa Orbiter will be exposed to 4 Mrad of radiation (behind 25 mm of Al), while other missions experience less than 100 krad. The Europa mission requires high data rate telecommunications to recover the science data within its brief lifetime on orbit. Some of the other missions need only minimal data rates.[1]

The DS-4 comet lander is severely power constrained, as are the Europa and Pluto spacecraft. All of these missions are mass constrained, but especially so is the Mars Sample Return Ascent Vehicle. Developing a common package of avionics and engineering sensors to meet the requirements of such a mission set is extremely challenging, so modularity, scaleability, and upgradability are key to the X2000 architecture.

In addition to technical challenges, the FDP must produce designs that can be replicated at low cost. These missions (except the Mars Sample Return) have development budgets that are much lower than NASA's Discovery class of missions. For example, the cost cap on Discovery proposals by the year 2003 will be approximately $245M. The Europa Orbiter and DS4/Champollion will cost $191M and $162M respectively in 2003 when they launch.

2.1 Europa Orbiter

In June 1996, the Galileo mission team found strong evidence for surface cracking and ice floe on Jupiter's moon Europa. Later observations have found evidence of water erupting. These were followed quickly by clear evidence of what appear to be icebergs now frozen into place, but which appear to have been floating on something that is difficult to conceive of as anything but liquid water.

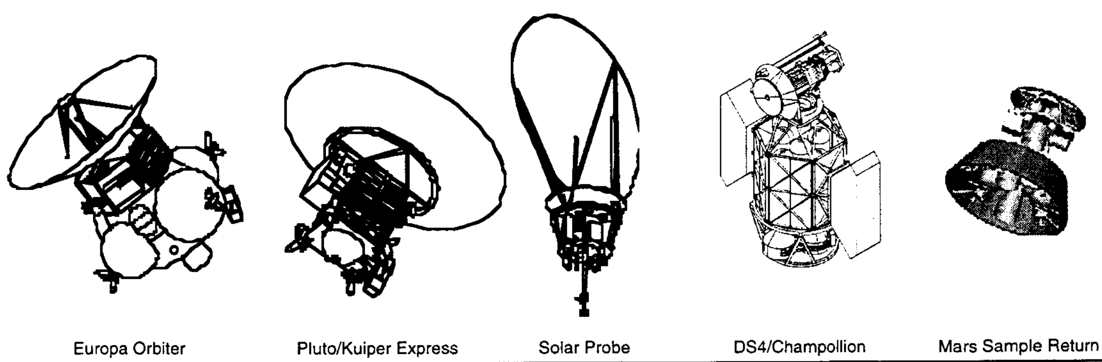

Figure 1. Spacecraft Configurations (each configuration is on a different scale)

The current design for the Europa Orbiter would take about three to four years to reach the Jovian system and an additional one and a half years to reach orbit around Europa. The primary science mission consists of one month in orbit around the moon taking data and relaying the data back to Earth. The mission duration is limited by the total ionizing dose radiation levels present in the Jovian system.

2.2 Pluto/Kuiper Express

Pluto is the only planet in our Solar System which has not been explored remotely. Pluto and its moon Charon form a system which has an orbit varying dramatically in distance from the Sun. Currently, Pluto's orbit is within the orbit of Neptune, but 124 years hence, it will be outside Neptune's orbit at an aphelion of 49 AU.

After a brief flyby of Pluto, the trajectory will be altered to fly into a group of objects referred to as the Kuiper Belt. Kuiper objects, predicted in the late 1940's by Edgeworth and Kuiper, were only discovered in the early 1990's. These small objects form a disk around our Solar System and are believed to be remnants of the formation of the Solar System and the primary source of short period comets. By studying at least one of these objects, scientists hope to learn more about the possible origin of volatiles which form the Earth's atmosphere and oceans.

2.3 Deep Space 4/Champollion

The New Millennium Program's Deep Space 4 mission is planned to rendezvous with Comet Tempel 1, land on its surface, recover a sample, and possibly return it to the Earth. The flight system uses a Solar Electric Propulsion (SEP) module to provide the 10.5 km/sec delta V required to perform the mission.

The lander contains avionics, comet surface science instruments, anchoring, and sample acquisition equipment. After arrival at the comet, the flight system will go into orbit around the nucleus, and the lander will separate from the SEP module, set down on the surface, anchor itself, and conduct a series of science experiments, including the acquisition of samples. During surface ops, the orbiting SEP module will act as a radio relay for the lander.

At the completion of data collection, the lander will jettison its anchoring module, leave the comet surface, and rendezvous and dock with the SEP module. The samples will be transferred to an Earth return entry capsule. Then the entire flight system will power up the ion thrusters and return to Earth. Just before arrival, the flight system will put the Earth entry capsule into the correct corridor and jettison the capsule for recovery on Earth.

2.4 Mars Sample Return--Ascent Vehicle

The 2004 Mars Sample Return mission will be one of the most challenging interplanetary ventures of the early 21st century. Extreme measures must be taken to minimize mass to perform the mission with a launch vehicle small enough to fit within the cost cap. The Ascent Vehicle is the most mass constrained component of the mission, since all of the propellant required to boost it back into Mars orbit must first be soft landed on the Martian surface.

2.5 Solar Probe

Solar Probe is an exploratory mission to our star. Scientists are only beginning to understand the relationship between the sun, its atmosphere (the corona), and the solar effects on the earth. The mission is designed to take scientific instruments to within 4 solar radii of the Sun's atmosphere where they will make measurements to determine what causes the heating of coronal particles, as well as what are the sources and acceleration mechanisms in the solar winds. The low altitude passes of the Solar Probe spacecraft over the polar regions will allow imaging that has here-to-fore been impossible and at perspectives that will never be attained from near Earth observatories.

3 X2000 FIRST DELIVERY ARCHITECTURE

The following diagram is the architectural framework used to develop the requirements and designs and it is divided into flight and ground systems and software and hardware. Several key concepts in the architecture can be seen here. One, ground based computing networks are high-speed and have become prevalent and easy and inexpensive to use. The FDP architecture carries this concept into the flight system for the connection of subsystems and assemblies. IEEE 1394 (sometimes called Firewire) connects CPUs, telecommunications equipment and science instruments; this bus was selected as more reliable and less power hungry than say ethernet. The IEEE 1394 bus also allows for multiple masters and provides an isochronous channel that gives developers the means to schedule regular and synchronous activities. 1394 also holds the opportunity to allow simple personal computers to be connected to the bus for software development or simulations between a personal computer and an instrument--this will lower costs for ground support equipment and s/w development.

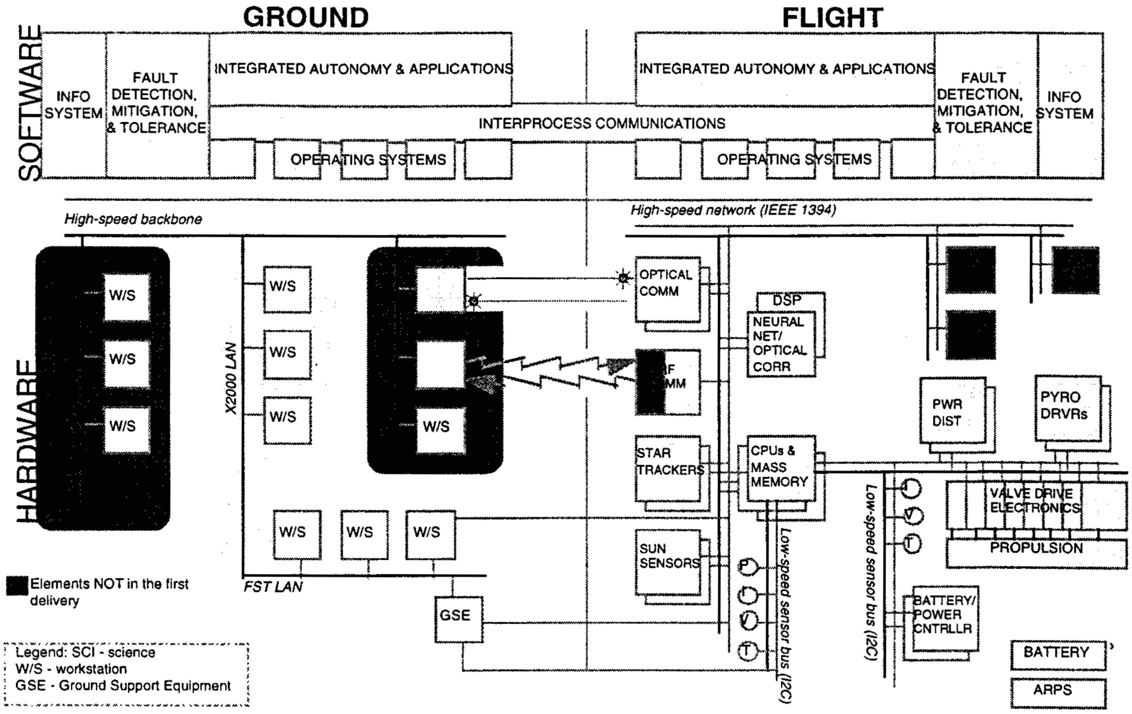

Figure 2. X2000 First Delivery Architectural Framework

Another key concept of this architecture is the symmetry between flight and ground software. For years, deep space missions have flown software architectures developed in separate organizations. This has led to incompatibilities in designs that are not discovered until system integration and test. The X2000 program is embarking on an effort to architect all software simultaneously. The effort will take years, but efforts to date suggest that a good deal of commonality can be achieved in the first delivery.

The first delivery will be in a configuration very close to that shown in figure two. The delivery can then be operated in a "closed-loop" mode.

4 SELECTED FIRST DELIVERY TECHNOLOGIES

The following is a brief description of selected technologies--a complete description of all technologies is beyond the scope of this paper:

Mission Data System (MDS): MDS engineers will architect all flight and ground software, ground data system, and the ground support equipment into a common architecture. The MDS faces several engineering challenges; the FDP MDS must deliver typical engineering functions, such as attitude control, command services, telemetry, fault protection and others, and the MDS must enable re-use and ease of modification. Five missions will need to use this software; the FDP must architect the software to minimize the challenges they will face in re-using the software and modifying the software for any mission specific applications.

The MDS will begin the development of autonomous tasks such as resource management and allocation on a highly constrained flight system and scheduling and planning of finely and coarsely specified events. Some of these problems have already been solved on previous missions. For example, the Cassini attitude control system has isolated examples of sophisticated resource handling, such as the main engine venting, priming, and firing software. Pathfinder used large numbers of asynchronous tasks to greatly simplify software design. FDP will build upon and generalize that work.

The MDS must specify designs so groups of programmers, analysts, hardware designers, and operations personnel can work in parallel, all the while inventing new ways of doing things.

Avionics: This subsystem integrates Command and Data Handling (CDH), Power System Electronics (PSE), and Attitude Control Sensors. CDH and PSE are composed of micro-electronics mounted on 100 mm x 100 mm (4 in x 4 in) slices which can be stacked together or separated and wired together in slices. The packaging approach is shown in figure 3. The baseline avionics for the first delivery includes 3 CPUs, mass memories, power switching, pyro control, propulsion valve drive electronics, battery control, power bus management electronics, star trackers, sun sensors, and inertial measurement units.

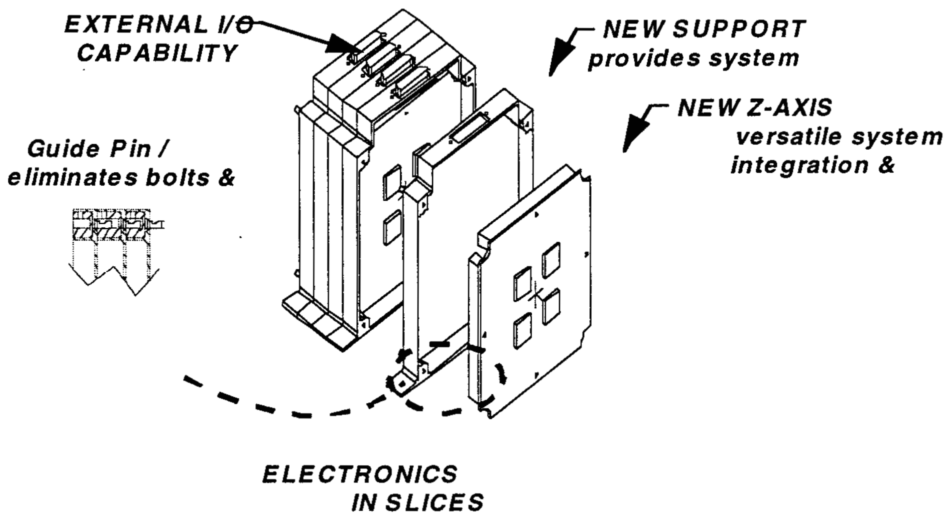

Figure 3. CDH and PSE Packaging

Mechanical: This subsystem integrates the components of the first delivery onto a rigid and easily integrable structure. It is divided into the following disciplines: mechanical, thermal, and cabling. The core of this design is an Integrated Avionics Structure (IAS). This approach mounts the electronics on load-bearing panels (there are no sub-frames or supports) and connects the electronics via circuit paths bonded to the panels--this approach minimizes the need for traditional cables. The panels are then bolted together and electrically integrated with flex connectors. See figure 4.

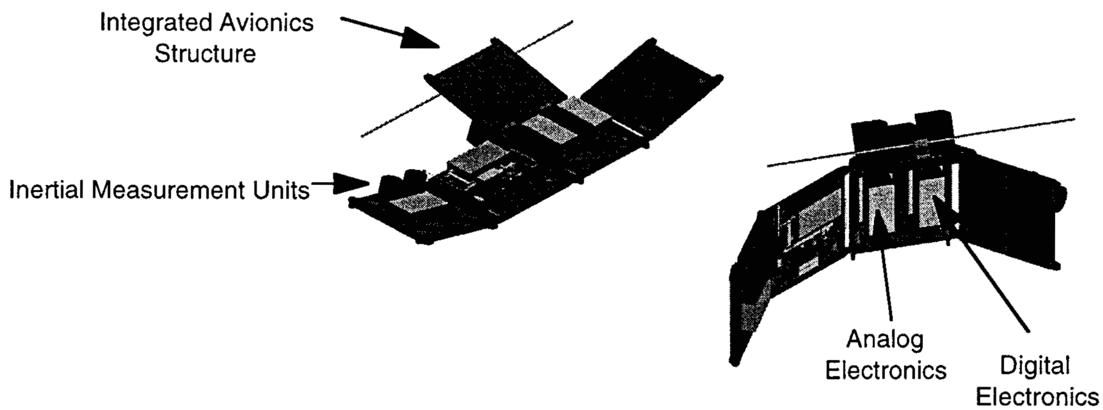

Figure 4. Integrated Avionics Structure

Propulsion: In this area, the FDP is building a hydrazine milli-Newton thruster (HmNT) for very fine pointing control. Nine-tenths Newton class thrusters cannot provide accurate pointing on spacecraft that are in the mission set. The HmNT provides a minimum impulse of 0.0001 N-s and Isp of 100 s. The FDP is also building a Variable Liquid Regulator (VLR) to regulate fuel and oxidizer flow to a bipropellant main engine--this greatly simplifies the propulsion system design and its accompanying fault protection. The VLR is being designed so that it can be set once just before a main engine burn and it will not have to be reset until a subsequent burn.

Telecommunications: This element is divided into an Optical Communications Subsystem and an RF Subsystem. The Optical System includes a telescope, tracking system, laser downlink, and uplink/downlink handling electronics. See figure 5. The Optical Communications Terminal (OCT; see figure 5) is a 30 cm diameter telescope mounted on top of an optics table and supporting electronics. The OCT is capable of producing telemetry from Jupiter at 100-300 kbps; for the same input power, an RF system would produce only 10 kbps. For the RF Subsystem, X2000 FDP is building the Spacecraft Transponding Modem (STM)--a consolidation of a traditional transponder, receiver, command detection unit, power supply, and telemetry modulation unit into a volume of 600 cm^3 (38.4 in^3)

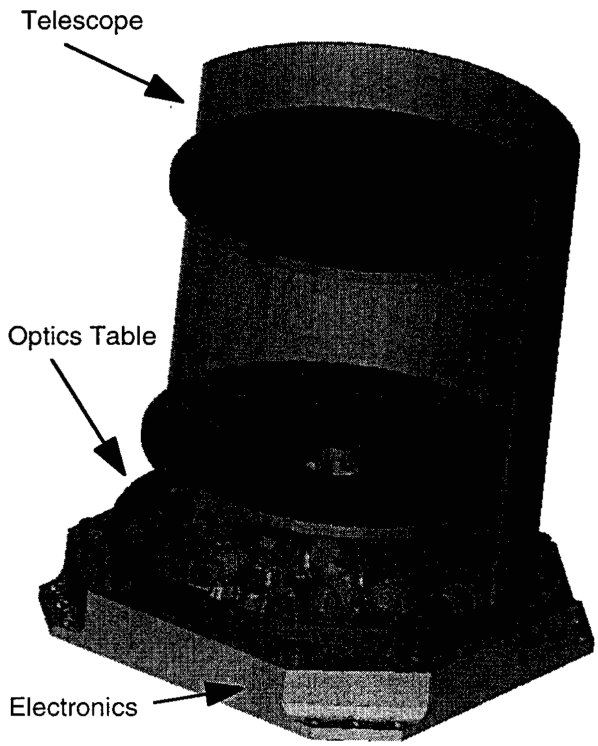

Figure 5. Optical Communications Terminal

5 ACKNOWLEDGMENTS

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