THE INTEGRATED HOUSEKEEPING UNIT: A METHOD OF TELEMETRY, COMMAND AND CONTROL FOR SMALL SPACECRAFT.

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ABSTRACT

In a small satellite environment where the total power budget for telemetry, command, ranging and all satellite control functions is not to exceed 2 Watts, rather focused measures must be taken to consolidate these functions. Since 1975 AMSAT has been developing the concept of the Integrated Housekeeping Unit (IHU) for this purpose. The IHU combines the traditional telemetry encoder and command decoder with a multi-tasking microcomputer so that this single module is capable of handling all spacecraft functions simultaneously. The nature of the orbit planned for the series of spacecraft for which this unit was developed results in a high radiation environment for the IHU. Special attention was paid to this in the design. A high-level language has been developed for the IHU. Called IPS, it operates on up to eight simultaneous tasks, including telemetry and command processing, and navigational functions concerned with orbital insertion and stationkeeping. The development of this concept is described in this paper.

MISSION OUTLINE

In 1975 AMSAT began planning the first in a series of high altitude communications satellites for the amateur radio community. Called Phase 3, the primary payload function was to provide one or more medium bandwidth linear transponders for general communications by licensed amateur radio operators. Frequency division multiple access (FDMA) allowed the available bandwidth to be shared among many simultaneous users.

An elliptical Moniya-type orbit was chosen (see Figure 1) with a perigee of about 1500 km and an apogee of 36000 km. With a period of about 700 minutes, and an inclination 63 degrees this orbit has the property that the argument of perigee remains almost fixed. The two daily apogees thus occur above the Northern hemisphere, in view of those parts of the earth with the greatest concentrations of potential users. A three year mission lifetime was the aim.

SPACECRAFT DESCRIPTION

The spacecraft is a three-armed structure. (see Figure 2). It is spin stabilized, spin rate and direction being controlled by a system of magnetic torquing coils which are activated near perigee, when the Earth's magnetic field is strongest.
Launch into an initial geostationary transfer orbit was selected as being compatible with a wide range of other missions, thus making effective use of the dual launch capabilities of vehicles such as Ariane. In order to get into a Molniya orbit, an apogee kick motor was included to raise the perigee and increase the inclination of the orbit.

The spacecraft has two sets of antennas; high gain for use near apogee, and low gain for use near perigee, since the high gain antennas are then pointing away from the Earth.

A functional block diagram of the Phase-3B spacecraft is shown in Figure 3. This was the second of the three spacecraft so far constructed, and is a good example of the series. There are five major systems; each will be described briefly.

**Power System**

Six solar panels provide a beginning-of-life power of about 50 Watts. A novel redundant battery-charge-regulator (BCR) keeps an 8AH battery charged. An auxiliary battery is maintained offline in a discharged state. The 14 Volt battery voltage is available for use directly by some modules; and a 10 Volt regulated supply is also distributed. A separation switch allows power to the transmitters only once separation from the launch vehicle has occurred, to prevent radiation of RF energy and possible interference with launch vehicle systems during launch.
Fig. 2 Phase 3 spacecraft after deployment. Spin axis is coincident with the axis of the helix antenna.

**Communication System**

Two linear transponders are provided. Only one can be active at any given time due to DC power limitations; additionally, on Phase-3B, the input band of one transponder is close to the output band of the other, making them incompatible from an interference point of view. Each transponder can feed either a high or low gain antenna system, as mentioned above.

**Attitude Control System**

The attitude control system is based around the sensor/electronics unit (SEU). Pulses from Sun and Earth sensors are pre-processed in the SEU and then passed on to the IHU, which uses them to update its navigational information. Near perigee, the IHU commands power control circuits in the SEU to pulse the torquing coils as needed to maintain desired spin rate and direction.
Fig. 3 Phase 3 spacecraft functional block diagram showing the IHU in relation to other systems.

**Motor System**

Phase-3B employed a 400 Newton bipropellant thruster [1]. Efficient use of the re-start capabilities of this motor was planned, allowing the desired orbit to be obtained by at least two burns. The liquid ignition unit (LIU) controlled the motor; it in turn was commanded by the IHU.

**IHU**

At the heart of the spacecraft is the IHU (Fig. 3). Once the spacecraft is on-orbit, it performs the following functions:

- Collection of data from 64 analog telemetry channels
- Generation of two separate telemetry streams
o Processing of all uplinked command information after command validation

o Processing of all sensor data from the SEU

o Execution of magnet torquing maneuvers to change spacecraft attitude (operates closed loop with sensors)

o Monitoring of the power status of the spacecraft and manipulation of the BCR when required. (under closed loop control)

o Execution of a schedule program which modifies the operating modes of the two transponders and four antennas at different points along the orbit track

o Management of a bulletin board within the spacecraft to allow command stations to advise one another on the health of the spacecraft and the last commands sent.

o Performance of other miscellaneous tasks

During the orbit-insertion phase, the IHU performs most of the above tasks, except that the transponders are not available for general use, and are only to be enabled to allow ranging to take place. During this phase the IHU must:

o Prepare the LIU for operation, by operating safety interlocks which pressurize the motor systems from a master helium tank

o Orient the spacecraft spin vector correctly for each burn

o Command the LIU to fire the motor at the correct time and for the correct duration

IHU HARDWARE

The IHU is comprised of four circuit boards, arranged in three layers, as follows:

Inner_layer: Random access memory (RAM) board
Middle_layer: Central processing unit (CPU) board
Outer_layer: Multiplexer (MUX) and command detector (CMD) boards

CPU_board

The RCA COSMAC CDP1802 microprocessor was selected as the processor, primarily because it was the only suitable CMOS device available at the time of the initial design. This choice has proven to be a good one, as the processor has been flexible and powerful enough to meet the more complex demands of the later missions. In addition, a radiation hardened version of the processor, built using silicon-on-sapphire technology became
The CPU runs at a clock rate of 1.68 MHz, and the card contains all the support circuitry for the 1802. Additionally, there are 5 general purpose latched 8-bit output ports; 4 general purpose 8-bit input ports; an 8-bit digital-to-analog converter; and circuitry to generate two separate serial data streams for telemetry beacons.

A novel feature of this design is that the IHU uses only RAM. There is no read-only-memory (ROM). Re-booting of the computer is accomplished by circuitry which senses a particular sequence of bits in the command uplink data stream, and then places the processor in the "Load" mode. In this mode, the 1802 simply resets a memory address pointer to zero, and performs a memory save operation on incoming data bytes, incrementing the address pointer after each operation. Thus, the bytes in the first valid command block after a reset are stored in sequential locations in low memory. After 128 bytes (1 command block) the processor is put back into "Run" mode, and begins execution with memory address 0. Thus, the first 128 byte block must contain a minimal bootstrap loader which will then load subsequent blocks in the appropriate memory locations until the entire operating system has been loaded, and control can be passed to it.

The reason for this somewhat unusual approach is that at the time of the initial design there were doubts that ROM then available would be able to survive the radiation expected in the proposed orbit. In fact, no problems have been experienced with this approach, which also possesses the property that the bootstrap loader could be changed in orbit as operational experience dictates.

**RAM board**

A computer memory of 2k bytes was envisaged early in the design cycle, but by the time the first flight unit had been built, this had grown to 16k. The latest unit completed had 32k of radiation-hardened memory.

The problem of radiation damage is explicitly attacked at the electrical design stage of the memory. An error-detection-and-correction (EDAC) scheme is used. The processor operates with 8-bit bytes; as a memory-save operation takes place, the byte to be saved passes through an encoding matrix which generates 4 additional bits. These are stored in memory at the same address as the main byte. On being retrieved from memory the twelve bits pass through another matrix which can detect a single-bit error, and tell in which bit it occurred, thus allowing it to be corrected. The processor, as a background task, is continuously cycling through the memory address space, reading each byte, and then writing it back. If a radiation induced bit-flip has occurred, it will be corrected during the read cycle, and the correct byte will be restored during the write cycle. The cycle time for this process is about 43 seconds for a 16k memory.
The memory is thus protected against radiation-induced bit-flips, provided that no more than one occurs in a word in about a 1-minute period.

MUX and CMD

The outermost layer of the IUH contains these two boards. The CMD is fed a differentially coded serial NRZ data stream, from the command receiver and performs bit timing recovery and differential data extraction. The CMD monitors the uplink, and on receipt of a valid unique flag, begins passing data to the CPU in a byte-parallel format. The 128 bytes following the flag represent an uplink "packet".

The MUX is a 64-way analog switch. This converts the single DAC on the CPU into a 64-channel scanning voltmeter. The input range is 0 to +2 volts, so each quantity to be measured must be converted to lie in this range. For voltages, this is easily achieved. Currents are measured by using a "magnetometer" approach: sensing the bias in the hysteresis loop of a metallic core through which a wire carrying the current to be measured is passing. Temperatures are measured by thermistors, which are biased to produce a voltage in the correct range over temperature.

RADIATION PROTECTION

A spacecraft in a Molniya type of orbit encounters the Van Allen radiation belts twice per orbit. Measures must be taken to ensure survival of the spacecraft electronics in the face of this large cumulative radiation dose.

It was determined early in the design that the most susceptible module to radiation would be the memory. This was the subject of special attention, which included the following measures, in addition to the EDAC design described above:

- Choosing RAM chips with the best possible radiation properties.
- Self shielding, by placing the RAM board as close to the center of an arm as possible, thus using outer modules as shields.
- Local shielding. Each integrated circuit was sandwiched between two small rectangular sheets of tantalum.
- Group shielding. The RAM ICs were grouped together on the circuit board, and the whole group surrounded by a brass enclosure.

SOFTWARE

Special purpose software was developed for the IUH. The main concern was to ensure that the spacecraft was capable of operation for extended periods out of view of a command station. This situation occurs because of the nature of the orbit, and the relatively small number of command stations and their geographic
The IHU runs a high-level language called IPS (Interpreter for Process Structures), a threaded-code language similar to Forth. In this language, a number of basic procedures are defined, and applications are built up by stringing together addresses of these routines in the order in which they are to be executed. Each application is given a new name, which can be used in subsequent definitions. The language is thus powerful, flexible, and extensible. An additional important consideration is that it is extremely efficient in terms of memory usage, making good use of scarce spacecraft resources.

Execution of multiple tasks is made possible by placing them in a special "chain". This is a circular list of very high level definitions to be executed. The IHU sequences through them executing each in turn. A task can "dechain" itself, leaving a no-op in its place; or it can "enchain" another task in its place. There are eight chain positions available for application tasks.

The IHU maintains a real time clock, and also contains an ephemeris which allows autonomous operation of the attitude control system. This is possible because the IHU also has a simple model of the geomagnetic field; this combined with orbital information allows the torquing coils to be energized at the proper times.

PERFORMANCE RESULTS

The IHU development effort is briefly outlined in Table 1. The major change over time has been in memory. Early units used NMOS RAM chips; the last unit built used CMOS. This change has had several important benefits:

- Power consumption is less
- Memory size has been doubled to 32k
- Radiation hardness has been increased.

The CMOS unit is currently undergoing qualification, and is expected to become the prime IHU for the Phase 3-C mission when this is completed.

The only unit to see service in orbit so far has been that on the Phase 3-B spacecraft (Oscar 10). This unit delivered nearly four years of satisfactory service before radiation damage reduced its usefulness. The unit is now only conditionally operational, as it is difficult to maintain large programs operational in memory.
<table>
<thead>
<tr>
<th>Model</th>
<th>Memory</th>
<th>Deployment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conceptual design</td>
<td>2k NMOS</td>
<td>N/A</td>
</tr>
<tr>
<td>Phase 3-A</td>
<td>16k NMOS</td>
<td>Lost (Launcher failure)</td>
</tr>
<tr>
<td>Phase 3-B</td>
<td>16k NMOS</td>
<td>1983-1987</td>
</tr>
<tr>
<td>Phase 3-C prime</td>
<td>16k NMOS</td>
<td>Awaiting launch in early 1988</td>
</tr>
<tr>
<td>Phase 3-C altern.</td>
<td>32k CMOS</td>
<td>In qual. May become prime</td>
</tr>
</tbody>
</table>

Table 1 IHU genealogy.

LESSONS LEARNED

The IHU concept has been remarkably successful. The design is still relatively stable 12 years after its conception. It has proved powerful and flexible enough to grow with the mission complexity.

It has also been responsible for bringing a certain amount of order to the interface control process. Since the prime interface of most modules is with the IHU, a document called "spacecraft as seen by the computer" was drawn up early in each mission. This detailed what was connected to each port, and how it was expected to respond in any situation. Thus, development of other spacecraft systems could proceed in parallel with the software development.

One problem that has been recognised is that as the spacecraft complexity grows, the sheer number of wires being brought into the IHU grows. This is because each control signal is fully decoded in the IHU. The last of the present series of IHUs has been built, and for future missions [2] AMSAT is studying the possibility of a bus-oriented control hierarchy. This will allow the use of a common IHU in different missions of widely varying complexity, with only minor variations in the wiring harness.

REFERENCES
